

Christian Breyer

Economics of Hybrid Photovoltaic Power Plants

This work has been accepted by the faculty of Electrical Engineering and Computer Science of the University of Kassel as a thesis for acquiring the academic degree of Doktor der Ingenieurwissenschaften (Dr.-Ing.).

Supervisor: Prof. Dr.-Ing. Jürgen Schmid, University of Kassel, Germany

Co-Supervisor: Prof. Dr.-Ing. Ingo Stadler, Applied University of Cologne, Germany

Defense day

16th August 2012

Bibliographic information published by Deutsche Nationalbibliothek

Die Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie;
detailed bibliographic data is available in the Internet at <http://dnb.d-nb.de>

Zugl.: Kassel, Univ., Diss. 2012

The Story Behind

This thesis is finally dedicated to the species we have already lost and we will lose due to the self-destroying men. The true treasure of planet earth is biodiversity and the uniqueness of ecosystems. The high complexity of the interdepending ecosystems is nothing else than the most precious mankind has ever found in the universe.

However, the current development of mankind and the impact of the resulting consequences on life will lead to an apocalyptic mass extinction – maybe including the human species and very likely in a rather short period of historic time.

The energy question might be the centrepiece of a survival strategy. This thesis is created in the mindset of better understanding the role of solar photovoltaics for the great transformation towards global sustainability. The following quotes shall express this way of thinking from different ethical, historical, social or even spatial view points.

Christian Breyer

Our grandchildren will surely blame us if they find that we understood the reality of anthropogenic climate change and failed to do anything about it.

Naomi Oreskes
Science, 2004, 306, 1686

The LORD God took the man and put him in the Garden of Eden to work it and take care of it.

Genesis 2:15

Following the light of the sun, we left the Old World.

Christopher Columbus



Blue Marble

the most printed photo in history

From space, we see a small and fragile ball. Humanity's inability to fit its doings into that pattern is changing planetary systems, fundamentally. Many such changes are accompanied by life-threatening hazards. We have the power to reconcile human affairs with natural laws and to thrive in the process. In this our cultural and spiritual heritages can reinforce our economic interests and survival imperatives.

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

World Commission on Environment and Development

Economics of Hybrid Photovoltaic Power Plants

Table of Contents

0. Overview on the Thesis	
0.1. Abstract	11
0.2. Executive Summary	13
0.3. Organization	23
1. Boundary Conditions of Electricity Generation in the 21st Century	27
1.1. Increasing Global Power Demand	28
1.2. Climate Change Impact	29
1.3. Diminishing Energy Fuel Resources	33
1.3.1. Crude Oil	34
1.3.2. Natural Gas	36
1.3.3. Coal	38
1.3.4. Uranium	39
1.4. Energy Injustice	43
1.5. Ecological Footprint	49
2. Solar Resources	51
2.1. Global Horizontal Irradiation as Basis for all Solar Resources	51
2.2. Resources Adapted for Basic Solar System Concepts	55
2.2.1. Overview on Solar System Concepts	55
2.2.2. Methodology for Solar Resource Calculations	56
2.2.3. Fixed Optimally Tilted Systems	59
2.2.4. 1-axis Horizontal East-West Continuous Tracking System	65
2.2.5. 1-axis Horizontal North-South Continuous Tracking System	67
2.2.6. 1-axis Vertical Optimally Tilted Continuous Tracking System	70
2.2.7. 1-axis Optimally Tilted North-South Continuous Tracking System	73
2.2.8. 2-axes Non-concentrating Continuous Tracking System: Global Normal Irradiation	75
2.2.9. 2-axes Concentrating Continuous Tracking System: Direct Normal Irradiation	79
2.3. Weighted Irradiation	81
2.3.1. Population and Area Weighted Irradiation	81
2.3.2. Electricity Generation Weighted Irradiation	85
2.4. Comparing Solar Resources	86
3. Photovoltaic Economics	89
3.1. Fundamental Trends	89
3.1.1. Historic Market Growth	89
3.1.1.1. Historic Photovoltaic Diffusion Phases	90
3.1.1.2. Photovoltaic Growth Rates	92
3.1.1.3. Global Photovoltaic Market Potential Estimate	94
3.1.2. Experience Curve Concept	95
3.1.3. Research and Development Investments	100
3.1.3.1. Public R&D Investments	100

3.1.3.1.1. Energy R&D Investments	100
3.1.3.1.2. Renewable Energy R&D Investments	101
3.1.3.2. Corporate PV R&D Investments	103
3.1.3.2.1. PV R&D Investments of Public Listed PV Focussed Companies	103
3.1.3.2.2. PV R&D Investment Estimates for Companies Without Disclosed PV R&D Financials	106
3.1.3.2.3. Current Global Corporate PV R&D Investments	107
3.1.3.3. Global Historic PV Patent Applications	108
3.1.3.3.1. National PV and Inverter Patent Applications	108
3.1.3.3.2. International PV and Inverter Patent Applications	110
3.1.3.3.3. Geographic Origin and Leading Assignees of International PV and Inverter Patent Applications	111
3.1.3.3.4. Academic and Business Origin of International PV Patent Applications	113
3.1.3.3.5. Global Annual and Historic Cumulated PV R&D Investments	114
3.1.3.3.6. Global PV R&D Workforce	118
3.1.3.4. Discussion of Major Results of PV R&D Investment Analysis	119
3.1.3.4.1. PV R&D and Market Potential in Relation to Relevant Comparable Industries	120
3.1.3.4.2. Sustainability Requirements and Public Renewable Energy R&D Investments	120
3.1.3.4.3. R&D Investment and Sustainability Impact – The Example of PV and Nuclear Energy	121
3.1.3.4.4. Willingness to Invest for Major Public Technological Projects: A 20 th Century Experience	122
3.1.4. Regional Markets	123
3.1.5. Technology Diffusion	128
3.1.6. Energetic Sustainability	141
3.1.6.1. Energy Payback Time	141
3.1.6.2. Energy Return on Energy Investment	144
3.1.6.3. Solar Breeder Concept	146
3.1.7. Specific Emissions	147
3.1.7.1. Greenhouse Gas Emissions	147
3.1.7.2. Heavy Metal Emissions	150
3.2. Systems Overview	152
3.2.1. Levelized Cost of Electricity of PV Systems	152
3.2.2. Cost Projections of Systems	156
3.2.2.1. Ground Cover Ratio and Shading	156
3.2.2.2. Financial Scenario Assumptions	159
3.2.2.3. Global Industry Cost Curves for PV Systems	166
3.2.3. Least Cost of Systems	169
3.2.4. Diffusion of Systems	173
3.3. On-grid End-user Systems: Grid-Parity	178
3.3.1. Grid-Parity Concept	179
3.3.2. Grid-Parity Model and its Assumptions	179
3.3.3. Results of Grid-Parity Analysis	183
3.3.3.1. Europe	183
3.3.3.2. The Americas	185
3.3.3.3. Africa	186

3.3.3.4. Asia-Pacific	187
3.3.3.5. Development over Time of Total Addressable Grid-Parity Market Segments	189
3.4. Off-grid End-user Systems: Fuel-Parity	194
3.4.1. Solar Home Systems	196
3.4.1.1. Economics of Solar Home Systems for the Case of Ethiopia	196
3.4.1.2. Global Market for Solar Home Systems	200
3.4.2. Hybrid PV Systems	204
3.4.2.1. General Overview on Small Scale Hybrid PV Systems	204
3.4.2.2. Hybrid PV-Diesel and PV-Storage Systems	210
4. Solar Thermal and Wind Power Plant Economics	217
4.1. Solar Thermal Electricity Generation	217
4.1.1. STEG Resource	217
4.1.2. STEG Plants	218
4.1.3. STEG Economics	221
4.2. Wind Power	228
4.2.1. Wind Resource	228
4.2.2. Wind Power Plants	231
4.2.2.1. Global Overview on Wind Power Capacity	232
4.2.2.2. Simple Electric Wind Power Modelling	235
4.2.3. Wind Power Economics	239
4.3. Integrated Assessment of PV, STEG and Wind Power Economics	244
5. Power Plants of the World	251
5.1. Overview on General Global Electricity Consumption Patterns and Power Plants	252
5.2. Biomass Power	262
5.3. Geothermal Power	267
5.4. Ocean Power	272
5.5. Nuclear Power	274
6. Hybrid Photovoltaic Fossil Power Plants	281
6.1. Preconditions for Successful PV Hybridization	281
6.1.1. Fundamentals on Hybridization	281
6.1.2. Flexible Operability of Fossil Power Plants	285
6.1.3. Energy Meteorology	288
6.1.4. Price Coupling of Fossil Fuels	290
6.2. Hybrid PV-Oil Power Plant	295
6.2.1. Global Overview on Oil Power Capacity	295
6.2.2. Oil Power Economics	301
6.2.3. Hybrid PV-Oil Power Plant Demand Curve	309
6.3. Hybrid PV-Gas Power Plant	315
6.3.1. Global Overview on Natural Gas Power Capacity	315
6.3.2. Natural Gas Power Economics	321
6.3.3. Hybrid PV-Gas Power Plant Demand Curve	330
6.4. Hybrid PV-Coal Power Plant	337
6.4.1. Global Overview on Coal Power Capacity	337
6.4.2. Coal Power Economics	342
6.4.3. Hybrid PV-Coal Power Plant Demand Curve	351
6.5. Hybrid PV-Fossil Power Plant Demand Curve	358

6.6. Total Global PV Market Potential	362
6.6.1. Overview on PV Scenarios	362
6.6.2. Overall Economic PV Market Potential	365
7. Hybrid Photovoltaic Renewable Power Plants	371
7.1. Hybrid PV-Hydro Power Plant	371
7.1.1. Global Overview on Hydro Power Capacity	371
7.1.2. Considerations on Hybrid PV-Hydro Power Plants	377
7.2. Hybrid PV-STEG Power Plant	380
7.3. Hybrid PV-Wind Power Plant	386
7.4. Hybrid PV-Wind-Renewable Power Methane-CCGT Power Plants	394
7.4.1. Renewable Power Methane Storage	395
7.4.2. Economics of Relevant System Components	399
7.4.3. Economic Analysis of Hybrid Renewable Power Methane Power Plants	409
7.4.3.1. Global Overview on Cost Trends	409
7.4.3.2. Case Studies for Selected Regions	420
7.4.3.2.1. Competitiveness of Hybrid RPM Power Plants in the US	421
7.4.3.2.2. Competitiveness of Hybrid RPM Power Plants in Chile	423
7.4.3.2.3. Competitiveness of Hybrid RPM Power Plants in Germany	425
7.4.3.2.4. Competitiveness of Hybrid RPM Power Plants in Saudi Arabia	427
7.4.3.2.5. Competitiveness of Hybrid RPM Power Plants in India	429
7.4.3.2.6. Competitiveness of Hybrid RPM Power Plants in China	431
7.4.4. Global Energy Supply Potential of Hybrid Renewable Power Methane Systems	434
Appendix	443
Table 1: Global Overview on Solar Resources (Population Weighted)	443
Table 2: Global Overview on PV Capacities Installed and Social Progress Indicators	447
Table 3: Global Overview on Grid-Parity	452
Table 4: Global Country Codes of Top Level Web Domain	455
Bibliography	459
List of Acronyms and Abbreviations	491
List of Figures	497
List of Tables	507
List of Equations	509
List of Publications	511
Danksagung	515

Overview on the Thesis

Abstract

The global power supply stability is faced to several severe and fundamental threats, in particular steadily increasing power demand, diminishing and degrading fossil and nuclear energy resources, very harmful greenhouse gas emissions, significant energy injustice and a structurally misbalanced ecological footprint. Photovoltaic (PV) power systems are analysed in various aspects focusing on economic and technical considerations of supplemental and substitutional power supply to the constraint conventional power system.

To infer the most relevant system approach for PV power plants several solar resources available for PV systems are compared. By combining the different solar resources and respective economics, two major PV systems are identified to be very competitive in almost all regions in the world. The experience curve concept is used as a key technique for the development of scenario assumptions on economic projections for the decade of the 2010s. Main drivers for cost reductions in PV systems are learning and production growth rate, thus several relevant aspects are discussed such as research and development investments, technical PV market potential, different PV technologies and the energetic sustainability of PV. Three major market segments for PV systems are identified: off-grid PV solutions, decentralised small scale on-grid PV systems (several kWp) and large scale PV power plants (tens of MWp). Mainly by application of 'grid-parity' and 'fuel-parity' concepts per country, local market and conventional power plant basis, the global economic market potential for all major PV system segments is derived.

PV power plant hybridization potential of all relevant power technologies and the global power plant structure are analyzed regarding technical, economical and geographical feasibility. Key success criteria for hybrid PV power plants are discussed and comprehensively analysed for all adequate power plant technologies, i.e. oil, gas and coal fired power plants, wind power, solar thermal power (STEG) and hydro power plants. For the 2010s, detailed global demand curves are derived for hybrid PV-Fossil power plants on a per power plant, per country and per fuel type basis. The fundamental technical and economic potentials for hybrid PV-STEG, hybrid PV-Wind and hybrid PV-Hydro power plants are considered. The global resource availability for PV and wind power plants is excellent, thus knowing the competitive or complementary characteristic of hybrid PV-Wind power plants on a local basis is identified as being of utmost relevance. The complementarity of hybrid PV-Wind power plants is confirmed. As a result of that almost no reduction of the global economic PV market potential need to be expected and more complex power system designs on basis of hybrid PV-Wind power plants are feasible.

The final target of implementing renewable power technologies into the global power system is a nearly 100% renewable power supply. Besides balancing facilities, storage options are needed, in particular for seasonal power storage. Renewable power methane (RPM) offers respective options. A comprehensive global and local analysis is performed for analysing a hybrid PV-Wind-RPM combined cycle gas turbine power system. Such a power system design might be competitive and could offer solutions for nearly all current energy system constraints including the heating and transportation sector and even the chemical industry.

Summing up, hybrid PV power plants become very attractive and PV power systems will very likely evolve together with wind power to the major and final source of energy for mankind.

Abstract (Deutsch)

Mehrere fundamentale Faktoren beschränken die Stabilität der weltweiten Elektrizitätsversorgung. Diese sind insbesondere die stetig zunehmende Nachfrage, sich erschöpfende fossile und nukleare Energieressourcen, Emissionen von sehr schädlichen Treibhausgasen, erhebliche Energieungerechtigkeit und ein global unausgeglichener ökologischer Fußabdruck. Photovoltaik (PV) Systeme werden hinsichtlich mehrerer Aspekte - speziell wirtschaftliche und technische - auf ihren ergänzenden und ersetzenden Energiebeitrag zum limitierten konventionellen Energiesystem untersucht.

Um den optimalen Systemansatz für PV Kraftwerke abzuleiten werden mehrere solare Ressourcen, die an die jeweiligen PV Systeme angepasst sind, verglichen. Infolge der ökonomischen Bewertung der solaren Ressourcen werden zwei besonders wettbewerbsfähige PV Systeme identifiziert. Das Konzept der Erfahrungskurven wird als wesentliche Methode für wirtschaftliche Projektionen in den 2010er Jahren genutzt. Die Haupttreiber für Kostensenkungen bei PV Systemen sind die Lernrate der Technologie und die Wachstumsrate der Produktion. Für diese werden die relevanten Aspekte diskutiert: Investitionen in Forschung und Entwicklung, technisches PV Marktpotenzial, zahlreiche PV Technologien und die energetische Nachhaltigkeit der PV. Die drei wesentlichen Marktsegmente der PV sind PV Lösungen für netzferne Gebiete, dezentralisierte kleinere netzgekoppelte PV Systeme (einige kWp) und große PV Kraftwerke (Vielfaches von 10 MWp). Das weltweite ökonomische Marktpotenzial für alle wesentlichen PV Marktsegmente wird hauptsächlich durch die Anwendung der 'grid-parity' und 'fuel-parity' Konzepte abgeleitet.

Das Hybridisierungspotenzial von PV Kraftwerken in Bezug auf alle relevanten Kraftwerksarten wird auf seine technische, wirtschaftliche und geografische Machbarkeit hin untersucht. Die wesentlichen Erfolgsfaktoren für hybride PV Kraftwerke werden diskutiert und umfassend für Öl, Gas und Kohle gefeuerte Kraftwerke, Windkraft, solarthermische Kraftwerke (STEG) und Wasserkraftwerke analysiert. Für die 2010er Jahre werden detaillierte weltweite Nachfragekurven für hybride PV-Fossile Kraftwerke unter Einbezug aller fossilen Kraftwerke, Länderdaten und Brennstoffarten ermittelt. Die fundamentalen technischen und ökonomischen Potenziale von hybriden PV-STEG, hybriden PV-Wind und hybriden PV-Wasserkraftwerken werden betrachtet. Die weltweite Ressourcenverfügbarkeit für PV und Windkraft ist exzellent, weswegen es von größter Bedeutung ist, ob sich PV und Windkraft durch eine kompetitive oder komplementäre Beziehung zueinander auszeichnen. Die Komplementarität von hybriden PV-Windkraftwerken wird bestätigt. Es ergibt sich daher keine Reduktion des globalen ökonomischen PV Marktpotenzials und Systeme auf der Basis von hybriden PV-Windkraftwerken sind sehr wahrscheinlich.

Das zentrale Ziel lautet erneuerbare Kraftwerkstechnologien in das globale Elektrizitätssystem zu integrieren und dabei eine Durchdringung von 100% zu erreichen. Neben Ausgleichskapazitäten werden hierfür Speicher benötigt, insbesondere für die saisonale Elektrizitätsspeicherung. Erneuerbares Methan (RPM) bietet sich hierfür an. Eine umfassende weltweite Analyse untersucht Elektrizitätssysteme auf der Basis von hybriden PV-Wind-RPM-Gaskraftwerken. Ein solches Elektrizitätssystem könnte unter Einbezug des Wärme- und Transportsektors und sogar der Chemieindustrie wettbewerbsfähig sein und nahezu alle heutigen Beschränkungen überwinden.

Hybride PV Kraftwerke stellen eine äußerst attraktive Option zur Elektrizitätsversorgung dar. Die Photovoltaik wird gemeinsam mit der Windkraft die Solar- und Windenergie als hauptsächliche und finale Energiequellen für die Menschheit etablieren.

Executive Summary

This thesis is dedicated scientifically to the fundamental economic potential of hybrid photovoltaic (PV) power plants. The considerations evolved from being focused on the concept of hybridization of PV and natural gas fired combined cycle gas turbines (CCGT) to various PV power plant combinations. Indications that PV sub-plants could become an integral cornerstone of global power supply in the years and decades to come are substantiated by the analysis leading to the conclusion that various hybrid PV power plant combinations need to be considered. A multitude of different hybrid PV power plants is possible, but the focus of the thesis are the economics of the following hybrid power plants: PV-Oil, PV-Gas, PV-Coal, PV-Hydro, PV-STEG, PV-Wind and PV-Wind-RPM-CCGT. Subsequently, key insights of the thesis are presented for the analysed hybrid PV power plants and underlying drivers.

Electricity generation needs to fulfil several **boundary conditions** for supporting a sustainable development in the 21st century. The total global electricity generation reached about 20,200 TWh_{el} in 2008, after an annual growth of 5.6% for the last six decades. It is expected to grow further to about 55,000 TWh_{el} annually by the mid of the century. Current status and expected demand growth in a business as usual approach violates several sustainability criteria.

Anthropogenic climate change is the largest and widest ranging market failure ever seen, according to Lord Nicolas Stern. Greenhouse gas (GHG) emissions, mainly caused by energetic use of fossil fuels are still increasing with soaring annual growth rates. Various local and global ecosystems are destabilized leading to disastrous social consequences for mankind. To a very large extent the global energy system is based on burning fossil fuels. Indications become pressing that one fuel after the other reaches global maximum production in the decades to come along with steadily increasing demand. The simple economic mechanism leads to steadily increasing fuel prices. Nuclear energy is no option due to violation of all sustainability criteria. The global energy consumption patterns document an enormous level of energy injustice, as the minor fraction of mankind use the major part of the conventional energy resources and about 20% of world population is still waiting for electricity. Access to electricity supply has been identified as a major driver of social progress, thus accelerating well working electrification is of utmost relevance. The business as usual developing path has failed, since the ecological footprint analysis reveals that current needs – of which more than 50% relate to energy use – of sources and sinks require a capacity of 1.5 planet earths for our way of living. The pathway of developing modern societies which has been successful in the past might very likely turn into a key driver for a complete collapse of civilization in the future. New approaches are desperately needed.

Economics of PV systems are determined by available **solar resources**. The localized total amount of global horizontal irradiation (GHI) and its composition of direct and diffuse irradiation specifies best adapted systems. The most widely used PV system configuration for power plants is a fixed optimally tilted one. For further analysis optimised tilt angles have been derived from irradiation and levelized cost of electricity (LCOE) for all relevant coordinates in the world. In part enormous deviations from the prevailing latitude angle assumption are found due to the inhomogeneously distributed diffuse fraction of GHI. In total seven different PV system technologies have been evaluated by the Hay-Davis-Klucher-Reindl (HDKR) model: fixed optimally tilted, 1-axis horizontal east-west, 1-axis horizontal north-south, 1-axis vertical optimally tilted, 1-axis optimally tilted north-south, 2-axes non-concentrating (GNI) and 2-axes concentrating (DNI) continuous tracking, respectively. The

fixed optimally tilted system increases the annual irradiation on module surface referenced to GHI by 0% up to 30% depending on the distance to the equator and the local composition of direct and diffuse irradiation. 1-axis tracking systems are able to increase the annual irradiation on module surface further by approximately 30%. Nearly all systems represent the best adapted solution in different geographic conditions. However, due to a good combination of irradiation increase and system design the 1-axis horizontal north-south continuous tracking system might be the most favourable solution across all geographic conditions. Whilst increasing system complexity the 2-axes GNI system does not lead to a very significant increase of irradiation, however the 2-axes DNI system might still be a competitive choice in case of sites with excellent solar resources and a highly efficient concentrating PV technology at appropriate cost. For general estimates the area, population and electricity generation weighted average irradiation has been derived for all mentioned solar resources and countries in the world. For fixed optimally tilted systems the weighted global average irradiation on module surface is calculated to 1,780 kWh/m²/y (area), 1,850 kWh/m²/y (population) and 1,690 kWh/m²/y (electricity generation).

The **fundamental PV economics** are the most relevant driver for the increasing competitiveness of hybrid PV power plants. An appropriate tool for future cost projections for PV systems is the experience curve concept, describing the cost reduction of products in dependence of doubling the historic cumulated production. This cost reduction is called learning rate and has been derived for the case of PV modules to slightly more than 19% per doubling for a period from the mid 1970s to the year 2010 and indications go back to the mid 1950s. The cost reduction over time is furthermore dependent on the growth rate, in case of PV being on a very high annual average of more than 30% for more than five decades and more than 45% for the last 15 years. No other power technology reaches such a high learning and growth rate long-term. For estimating the learning rate in the years to come a comprehensive assessment of PV research and development (R&D) expenditures has been performed. The current annual R&D expenditures are estimated to about 3 bn€ by bottom-up assessment of more than 100 PV companies and to about 6 bn€ by top-down assessment of PV patent filings. Based on these numbers the learning rate is assumed to be stable at least in the 2010s. Annual PV R&D expenditures reach about 12% of total PV sales which is comparable to the semiconductor industry. In terms of public PV R&D expenditures the potential of sustainable PV technology has been hugely underestimated up to the late 2000s as less than 2% of the public nuclear R&D expenditures have been invested in the total PV development (about 44 to 50 bn€), contrasted by more than 80% direct private financing in case of PV. This fundamental misbalance had been fully understood in the late 1970s but a dramatic international policy failure of historic dimension led to massive public misallocations of financial means since then. The fundamental limit for mid- to long-term PV growth has been estimated at 1,500 GW to 12,000 GW at that stage of the thesis, depending on restrictions like storage availability and long-term global energy needs. By end of 2010 about 40 GW cumulative global installed PV capacity has been reached. Based on the fundamental growth limits and the fast technological progress a continued learning rate of about 20% and a growth rate of about 30% seem to be very feasible for the entire 2010s. The in depth PV R&D expenditure analysis has been the first of its kind quantifying the total current and historic cumulated PV R&D expenditures.

This thesis educes a global overview on cumulative installed PV capacity for about 190 countries in the world for the first time. Several developing countries invest more in PV per gross domestic product (GDP) than leading industrialized countries, indicating the potential of PV for new and sustainable development pathways. PV technology offers various options but crystalline silicon (c-Si) technology has been dominating the market for decades and may

sustain that high market share for at least the 2010s due to strong technological and industrial progress. The energetic sustainability of PV reaches a very good level of GHG emissions of about 10 to 40 gCO_{2eq}/kWh, a reduction of harmful heavy metal emissions by typically more than 90% per kWh in comparison to the conventional fossil fuel based energy mix and an energetic return of energy invested of about 15:1 to 50:1 depending on applied technology and geographic conditions. All indicators are being improved further as technology develops.

Different **economic scenarios** have been created for estimating the economic market potential of PV power plants. The analysis of the realistic scenario leads to LCOE of about 9 to 25 €/kWh in 2010 for the best adapted local PV system. Best adapted are the 1-axis horizontal north-south continuous tracking system for very good solar resource conditions, the 1-axis horizontal east-west variation in the very north and elsewhere the fixed optimally tilted system. By the end of the decade, the LCOE decrease to about 7 to 12 €/kWh in the realistic scenario, whereas the aggressive scenario leads to about 40% lower LCOE by 2020. The two most competitive PV systems are the fixed optimally tilted and the 1-axis horizontal north-south continuous tracking ones for nearly all variations of the scenarios over time, the former in the higher and lower latitudes and regions of high relative diffusive irradiation and the latter in all the remaining sunny regions in the world.

A very relevant economic market diffusion milestone for PV systems is the **on-grid end-user grid-parity**, i.e. parity of PV LCOE and end-user electricity prices. These dynamics have been analysed the first time on a global basis for more than 150 countries and 98% of world population. Grid-parity will be observed in the next years in several countries around the world. First grid-parity events occur right now. The 2010s are characterized by ongoing grid-parity events throughout most regions in the world, reaching an addressable market of about 75% up to 90% of total global electricity market by the end of the decade.

The **off-grid end-user** economics are best described by the **fuel-parity** concept, i.e. parity of end-user energy prices and PV based energy services. For the case of small PV applications in the sub 100 Wp system class, the amortization of the entire system lays between 6 to 18 months for very small and between 12 to 36 months for small PV systems representing the least cost energy solution for nearly all of the 1.4 billion still not electrified people in the world. Hybrid PV systems have been known for years in off-grid applications. A variety of solutions exists, but a minimum level of competitiveness can only be reached through relative high consumptions of at least 100 to 300 kWh/user/y. This necessity leaves no option for the very poor but for nearly all other people to be supplied in electric island grids, also in particular in existing diesel powered ones.

Relative competitiveness of PV power plants has to be assessed in comparison to **solar thermal electricity generation** (STEG) and wind power. STEG technology can only be applied at excellent solar resource conditions. Whilst economics are worse than those of PV thermal energy storage enables the reduction of the fluctuating solar power availability on a daily basis to a large extent. The long-term relative competitiveness of the two major solar power technologies remains unclear, however on a pure LCOE basis PV is in the lead and it is very likely to sustain that competitive edge due to a higher learning rate and a higher growth rate than those of STEG technology. **Wind power** is an almost mature power technology already reaching a LCOE level of 3 to 8 €/kWh for good onshore wind resources. Further cost development of wind power is rather limited due to a learning rate of even below 10%. The offshore wind LCOE are high and might need significant further support for reaching competitiveness, in particular for sites of significant distance to the coast. An integrated assessment of LCOE of PV, STEG and wind power plants further emphasises the

overwhelming economics of PV versus STEG. Wind power plants at good wind resources generate electricity on a very competitive LCOE level, however at the end of the 2010s the LCOE of PV and wind power might reach a very similar level in the regions of good resource availability. Due to the complementary resource availability, PV and wind power support each other in market diffusion and no competition between the two technologies has to be expected.

The total **global power plant capacity** being in operation has been about 4,720 GW by early 2009, composed by coal (about 1,465 GW), gas (about 1,100 GW), hydro (about 890 GW), oil (about 560 GW), nuclear (about 390 GW), wind (about 120 GW), biomass (about 30 GW), PV (about 15 GW) and others. A database of about 145,000 power plants in the world has been made available by the extension of their coordinates for analysing the georeferenced global power plant capacity. Some countries are heavily dependent on a single power technology, in particular on coal, gas and hydro. In the last two decades most newly commissioned power plant technology were gas fired CCGTs. In addition a significant and constant rate of new hydro plants, several hundred new GW in coal fired plants (almost all in China) and steadily decreasing and nearly negligible new nuclear capacities have been installed. About 70% of global power plant capacity ranges between 100 and 1,000 MW per unit. Biomass, geothermal and ocean power plants are at a different development stage and achieve only limited installed capacities and growth rates up to now. After the Fukushima melt-down an increasing awareness of security and economic failures of nuclear power can be recognized in more and more countries in the world. Due to the limited significance of these four technologies in the next one to two decades they have been excluded in the subsequent PV hybridization analyses.

Several preconditions should be fulfilled for a **successful PV hybridization** of at least two power sub-plants being operated in a coordinated manner. Flexibility in the operation mode is very relevant, as PV is only available during daytime hours but fluctuating according to cloud conditions. The CCGT technology has been improved over the last two decades and reaches now a very good level of flexibility being capable of high power ramp rates in the minutes time scale. CCGT technology can be used by firing gas and oil, is in preparation for coal and is introduced to STEG technology. Besides CCGTs the hydro power plants and some storage technologies are well suited for PV hybridization. Sophisticated forecasting tools are needed for a well coordinated power generation in hybrid plants. Such prognosis techniques are available for PV and wind power and can be implemented all around the world where the demand exists. The approach of PV hybridization with fossil fuel fired power plants is based on the assumption of substituting the fuels, i.e. the PV power plant should be in operation during daytime hours and the replaced fuel should be available for the market, hence power plants of less than 2,000 full load hours (FLh) and lignite fired coal plants have been excluded from the analyses. The fossil fuel price scenarios have been aligned to the crude oil price, since both the international natural gas and coal prices are coupled to crude oil in the long-term at about 80% and 30% of the crude oil price on basis of the primary energy content.

The **fossil fuel fired power plants** are analysed in a structural identical approach. The fossil fuel base case scenario assumes a crude oil price of 80 USD/barrel, a moderate annual escalation rate of 3% in real terms and a fuel price coupling of 0.8 for natural gas and 0.3 for coal in primary energy units. The total fossil power plant LCOE and the fuel-only LCOE is compared to the total PV LCOE at the geocoordinate of the fossil power plant. Slightly higher LCOE as a consequence of reduced FLh of fossil fuel fired power plants have to be balanced by further reduced PV LCOE. This parity is defined as fuel-parity on the level of power generation in contrast to the end-user oriented grid-parity.

Results for **hybrid PV-Oil power plant economics** give plenty of insights for excellent competitiveness of this approach for upgrading existing oil fired power plants. Most regions in the world in which oil power plants are operated on a significant FLh level have good and excellent solar resources which lead to favourable PV power plant economics, e.g. in Saudi Arabia. Already in the year 2010, most oil power plants in the world could lower the LCOE by upgrading with nearby PV power plants. Financial benefits of upgrading to hybrid PV-Oil power plants is fast increasing as a consequence of fast PV LCOE reductions and might become even higher for faster than expected crude oil price escalation. Depending on scenario assumptions, the market potential for hybrid PV-Oil power plants has been about 50 GW in 2010 and might fast rise to 200 GW by the mid of the 2010s. The maximum market potential is about 220 GW due to limited oil power plant capacity operated in average for at least 2,000 FLh.

Results for **hybrid PV-Gas power plant economics** give plenty of insights for excellent competitiveness of this approach for upgrading existing gas fired power plants. Many regions in the world in which gas power plants are operated on a significant FLh level have good and excellent solar resources which lead to favourable PV power plant economics, in particular in the US, Italy, Iran, United Arab Emirates, Thailand, Spain, Mexico, Egypt, India, Malaysia, Australia and Turkey followed by Russia, UK, Germany and the Netherlands. Already in the year 2010, several gas power plants in the world could lower the LCOE by upgrading with nearby PV power plants. Financial upgrading benefit for resulting hybrid PV-Gas power plants is fast increasing as a consequence of fast PV LCOE reductions and might become even higher for faster than expected crude oil price escalation and collateral natural gas price adaption. Depending on scenario assumptions, the market potential for hybrid PV-Gas power plants has been more than 150 GW in 2010 and might fast rise to 750 GW by the end of the 2010s. The maximum market potential is about 1,000 GW due to limited gas power plant capacity operated in average for at least 2,000 FLh.

Results for **hybrid PV-Coal power plant economics** give plenty of insights for fast growing competitiveness of this approach for upgrading existing coal fired power plants. Many regions in the world in which coal power plants are operated on a significant FLh level and of sufficient coal quality have good and excellent solar resources which lead to favourable PV power plant economics. Already in the mid of the 2010s, several coal power plants in the world could lower the LCOE by upgrading with nearby PV power plants. By the end of the 2010s, the largest markets for hybrid PV-Coal power plants are China, India, South Africa, the US and Ukraine. In the aggressive PV scenario, i.e. fast PV cost reduction dynamics, five further major markets are beyond economic breakeven: Japan, Germany, UK, Russia and South Korea. Financial upgrading benefit for resulting hybrid PV-Coal power plants is fast increasing as a consequence of fast PV LCOE reductions and might become even higher for faster than expected crude oil price escalation and collateral coal price adaption. Depending on scenario assumptions, the market potential for hybrid PV-Coal power plants has been more than 20 GW in 2015 and might fast rise to 480 GW by the end of the 2010s. The maximum market potential is about 1,150 GW due to firing at least bituminous coal quality.

Total fossil fuel power plant capacity of 3,130 GW by early 2009 is by about 70% (2,170 GW) suitable for upgrading with PV power plants. By 2020, this PV power plant upgrading market potential for fossil fuel power plants is at least 30% of the suitable capacity due to very conservative scenario assumptions, i.e. realistic (PV), low cost case (Fossil) and fuel-only LCOE parity. A more realistic, maybe slightly optimistic, consideration is beyond 90% of suitable capacity, i.e. aggressive (PV), base case (Fossil) but still fuel-only LCOE parity.

The **fuel-parity market potential for hybrid PV-Fossil power plants** can be expected to be in the range of at least 700 GW up to even more than 2,100 GW by 2020. These numbers are very likely to grow in parallel to new net installed fossil power plant capacity during the 2010s. The fuel-parity concept and the analysis approach by power plant has been firstly developed in this thesis.

The **global economic market potential** for installed PV capacity in the year 2020 based on the **grid-parity** analysis can be estimated to be about 1,000 GWp to 3,900 GWp, whereas the estimate based on **fuel-parity** analysis results in approximately about 1,500 GWp. The outcome for the first integrated sustainable economic market potential estimate for PV systems is based on a learning rate of 20% for modules and inverter and 15% for the other balance of system components. The total economic on-grid market potential can be estimated to about 2,700 GW to 4,200 GW for the year 2020.

Off-grid PV applications in rural areas are highly profitable for years. 1.4 billion people have no access to electricity, but for the poorest of them small PV applications are an excellent solution due to very short financial amortization periods. For emerging countries requiring larger amounts of electricity per capita local hybrid PV mini-grids are an energy option realizable in a fast way, especially compared to costly expansions of national grids. **Market potential for off-grid PV systems** in rural regions is in the order of about 70 GW and dominated by hybrid mini-grid in capacity, but dominated by small PV applications by people using a PV off-grid solution. This is caused by diverse energy consumption patterns.

The **total global economic PV market potential in the year 2020** might be in the order of 2,800 to 4,300 GWp. However, only a fraction of this economic market potential will be realised in time, i.e. 20% (pessimistic), 35% (realistic) and 50% (optimistic) might be assumed. Applying these scenario assumptions a cumulated installed PV capacity of about 600 GWp (pessimistic case), 1,000 GWp (realistic case) and 1,600 GWp (optimistic case) can be expected in the year 2020. These three cases are equivalent to average annual growth rates of new installations of 20%, 30% and 40%, i.e. fully in line to the long-term growth of global PV installations. Technological restrictions for these installation numbers need not to be feared, since the fuel-parity approach requires only grid access of PV power plants nearby to existing power plants and many grid-parity market segments become profitable even including local storage options. These PV market expectations are drastically contrasting market projections of major institutions in the field of PV scenarios, since only the progressive group fulfils the pessimistic case derived in this thesis, i.e. only EPIA and partly Greenpeace can really imagine that PV can show such a fast progress towards the long-term target of becoming a major source of energy supply. This thesis is the first work deriving a full economic market potential for PV systems on a global basis of on-grid end-user grid-parity analyses for more than 300 market segments, on-grid fuel-parity analyses for more than 3,000 GW fossil fuel power plant capacity on a per power plant basis and off-grid fuel-parity market potential estimates for the not electrified people in the world.

As a consequence of PV economics, there will be at least two driving forces for the economic pressure of on-grid PV systems on conventional fossil fuel fired power plants. Firstly, grid-parity economics for end-users will generate highly attractive returns for PV investments for partly substituting high priced end-user electricity cost mainly dominated by conventional fossil fuel fired power plants. Secondly, fuel-parity economics on power plant level steadily increases the LCOE gap of fossil fuel fired plants to PV power plants, since the PV LCOE are expected to be below those of nearby conventional fossil fuel fired power plants at an increasing number of sites in the world, starting with oil, than natural gas and in the end also

coal fired power plants. A **stakeholder analysis** gives some indication that positive effects of strong PV economics are attractive for power plant technology providers, electricity end-users and utilities. Attractiveness remains somewhat unclear for some policy makers and some fossil fuel producing and mining companies, whereas attractiveness seems to be negative for most public listed and privately held fossil fuel companies and policy makers in close relation to those companies. The impact of PV on the fossil fuel power plant business will be very beneficial for those being aware of the enormous dynamics of PV economics, as most of the players can increase their profits or lower their cost, but there will be also players that are not capable of generating benefits for their own businesses and interests.

Not only fossil fuel fired power plants can be used for upgrading with PV power plants to hybrid PV-Fossil power plants, but also renewable power plants. Hydro power plants are well suited for upgrading to **hybrid PV-Hydro power plants**. About 340 GW existing hydro power plant capacities are installed in regions of very good solar resource conditions and about 40% of these capacities might be appropriate as hydro power sub-plant of potential hybrid PV-Hydro power plants. At a crude oil price of at least 70 USD/barrel most of these capacities are expected to generate additional financial benefits if upgraded by PV power plants.

Key advantage of STEG is the thermal energy storage which enables a flexible and dispatchable power plant configuration being easily adaptable to existing power grids and power plant portfolios. A major advantage of PV power plants is the already achieved lower LCOE. The cost advantage of PV seems to be very stable in time due to significantly higher learning and growth rates than those of STEG. Combining both major solar electricity technologies creates a **hybrid PV-STEG power plant**. The PV sub-plant provides power to the grid whenever the sun is shining. The STEG sub-plant is used only in case of power demand and no available power by the PV sub-plant, in particular in the evenings or at night. For the economic assessment the PV LCOE potential is defined as the STEG LCOE without PV hybridization minus higher LCOE of the STEG sub-plant due to lower STEG FLh of a hybrid PV-STEG power plant. In case of an original STEG being able to run 12 h at full load the PV LCOE benefit, i.e. PV LCOE potential minus PV LCOE of least cost system, is in the range of 4 to 6 €/kWh for the 2010s corresponding to a ratio of hybridization PV LCOE potential to PV LCOE of least cost system of about 190% to 230%, i.e. the PV LCOE might be only about 50% of the hybridization PV LCOE potential. As a consequence the economics of a hybrid PV-STEG plant of an original STEG being able to run 12 h at full load are excellent, since the total LCOE of the hybrid PV-STEG plant are lower than the single STEG plant. Hybrid PV-STEG plants would be a new market segment for PV power plants and might further increase the growth rate of PV systems. Hybrid PV-STEG plants combine the key advantage of each single solar power technology for overcoming the respective key disadvantage. By combining complementary strengths of the two major solar power technologies, both PV and STEG might increase the technological diffusion of each other – an obvious win-win situation for both technologies. The hybrid PV-STEG power plant was firstly suggested in conjunction with respective analyses for this thesis.

The global energy supply potential of PV and wind power exceeds by far the energy demand of mankind. In addition, several analyses in this thesis point out an excellent power supply potential of PV and wind power. An integrated economic assessment of PV and wind power clearly results in equalling LCOE levels of both major new renewable power technologies in the range of about 4 to 7 €/kWh projected for the end of the 2010s at sites of at least good resource availability. Several regions in the world have good or even better resource and thus LCOE availability for both technologies, e.g. the US, southern South America, North Africa,

China or Australia. This is confirmed by literature being available for **hybrid PV-Wind systems**. Only very few research on utility scale systems and no publication has been found addressing the complementarity question on a global scale, except one study for at least Europe. In case of at least good wind resource availability a very tough competition between wind power and PV power plants has to be expected, since both technologies might compete for the balancing power of remaining fossil fuel fired power plants and power line capacities. This might be true in case of excellent wind and solar resource availability at the same time. But for largely disjunct resource availability in time, the result would be vice versa.

For answering this essential scientific question on the **competitiveness or complementarity of PV and wind power**, a very comprehensive dataset has been analysed on basis of wind speed and GHI data for a spatial resolution of $1^\circ \times 1^\circ$ of latitude and longitude and all hours for the mid 1980s to mid 2000s. The wind and solar resource data are transformed to power data of respective wind and PV power plants by applying appropriate power plant models. Power generation of PV and wind power plants is normalized to hourly FLh and aggregated for periods of months and years. Such data enable the extraction of overlap FLh of PV and wind power plants in order to eventually derive the critical extent of these overlap FLh. Critical FLh are identified for the amount of feed-in power exceeding the rated power of either PV or wind power plants installed within a region of $1^\circ \times 1^\circ$ of latitude and longitude on basis of an equally installed rated power capacity. The critical overlap FLh range between 1% to 8% of total FLh of PV plus wind power plants. The critical overlap FLh are about $2\% \pm 1\%$ for most regions in the world. The highest relative critical overlap FLh is found in regions near the Andes like Bolivia, Chile and Argentina, in some areas of the US Midwest, the Horn of Africa, the Himalayas and areas near Inner Mongolia. All the other regions in the world show very low critical overlap FLh. The complementarity characteristic of PV and wind power becomes relevant when either of them is built-up on the capacity level of existing balancing and storage plants within the power system.

The fluctuation of the **hybrid PV-Wind power plant** is expected to be lower due to the complementary resource availability. However, the hybrid PV-Wind power plant is still not dispatchable but at least predictable due to the energy meteorology tools and need further balancing power plants or power storage facilities. Nevertheless, the fuel requirements for the balancing power plants and storage capacities are significantly lowered due to the complementary characteristic of PV and wind power plants. This fundamental characteristic of hybrid PV-Wind power plants is of utmost relevance for the further evolution of the global power system, since PV and wind power capacities can be built in parallel and in cooperation as capital expenditures for further system components are decreased due to better respective utilization. This work was carried out in a diploma thesis but prepared and supervised by the author and may be the by far most relevant result of this thesis.

Hybrid PV-Wind-CCGT power plants based on natural gas are an excellent power plant option in the years to come, but this technological approach still depends on fossil fuels. The economic impact potential of **renewable power methane (RPM) storage** has been analysed the first time on a global scale for a better understanding whether hybrid PV-Wind-RPM-CCGT power plants would enable a fully dispatchable power supply based on fluctuating wind and solar resources. Three elementary core processes are needed for RPM: electrolysis (conversion of electricity and water into hydrogen and oxygen), carbon dioxide supply (e.g. extraction from ambient air via dialysis process, by-product of biogas plants, fossil fuel power plants or industrial processes) and methanation (conversion of hydrogen, carbon dioxide and electricity into methane and water). In case of burning RPM in modern gas power plants the full cycle efficiency would be about 37% and 29% for CO_2 being easily available for the

methanation process and CO₂ extracted from ambient air, respectively. This full cycle storage efficiency is rather low and induces high specific cost for such stored electricity, however an easy to use seasonal energy storage would be enabled and the entire natural gas infrastructure could be used. RPM versus hydrogen shows significant advantages, in particular for a fast transition from non sustainable fossil to sustainable renewable power supply.

Economic analyses have been performed for the projected technological and economic status for the year 2020. Upgrading natural gas (NG) fired CCGT power plants by hybrid PV-Wind power plants typically leads to lower LCOE for fossil fuel prices of about 50 to 90 USD/barrel. In case of good solar and wind resource availability the **hybrid PV-Wind-NG-CCGT power plant** is very competitive beginning between fossil fuel prices of 70 to 90 USD/barrel onwards. The remaining natural gas fired in the NG-CCGT sub-plant still leads to CO₂ emissions but the natural gas can be replaced by RPM, however it will be higher in cost than the natural gas option in nearly all regions in the world and for fossil fuel prices up to 250 USD/barrel assuming no carbon emission cost.

LCOE results of **hybrid PV-Wind-RPM-CCGT power plants** clearly indicate a growing competitiveness of 100% renewable systems. Optimised economics in regions of at least good solar and wind resources are typically achieved for hybrid PV-Wind sub-plants of a 1-axis horizontal north-south continuous tracking PV component and a CO₂ extraction from ambient air. The RPM production cost is significantly lower in cost for sourcing CO₂ from carbon capture and storage (CCS), but high capital expenditures and lower efficiencies of CCGT-CCS power plants lead to slightly better economics of systems extracting CO₂ from the ambient air. Hybrid PV-Wind-RPM-CCGT power plants are lower in total LCOE than coal-CCS power plants in case of at least good solar and wind resource availability. This remarkable economic competitiveness might mark the beginning of a new era in sustainable power supply in the world.

The **hybrid PV-Wind-RPM-CCGT power plant** extracting CO₂ from ambient air is an excellent **potential centrepiece of a 100% renewable power supply**, which might be established on a LCOE level of about 80 to 90 €/MWh in regions of very good solar and wind resource availability. This LCOE level is fully fossil fuel decoupled and represents the full social cost, i.e. no further external cost create an additional financial burden. Moreover, no CCS route is needed. CO₂ extraction from air leads in most cases to lower total LCOE and in cases of lower CCS CO₂ sourcing this is only slightly lower in cost. It is not clear whether CCS technology will be really available by 2020 or even in 2030, hence waiting for this route might waste a lot of valuable time. By the year 2020 about 90% of mankind might be economically in reach to be supplied by 100% renewable power fully competitive to fossil fuel prices of about 150 USD/barrel within less than 1,000 km to the sites of least cost power generation and for practically unlimited amounts of sustainable energy. Such a low distance is very important for lowering the political obstacles for the issues of transmitting large power amounts through various countries and the time consuming construction process of power lines. The renewable power methane approach enables long-term cost stability due to a fully decoupled cost structure from fossil fuels, no net CO₂ emissions and enormous power supply potential offering long-term sustainable economic growth. Hybrid PV-Wind-RPM-CCGT power plants might become the centrepiece of a sustainable and affordable power supply desperately needed for the survival of our technological driven global society.

Summing up all the various insights of this thesis, the fundamental drivers for the economics of PV position this power technology as a very valuable option for solving all major electricity generation constraints in the 21st century. In the decade of the 2010s all

relevant price references will be strongly outperformed by PV systems leading to sustainable on-grid markets based on grid-parity (relevant for end-users) and fuel-parity (relevant for power plant operators) complemented by already highly economic off-grid markets. PV systems are modular and scalable from very small PV applications in the Wp class up to large scale power plants in the multi hundred MW class. Almost all relevant power plant technologies can be upgraded by PV power plants leading to improved economics of the hybrid PV power plant. This hybridization value can be improved by combining complementary PV and wind power plants. A 100% renewable powered energy system is economically feasible on the basis of renewable power methane and might be already a real option in the early 2020s.

Organization

Chapter 1 - Boundary Conditions of Electricity Generation in the 21st Century

The key drivers of the electricity generation in the early up to mid 21st century are discussed. Most relevant cornerstones of the further development are the increasing global power demand, climate change impact, diminishing fossil and nuclear energy fuel resources, overcoming energy injustice and rebalancing our global society's ecological footprint. All fundamental path decisions in the power sector must not violate these basic requirements. Consequences for photovoltaic (PV) energy solutions as part of a sustainable new global power infrastructure are highlighted in the context in this chapter.

Chapter 2 - Solar Resources

The energy resource availability is decisive for all power technologies. Basis for all solar energy technologies is the amount and the composition of the global horizontal irradiation. Different solar system concepts have been developed for optimising the energy yield. Systems' requirements adapted to solar resources are derived and compared among each other. For assessing solar potentials regional irradiation mean values are calculated. Impact of heterogeneous population and electricity generation distribution on average irradiation is analysed. Fundamental consequences of solar resource distribution are discussed in context of PV system solutions in this chapter.

Chapter 3 - Photovoltaic Economics

Sustainable power technologies need to fulfil the major criteria of competitive economics. The fundamental trends of PV economics, like growth rates, learning rates, research and development investments, PV technology diffusion, energetic sustainability and specific emissions are discussed in respect to this major requirement. Depending on geographic and technological conditions some PV system concepts for PV power plants are best adapted in maximizing economics. On end-users' level grid-parity concept is a well known metric for evaluating on-grid PV competitiveness, whereas fuel-parity concept is more appropriate for assessing off-grid PV benefits. Fundamental consequences of key aspects of PV economics are discussed in this chapter.

Chapter 4 - Solar Thermal and Wind Power Plant Economics

Economics of PV systems need to be assessed by relative economics in comparison to other renewable power technologies. In this thesis PV is focussed but for evaluating relative significance both solar thermal electricity generation (STEG) and wind power are analysed in more detail. These two renewable power technologies could be very competitive to PV but also complementary, as a consequence of respective economics, technological characteristics and resource availability. Furthermore, PV, STEG and wind power show by far the highest supply potentials of all renewable energy technologies. An integrated economic assessment of PV, STEG and wind power plants concludes this chapter.

Chapter 5 - Power Plants of the World

The fast growing new core technologies need to be integrated into the current power infrastructure and the energy system has to be prepared for a rapid market diffusion of these technologies, in particular solar PV and wind power. For a better understanding of all these circumstances the currently used power technologies are illustrated in some key characteristics and typically from a global perspective, as PV and wind power will diffuse fast in all regions in the world. Therefore a general overview on the global electricity consumption patterns and the power plants of the world is given. In this chapter only these power plant technologies are discussed which are not treated elsewhere due to their negligible role for hybrid PV power plants in the next one to two decades, i.e. biomass power, geothermal power, ocean power and nuclear power. However, all major power plant technologies are discussed in this thesis in different chapters representing the special view of this thesis.

Chapter 6 - Hybrid Photovoltaic Fossil Power Plants

Analyses in previous chapters already emphasize the fast increasing beneficial PV economics. However the most relevant reference for PV power plant economics are the fully-loaded and not directly subsidized power generation costs of fossil fuel fired conventional power plants. Due to the fluctuating solar resource availability, the hybrid combination of fossil fuel fired power plants and PV power plants appears financially advantageous. For an integrated economic assessment of hybrid PV-Fossil power plants the preconditions are considered being necessary for a successful PV hybridization. Based on these requirements the major fossil fuel fired power plants are analysed, i.e. hybrid PV-Oil power plants, hybrid PV-Gas power plants and hybrid PV-Coal power plants. The results of these analyses are summarized in the hybrid PV-Fossil power plant demand curve for the 2010s. This economic PV market potential based on fuel-parity is complemented by the economic PV market potential derived by grid-parity analyses and compared to existing PV scenarios.

Chapter 7 - Hybrid Photovoltaic Renewable Power Plants

Hybrid PV-Fossil power plants can be only the first step towards a 100% sustainable power supply. PV power plants can be also operated as one sub-plant among other renewable (RES) sub-plants of a hybrid PV-RES power plant. For the case of full dispatchability of the RES sub-plant the hybrid PV-RES power plant is also fully dispatchable. Two such combinations are briefly discussed: the hybrid PV-Hydro power plant and the hybrid PV-STEG power plant. The two major power sources in this century might be PV and wind power, hence a hybrid PV-Wind power plant is of utmost relevance. But both PV and wind power show a fluctuating power availability, thus flexible balancing capacities are needed. For balancing the hybrid PV-Wind sub-plant power to the load, some additional storage sub-plant components could guarantee a stable power supply over the entire year including even seasonal storage. Such an option could be the hybrid PV-Wind-Renewable Power Methane-Combined Cycle Gas Turbine power plant. The latter hybrid power plant is also analysed in its global energy supply potential.

Chapter 1

Boundary Conditions of Electricity Generation in the 21st Century

In the following chapter cornerstones of electricity generation in the first half of the 21st century are discussed: **increasing global power demand** (sub-chapter 1.1), **climate change impact** (sub-chapter 1.2), **diminishing energy fuel resources** (sub-chapter 1.3), overcoming **energy injustice** (sub-chapter 1.4) and rebalancing our global society's **ecological footprint** (sub-chapter 1.5). All decisions on the fundamental path in the power sector must not violate these basic requirements. Consequences for photovoltaic energy solutions as part of a sustainable new global power infrastructure are put into context at the end of each sub-chapter in this chapter.

The history and evolution of sustainability is comprehensively presented by Grober ¹ and discussed in its ecological, economic, social and cultural dimension. The most widely accepted definition of sustainability has been formulated by the Bundtland Commission ² in 1987: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The need for sustainable energy supply is eminent, due to consequences of fast increasing global power demand, climate change, looming peak energy fuel security concerns, lack of global energy justice and disastrous global ecological footprint. All these issues have a long history, e.g. the first scientific discussion on climate change took place in 1938 ³, on peak-oil in 1949 and 1956 ^{4,5}, solar energy as best solution against energy insecurity was preferred by US President Jimmy Carter in 1979 ⁶, energy injustice is as old as human civilization ⁷ and fundamental growth limits had been fully understood in late 1960s ⁸. All these problems have reached a dramatic high level and are present at the same time today. ^{9,10,11,12,13,14,15}

Moreover, there is a tremendous pressure to establish a sustainable energy industry as 87% of global energy market is structural not sustainable ¹⁶, either due to diminishing resources (crude oil, natural gas, coal, uranium) ^{17,18,19,20}, climate change restrictions (coal, crude oil,

¹ Grober U., Die Entdeckung der Nachhaltigkeit, 2010

² Bundtland G.H., Our Common Future, 1987, p. 43

³ Callendar G.S., The Artificial Production of Carbon Dioxide and its Influence on Temperature, 1938

⁴ Hubbert M.K., Energy from Fossil Fuels, 1949

⁵ Hubbert M.K., Nuclear Energy and the Fossil Fuels, 1956

⁶ Carter J., Solar Energy, 1979

⁷ Diamond J., Guns, Germs, and Steel: The Fates of Human Societies, 1999

⁸ Meadows D.H. et al., The limits to growth, 1972

⁹ IPCC, IPCC 4th Assessment Report: Climate Change 2007, 2007

¹⁰ Stern N. (ed.), Stern Review on the economics of climate change, 2006

¹¹ Nashawi I.S. et al., Forecasting World Crude Oil Production using Multicyclic Hubbert Model, 2010

¹² Müller-Kraenner S., Energy Security: Re-Measuring the World, 2008

¹³ UNDP, Human Development Report 2007/2008, 2008

¹⁴ IEA, World Energy Outlook 2010, 2010

¹⁵ Wackernagel M. and Beyers B., Der Ecological Footprint: Die Welt neu vermessen, 2010

¹⁶ IEA, World Energy Outlook 2010, 2010

¹⁷ Schindler J. and Zittel W., (eds.), Crude Oil - The supply outlook, 2008

¹⁸ Nashawi I.S. et al., Forecasting World Crude Oil Production using Multicyclic Hubbert Model, 2010

¹⁹ Almeida de P. and Silva P.D., The peak of oil production – Timings and market recognition, 2009

²⁰ Bardi U., Peak oil: The four stages of a new idea, 2009

natural gas)^{21,22} or severe lasting security problems (nuclear power)²³. Need for sustainable energy supply is greater than ever in human history.

Photovoltaic (PV) has the potential to provide solutions to these major challenges. PV uses the most uniformly distributed energy source in the world, the sun, (chapter 2) shows a steep decline in greenhouse gas (GHG) emissions (section 3.1.7.1) and has the potential to become the lowest GHG emitting energy technology of all. Furthermore, the cost reduction of solar PV is at a constant high level with the potential to make PV the least cost energy technology in the world.^{24,25} The growth rates of very modular PV technology have been outstandingly high in recent decades (section 3.1.1). Due to these facts, PV represents an energy technology of highest importance for managing the above mentioned five major (energy) problems of today's technological globalized civilization.

1.1 Increasing Global Power Demand

The decades after World War II have generated an enormous increase of wealth in the industrialized countries, but have also led to an impressive aggregation of industrial production in former second and partly third world regions. This is reflected by the global electricity consumption that increased from about 600 TWh in 1945 to about 19,000 TWh in 2008 featuring an annual growth rate of 5.6% for more than six decades (Fig. 1.1-1).

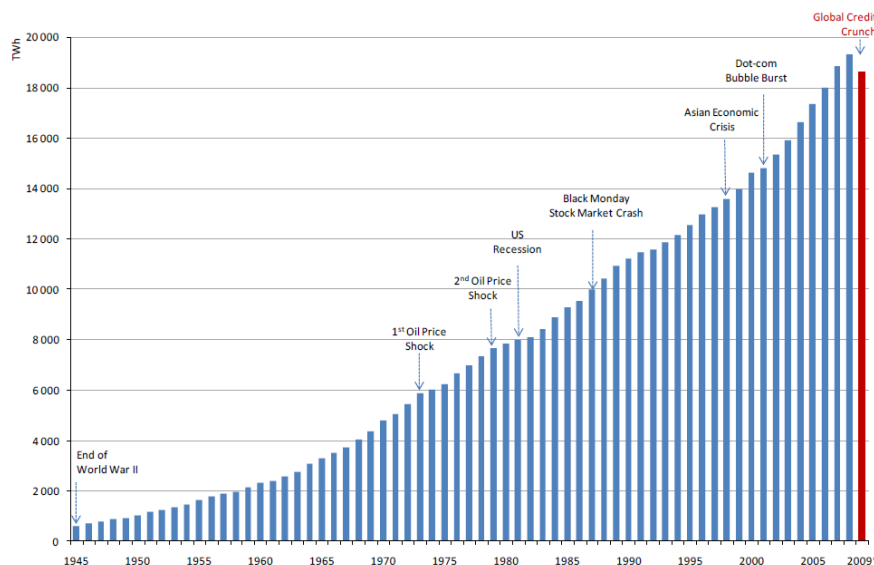


Figure 1.1-1: Global electricity consumption in the years 1945 to 2009.²⁶ Numbers for electricity consumption are roughly 5% lower than those for generation due to distribution losses.

Fast economic growth in emerging and developing economies such as China induces a further ongoing power demand increase in the years and decades to come. Total global electricity generation of about 20,180 TWh in 2008 is expected to grow to about 35,340 TWh in 2035²⁷,

²¹ IPCC, IPCC 4th Assessment Report: Climate Change 2007, 2007

²² Stern N. (ed.), Stern Review on the economics of climate change, 2006

²³ Barnaby F. and Kemp J. (eds.), Secure Energy? – Civil Nuclear Power, Security and Global Warming, 2007

²⁴ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

²⁵ Pietzcker R. et al., The Role of Concentrating Solar Power and Photovoltaics for Climate Protection, 2009

²⁶ IEA, The Impact of the Financial and Economic Crisis on Global Energy Investment, 2009

²⁷ IEA, World Energy Outlook 2010, 2010

i.e. a further annual growth of about 2.1% and a total additional electricity generation of about 75% within about a quarter of a century. Hundreds of millions of people in emerging and developing economies will escape from poverty in case of ongoing economic development which needs the global expansion of power generation capacities as integral backbone (Fig. 1.4-4 and 1.4-5).

This expected growth will not end in 2035. In 2050, the world could be populated by about 9.15 billion people ²⁸ being hungry for energy. Currently the global average electricity generation per capita is about 3.0 MWh_{el}, whereas the average of the entire OECD and OECD-Europe is about 8.9 MWh_{el}/capita and 6.6 MWh_{el}/capita, respectively.²⁹ Despite of modal shifts of energy consumption patterns from heat and fuels to electricity, it can be assumed that the energetic wealth level of OECD-Europe might be achievable for the world population. Energy efficiency improvements might allow a stabilization of per capita energy generation. As a consequence, 9.15 billion people living on earth might need about 55,000 TWh_{el} of electricity, this is equivalent to an annual growth rate of about 2.4% being close to the expected growth rate for the year to 2035, and would equal an increase in electricity generation of additional 175%. Furthermore, the non-electric energy demand is about 24 MWh_{th}/capita in OECD-Europe.³⁰ In case of providing heat and fuels based on electric sources due to modal shifts or energy conversion the demand for a sustainable power generation base is expected to be very pressing.

However, as mentioned above the limited traditional energy resources of our planet and even worse its emission absorption capacity might block this business-as-usual pathway.³¹ Due to resource and absorption limitations it is absolutely obvious that the answers and solutions of the past would lead to a failure tomorrow.^{32,33} The only nearly untapped energy resources being available to the market today and fulfilling the sustainability criteria ³⁴ are solar electricity and wind power (sub-chapter 7.3).^{35,36,37}

1.2 Climate Change Impact

Man made climate change was first noticed by Callendar in 1938.³⁸ In the meantime, the disastrous consequences of anthropogenic ³⁹ climate change on ecosystems and social systems are well understood ^{40,41,42,43}, but mankind seems not to react in an appropriate manner, best documented by the Copenhagen failure in December 2009. Interestingly, the current situation potentially fulfils three in five major preconditions for a collapse of human society repeatedly

²⁸ UN, World Population Prospects: The 2008 Revision Highlights, 2009

²⁹ IEA, World Energy Outlook 2010, 2010

³⁰ IEA, World Energy Outlook 2010, 2010

³¹ Meadows D.H. et al., Limits to growth: the 30-year update, 2004

³² Meadows D.H. et al., The limits to growth, 1972

³³ Meadows D.H. et al., Limits to growth: the 30-year update, 2004

³⁴ Bundtland G.H., Our Common Future, 1987

³⁵ Weingart J.M., The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, 1978

³⁶ Weingart J.M., Global aspects of sunlight as a major energy source, 1979

³⁷ Kohn W., A world powered predominantly by solar and wind energy, 2010

³⁸ Callendar G.S., The Artificial Production of Carbon Dioxide and its Influence on Temperature, 1938

³⁹ Oreskes N., The Scientific Consensus on Climate Change, 2004

⁴⁰ IPCC, IPCC 4th Assessment Report: Climate Change 2007, 2007

⁴¹ Stern N. (ed.), Stern Review on the economics of climate change, 2006

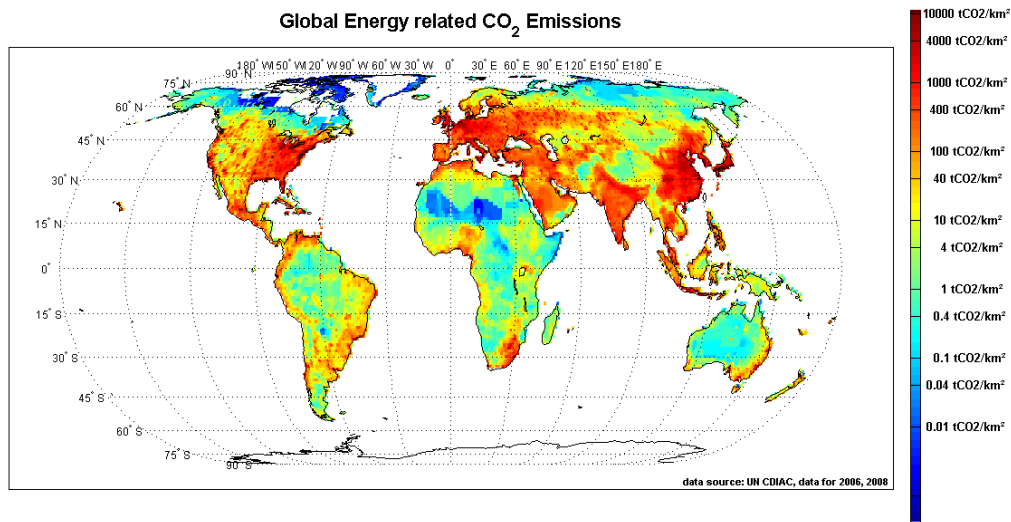
⁴² WBGU, Climate Chance as a Security Risk, 2007

⁴³ Welzer H., Klimakriege – Wofür im 21. Jahrhundert getötet wird, 2008

observed in history: firstly, the occurrence of climate change, secondly over-exploitation of natural resources (sub-chapters 1.3 and 1.5) and, thirdly, inappropriate adaption to a fundamental shift of the basis of our existence.⁴⁴

If our technological global society was really interested in having a significant chance on the survival of climate change, the only answer would be a zero greenhouse gas emission strategy, as soon as possible.⁴⁵ However, short-term economic benefits of a non adaption strategy are high. Therefore, global society agreed to a non binding minimum target of 2°C, i.e. mankind attempts not to induce a temperature increase of more than 2°C in reference to the pre-industrial level. Basis of the 2°C target is the scientifically based fear of starting irreversible processes on a planetary level we can not control beyond a specific tipping point.⁴⁶ Such major collapse events are for example irreversible melt-down of the Greenland ice sheet, drought in the Amazon rainforest, breakage of the West Antarctic ice sheet, stop of the Atlantic thermohaline circulation, fundamental disturbance of the monsoon season in India and West Africa and the El Niño-Southern Oscillation, ocean anoxia, melting of permafrost soil and release of enormous amounts of methane.^{47,48}

Emissions of greenhouse gases, e.g. CO₂, CH₄ and N₂O, originate to about 61% in energy use⁴⁹ and within the energy sector to about 41% by power generation⁵⁰. In this thesis, GHG, CO₂ and CO_{2eq} are used as synonyms. Concentration of GHG in the atmosphere increased from about 280 ppm in the pre-industrial age (about 1850) to a current level of about 390 ppm and a still growing current average annual increase by about 2.40 ppm (2010), about 1.96 ppm (2006 – 2010), about 2.02 ppm (2001 – 2010), about 1.75 ppm (1991 – 2010) and 1.68 ppm (1980 – 2010).⁵¹ Global distribution of energy related CO₂ emissions is depicted in Figure 1.2-1 according to CO₂ emissions per country and local population density distribution. The distribution of CO₂ emissions on a per capita and per country basis is illustrated in Figure 1.2-2.



⁴⁴ Diamond J., Guns, Germs, and Steel: The Fates of Human Societies, 1999

⁴⁵ Fell H.-J. et al. Die Klimakatastrophe lässt sich nur mit einer Nullemissionsstrategie abwenden, 2006

⁴⁶ Lenton T.M. et al., Tipping elements in the Earth's climate system, 2008

⁴⁷ Lenton T.M. et al., Tipping elements in the Earth's climate system, 2008

⁴⁸ Rahmstorf S. and Schellnhuber H.J., Der Klimawandel, 2006, p. 54-81

⁴⁹ IPCC, IPCC 4th Assessment Report: Climate Change 2007 – WG III (Mitigation), 2007, p. 102-112

⁵⁰ IEA, World Energy Outlook 2010, 2010

⁵¹ NOAA, Trends in Atmospheric Carbon Dioxide – Recent Global CO₂, 2011

Figure 1.2-1: Global distribution of energy related CO₂ emissions per area for the year 2006. Areas coloured red show a high and dark red a very high energy related CO₂ emission density. Data comprise all energy related GHG emissions being summarized on a CO_{2eq} (equivalent) basis. The unit for energy related CO₂ emission density is tCO₂/km². Energy related CO₂ emission data are used on a per country basis. Population input data are used in a 1°x1° mesh. Data are taken from United Nations ⁵² and Center for International Earth Science Information Network (CIESIN).⁵³

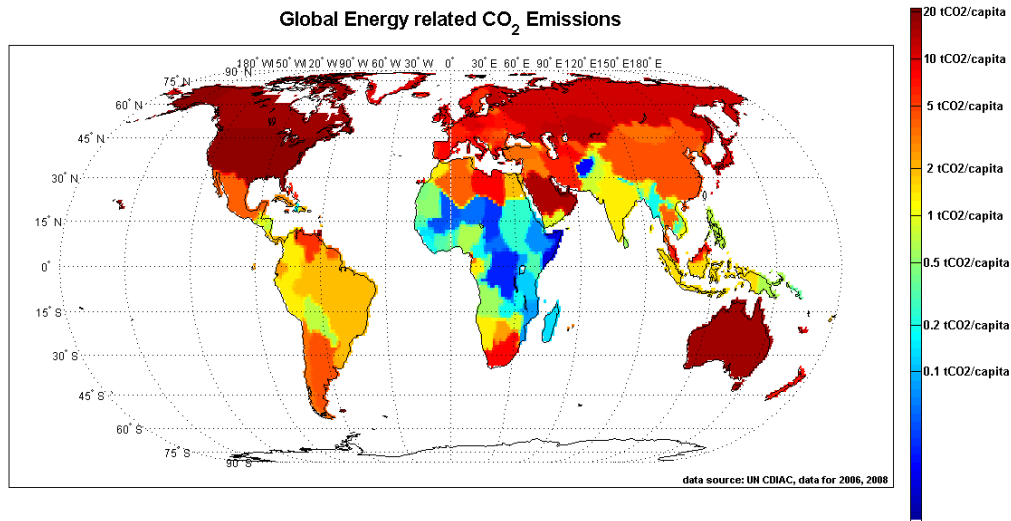


Figure 1.2-2: Global distribution of energy related CO₂ emissions per capita for the year 2006. Energy related CO₂ emission data are used on a per country basis. Data comprise all energy related GHG emissions being summarized on a CO_{2eq} (equivalent) basis. Data are taken from United Nations ^{54,55}.

Regions of high population density and significant economic activities show enormous CO₂ emissions per area, e.g. US East Coast, Central Europe, Eastern China, South Korea and Japan. The formal economic status of a country is not the only factor resulting in high CO₂ emissions, documented for example by Spain and Eastern China, since the formal categories for Spain and China are industrialized (GDP of 35,400 USD/capita) and developing (GDP of 3,200 USD/capita) ^{56,57}, respectively, but the CO₂ emissions per area are significantly higher in Eastern China (Fig. 1.2-1). In general, regions of low income and low to moderate population density show significantly lower CO₂ emissions per area than highly populated and industrialized regions, by several orders of magnitude. Nearly identical outcome can be stated by comparing countries on basis of energy related CO₂ emissions per capita (Fig. 1.2-2), since factors of more than 200 can be found between the group of least developed countries and the group of countries emitting the most energy related CO₂ per capita. The trend of GHG emissions is still increasing, whereas the already cumulated GHG emissions show considerable climate change impact in the world. The CO₂ emission pathway has to be reversed as soon as possible.

Social cost of climate change mitigation will have to be internalized in energy cost for having real price signals of energy use.⁵⁸ Conservative estimates clearly show that social cost of climate change are in the order of 70 €/tCO₂.⁵⁹ Electricity prices outside the EU reflect no CO₂

⁵² UN, Carbon Dioxide Emissions (CO₂), 2009

⁵³ Balk D. and Yetman G., The Global Distribution of Population: Gridded Population of the World, 2005

⁵⁴ UN, Carbon Dioxide Emissions (CO₂), 2009

⁵⁵ UN, World Population Prospects: The 2008 Revision Highlights, 2009

⁵⁶ UN, World Population Prospects: The 2008 Revision Highlights, 2009

⁵⁷ World Bank, Gross domestic product 2008, 2009

⁵⁸ Stern N. (ed.), Stern Review on the economics of climate change, 2006

⁵⁹ Stern N. (ed.), Stern Review on the economics of climate change, 2006

cost and respective prices in the EU started to internalize GHG emissions in the mid 2000s, but on a subcritical low level of 0 – 30 €/t_{CO2} in the period of 2005 to 2011 and roughly 10 – 15 €/t_{CO2} in the period of 2009 to 2011.⁶⁰ Maybe marginal cost of GHG emissions to tackle climate change will have to be even higher than 70 €/t_{CO2}. Regions dependent on fossil fuel fired power plants, in particular coal, will be affected by high escalation rates of true electricity cost.

In addition to economic considerations, the multiple crises and risk sources (Fig. 1.2-3) driven by climate change induced social consequences have the potential to fully destabilize our global society.⁶¹

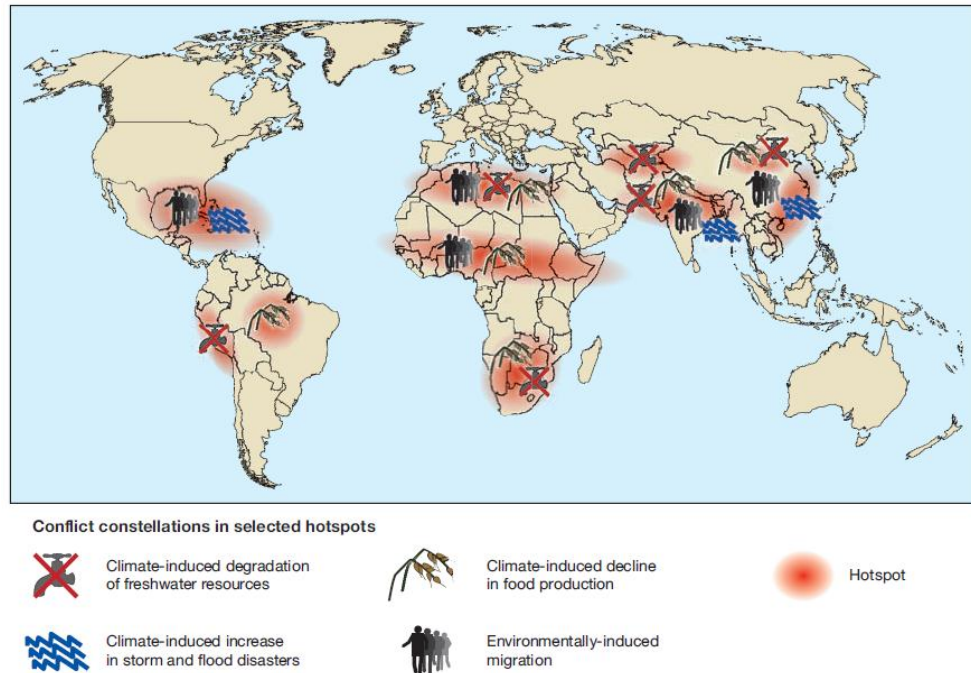


Figure 1.2-3: Security risks associated with climate change at selected hotspots.⁶² The map only shows the regions which could develop into crisis hotspots created by climate induced degradation of freshwater resources, increase in storm and flood disasters, decline in food production and environmentally-induced migration.

A strategy aiming at avoiding a collapse scenario (Fig. 1.2-3) would result in a zero emission pathway for the entire power sector – on a global scale, the sooner the better. The power sector is the most relevant battlefield, due to modal shifts to electricity and more difficult adaption possibilities in other energy sectors, in particular in the transportation sector. The first energy scenarios fully incorporating the strict boundary conditions are published by Greenpeace International⁶³, the German Advisory Council on Global Change (WBGU)⁶⁴, the European Climate Foundation (ECF)⁶⁵ and the International Energy Agency (IEA)⁶⁶. However, these publications can be separated in two groups with fundamentally different pathways that might reach the emission targets but based on a structurally different risk profile. Greenpeace and WBGU propose a paradigm shift towards renewable energy sources

⁶⁰ EEX, EU Emission Allowances – Prices and Trading Volumes, 2011

⁶¹ WBGU, Climate Chance as a Security Risk, 2007

⁶² WBGU, Climate Chance as a Security Risk, 2007

⁶³ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

⁶⁴ WBGU, Welt im Wandel: Gesellschaftsvertrag für eine Große Transformation, 2011

⁶⁵ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

⁶⁶ IEA, World Energy Outlook 2010, 2010

on a low social risk basis in contradiction to the IEA and the ECF suggesting massive investments in nuclear power and coal based carbon capture and storage (CCS) technology both inducing outstanding high social risk including the collapse of technological based global society.

The nuclear technology does not match to the risk profile being necessary for survival of mankind on earth, as documented by major accidents near Sellafield (UK), Harrisburg (USA), Mayak and Chernobyl (both former Soviet Union), Chalk River (Canada), Lucens (Switzerland), Forsmark (Sweden) and Fukushima (Japan). Moreover, there is no convincing nuclear waste disposal strategy, no working protection against terrorism attacks, no effective proliferation procedure and no economic competitiveness best documented by having no privately covered full liability insurance for a single nuclear power plant in the world. The costs of a nuclear failure in the EU in the dimension of the Chernobyl disaster are estimated to about 6,100 bn€ resulting to liability insurance cost of about 0.14 to 2.36 € per generated nuclear kWh for a low cost case due to a very long financial recovery period of 100 years.⁶⁷ In summary, one comes to the conclusion, that nuclear power can be recognized as a failed energy technology. This might be also the case for CCS. It takes at least further ten years in the most optimistic case for having the technology in the market and maybe 25 years in a pessimistic case. The leakage mechanisms of underground disposal sites are not fully understood and enormous capital expenditures for this highly complex technology are needed. As a consequence, poor developing but also emerging countries might further heavily invest in destructive coal power plants without CCS and even worse, in case of higher than expected CO₂ leakage rates the process of a dramatic climate change cannot be reversed. Furthermore, the exploitation of coal resources on earth would be heavily increased and the coal-peak (section 1.3.3), i.e. historic maximum annual coal production, would be much earlier but the nearly eternal sustainable renewable power pathway has to be further delayed. It is not the topic of this thesis, but future energy systems research need to assess the social risk profile of energy scenarios for finding true sustainable pathways and sorting out those being not compatible to the survival of our global society.

1.3 Diminishing Energy Fuel Resources

Global power generation is heavily dependent on diminishing fossil and nuclear energy resources, i.e. about 81.3% (fossil and nuclear) subdivided into about 41.0% (coal), 21.3% (natural gas), 13.5% (nuclear) and 5.5% (oil).⁶⁸ The rates of diminishing and degrading fossil and nuclear resources differ but it is expected that all four major energy fuels show a peak in historic absolute annual production volumes significantly before 2050. Such a physical supply limitation will create a substantial price increase of respective fuels. Currently, prices are based on industrial cost curves for the different fuels and the price of the most expensive supplier needed for covering the demand equals typically the global average price for the fuel. In case of higher demand than supply potential no such clearing price would be possible, therefore the fuel price might be significantly above the production cost. As a consequence of substitution processes the fossil fuels show a more or less stable price coupling over the decades (section 6.1.4), which is superposed by demand and supply fluctuations of each single fuel and respective price reactions. The price coupling is a function of specific primary energy content of the fuels, transport and storage constraints, competing energy sectors and typical power plant energy conversion efficiencies.

⁶⁷ Günter B. et al., Berechnung einer risikoadäquaten Versicherungsprämie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren, 2011

⁶⁸ IEA, World Energy Outlook 2010, 2010

In the following sections an overview is given on the historic and current fuel production and a realistic estimate on future production trends and resource availability for crude oil (section 1.3.1), natural gas (section 1.3.2), coal (section 1.3.3) and uranium (section 1.3.4).

1.3.1 Crude Oil

About 4,060 Mtoe crude oil have been produced in the world in the year 2008, but only about 270 Mtoe (6.7%) were used for power generation.⁶⁹ It has been observed that in the last three decades gas and coal prices were correlated to crude oil prices (section 6.1.4), thus in the end the global crude oil price determines end-users electricity prices via natural gas fired power plants, which set the wholesale price for electricity in liberalized electricity markets.⁷⁰ It is very likely that first crude oil supply constraints will happen very soon. The annual crude oil production has been higher than new found oil fields since the 1980s except one single year in early 1990s (Fig. 1.3-1).

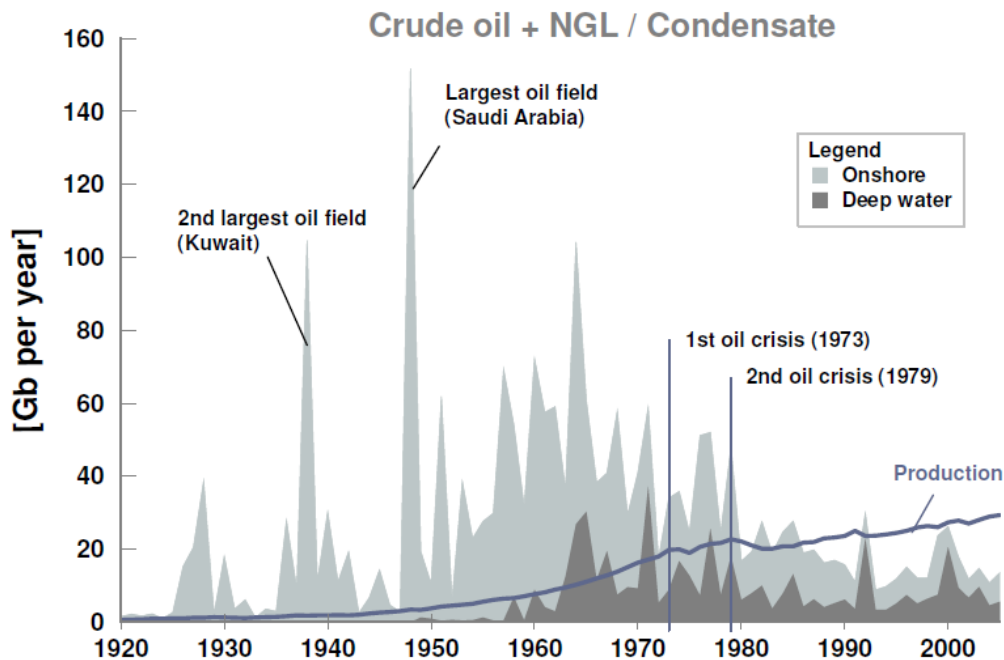


Figure 1.3-1: Annual discoveries and production of crude oil for the years 1920 – 2006.⁷¹ The crude oil and natural gas liquids (NGL) discoveries are rated as proved and probable. Abbreviation Gb stands for giga barrel.

General peak in oil discovers has been in 1960s and the two largest oil fields in the world were found before 1950. Since the 1960s substantial proportion of new found oil resources are located in deep water and need highly sophisticated production technologies being high in cost and at the edge of controllability, reflected by the oil disaster in the Gulf of Mexico in 2010. Despite of high crude oil prices it has been not possible to find more new conventional crude oil resources than annually produced for more than two decades. This poses the question, when the historic peak in annual oil production is reached which would mark the beginning of the end of the oil age.

⁶⁹ IEA, World Energy Outlook 2010, 2010

⁷⁰ IEA, World Energy Outlook 2010, 2010

⁷¹ Schindler J. and Zittel W., (eds.), Crude Oil - The supply outlook, 2008

Back in 1949 Hubbert published his first results on the historic peak production of fossil fuels and stated that fossil fuel consumption would be only a very tiny period in the history of mankind and that solar energy would be the final answer to the energy question.⁷² A few years later he published very precise prognoses on the historic peak in annual oil production for the US in 1970 and for the world around the year 2000 based on observations in many regions.⁷³ He found out that the oil production in oil fields is best described by Gaussian shaped curves, which allow the prediction of the entire curve in case of enough data for the beginning. The historic oil production curve of an oil region or entire nations is a simple superposition of all oil production curves of the respective fields. More than two dozens oil producing nations have already passed the peak in annual production (Fig. 1.3-2).

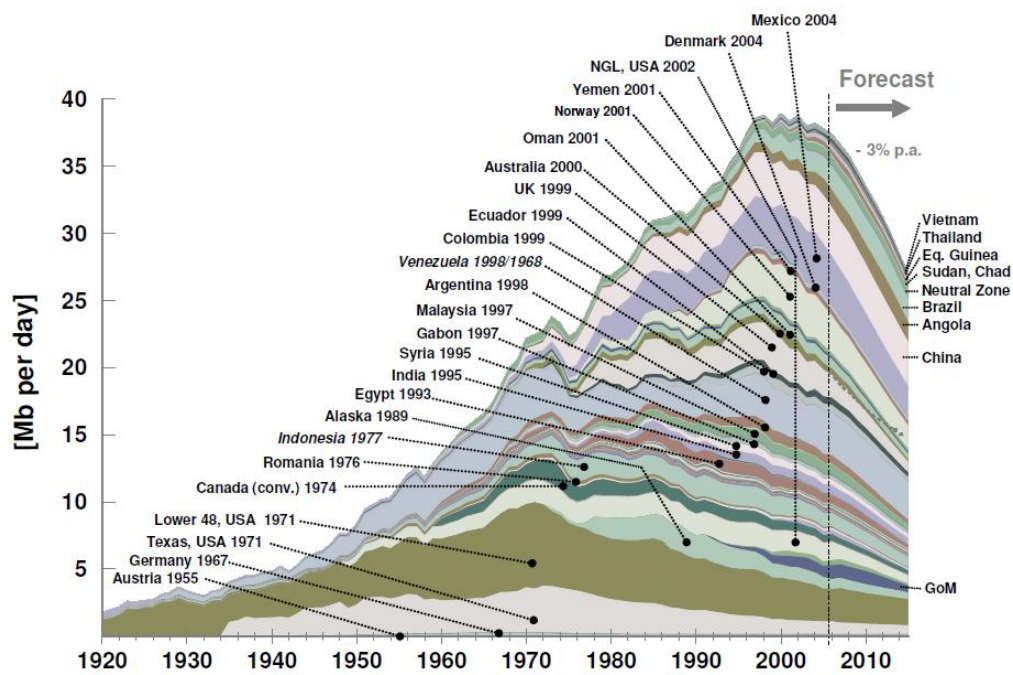


Figure 1.3-2: Oil producing nations being already beyond the peak in annual production.⁷⁴

It is of utmost relevance for the global fossil fuel prices in what year the global peak in oil production occurs, since other fossil fuels would have to immediately substitute that physical shortage. Otherwise an enormous escalation in fossil fuel prices might induce large economic disruptions all around the world. A recent estimate by the Energy Watch Group founded by Hans-Josef Fell expected the historic peak in oil production around the year 2006 (Fig. 1.3-3).⁷⁵

⁷² Hubbert M.K., Energy from Fossil Fuels, 1949

⁷³ Hubbert M.K., Nuclear Energy and the Fossil Fuels, 1956

⁷⁴ Schindler J. and Zittel W., (eds.), Crude Oil - The supply outlook, 2008

⁷⁵ Schindler J. and Zittel W., (eds.), Crude Oil - The supply outlook, 2008

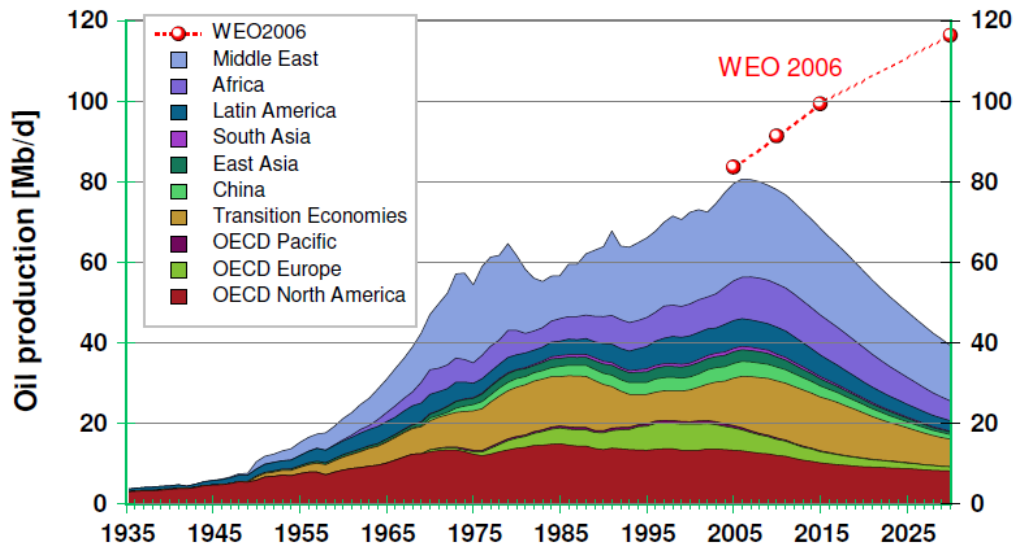


Figure 1.3-3: Historic global oil production in the past and prognosis on the future.⁷⁶ The physical oil production potential is shown in contradiction to the demand estimated by the IEA in its World Energy Outlook.

In 2010 the International Energy Agency confirmed the historic peak in oil production of conventional crude oil for the year 2006.⁷⁷ It is not clear whether natural gas liquids counted in the oil category could substitute the decline in production of conventional crude oil. IEA hopes that unconventional crude oil production might fill the gap and prevent a fast escalation in oil price fired by a global decline in oil production. However, unconventional oil production, like tar sands, are very high in social cost due to enormous damages to the ecosystem, e.g. in Canada, and a very low energy return on energy invested (section. 3.1.6.2). Recently, researchers from the oil sector in Kuwait published results of a detailed analysis based on historic data on oil production for all relevant oil producing countries in the world and an enhanced multicyclic Hubbert model and estimate the historic peak in crude oil production for the year 2014.⁷⁸ Nevertheless, similar to climate change debate it is still not commonly accepted that the crude oil supply problem is a matter of fact.^{79,80} Summing up, indications are eminent that the oil age is passing away right now.

1.3.2 Natural Gas

About 2,600 Mtoe natural gas have been produced in the world in the year 2008 and about 1,020 Mtoe (39%) were used for power generation.⁸¹ The large scale exploitation of natural gas started later than that of crude oil and does not achieve a similar level of contribution to the global energy supply, but in contrast to crude oil the relative peak in total global energy supply has not yet been reached.⁸² The global historic peak in natural gas production is assumed to be later than that of crude oil, but might happen during the 2020s (Fig. 1.3-4). The decline in production rates of natural gas fields is typically faster than for oil fields, e.g. the natural gas production in UK peaked in the year 2000 and has declined by about 40% until the

⁷⁶ Schindler J. and Zittel W., (eds.), Crude Oil - The supply outlook, 2008

⁷⁷ IEA, World Energy Outlook 2010, 2010

⁷⁸ Nashawi I.S. et al., Forecasting World Crude Oil Production using Multicyclic Hubbert Model, 2010

⁷⁹ Bardi U., Peak oil: The four stages of a new idea, 2009

⁸⁰ Almeida de P. and Silva P.D., The peak of oil production – Timings and market recognition, 2009

⁸¹ IEA, World Energy Outlook 2010, 2010

⁸² WBGU, World in Transition: Towards Sustainable Energy Systems, 2003, p. 13

end of the 2000s.⁸³ It has been observed for the last three decades that gas and coal prices are correlated to crude oil prices (section 6.1.4), thus in the end the global crude oil price determines end-users electricity prices at least in liberalized electricity markets showing low energy subsidies⁸⁴. However, natural gas markets show a much more regional structure than crude oil or hard coal trade. The transport costs of natural gas are by at least a factor of ten higher than crude oil per transported primary energy assuming a transport distance of at least 2,000 km being the case for instance for Siberian gas exported per pipeline to Europe or liquefied natural gas traded over the oceans.⁸⁵

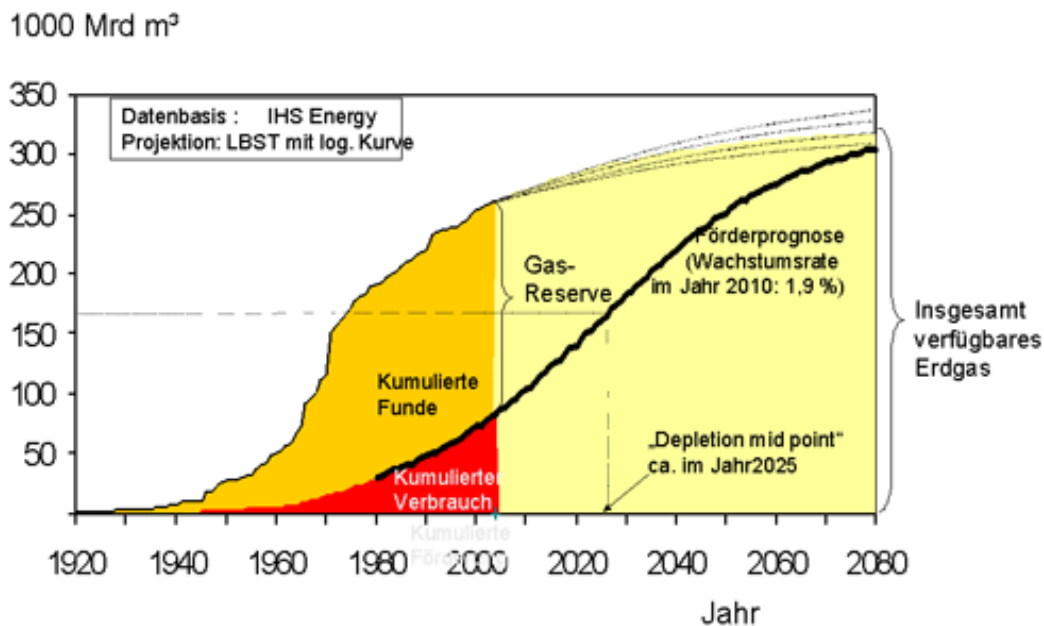


Figure 1.3-4: Natural gas discoveries and exploitation curve for the 1920s – 2000s and projected expectations.⁸⁶ The diagram is based on reserve assumption of 220,000 bn m³ natural gas being more than the proved reserved of about 187,500 bn m³ accounted by BP⁸⁷. The peak in natural gas production, i.e. the depletion mid point, is expected to occur around the year 2025.

Total conventional natural gas resources ('resource in place') are expected to be about 420,000 bn m³, but only 180,000 – 220,000 bn m³ are accounted as reserves, since only a part of total resources is technically recoverable which need to be economically recoverable.⁸⁸ Further non-conventional natural gas resources are gas hydrates, coal-bed methane, shallow biogenic gas, tight gas and shale gas. Total 'resource in place' of shale gas and coal-bed methane plus tight gas is estimated to be in the order of conventional gas each.⁸⁹ However, only a minor fraction of these resources might be exploitable reserves. Some of these resources have always been exploited, but after lowering the environmental legislation in the US in 2005 a shale gas hype has started.^{90,91} Within some years the fraction of unconventional gas production reached about 10% in the US. The production technique is rather old and was

⁸³ Selmann T. and Zittel W., Natural gas reserves: a false hope, 2009

⁸⁴ IEA, World Energy Outlook 2010, 2010

⁸⁵ Stevens P., The 'Shale Gas Revolution': Hype and Reality, 2010, p. 29

⁸⁶ Zittel W., Ist Erdgas eine Alternative zum Erdöl?, 2008

⁸⁷ BP, Statistical Review of World Energy, 2010

⁸⁸ Zittel W., Unkonventionelles Erdgas, 2010

⁸⁹ Zittel W., Unkonventionelles Erdgas, 2010

⁹⁰ Stevens P., The 'Shale Gas Revolution': Hype and Reality, 2010

⁹¹ Zittel W., Unkonventionelles Erdgas, 2010

introduced as hydraulic fracturing in the late 1940s. In recent years no substantial technological progress was achieved.

Large amounts of water, sand and a mixture of dozens of toxic materials⁹² are pressed into the ground for crushing the shale gas deposits. Depending on the specific site either only 10% - 35% of that mixture is recovered afterwards and has to be treated as hazardous waste or a multiple of the original volumes flows back contaminated by radioactive elements like radium and radon.^{93,94} The production technology and economics for shale gas differs significantly from conventional gas, since about six drillings per km² are needed for shale gas and most shale wells are expected to have only a lifetime of 8 – 12 years compared to 30 – 40 years for conventional gas.⁹⁵ The typical decline rates of shale gas production are a magnitude higher than for conventional gas, i.e. the decline rates are several percent per month instead per year.⁹⁶ The environmental problems range from the use of chemicals having toxic, carcinogenic and other hazardous properties, contamination of the ground water with these chemicals but also methane and non appropriate waste disposal of the flow back fluid and last but not least greenhouse gas emissions comprising the entire value chain being even worse than those of coal.^{97,98,99}

Summing up, a major shift of global primary energy supply to natural gas after reaching peak-oil (section 1.3.1) will not happen, since only 10 – 15 years later the global historic peak in natural gas production might occur. Unconventional natural gas resources like shale gas show not the necessary characteristics for a fundamental change in natural gas supply.

1.3.3 Coal

About 3,320 Mtoe coal were used for energetic needs in total in the world in 2008 and about 2,170 Mtoe (65%) were used for power generation being equivalent to about 41% of global electricity supply.¹⁰⁰ Whereas mid-term coal-supply shortages might be a relief to ongoing climate change (sub-chapter 1.2), the global power supply system would be subject to enormous pressure.

Already in 1956 Hubbert assumed a peak in annual coal production on a time scale of about 200 years.¹⁰¹ Only 15 years later he reduced the time needed for a peaking production by about 50 years based on latest production numbers and an assumption of about $4.3 \cdot 10^{12}$ tonnes of minable coal.¹⁰² In 1990s and 2000s several countries adjusted their coal reserves on a lower realistic level which led to a current assumption of about $4.5 \cdot 10^{12}$ tonnes of global coal resources and a historic coal production curve which might be in the shape depicted in Figure 1.3-5.¹⁰³

⁹² Wood R. et al., Shale gas: a provisional assessment of climate change and environmental impacts, 2011

⁹³ NYS, Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining, 2009

⁹⁴ Zittel W., Unkonventionelles Erdgas, 2010

⁹⁵ Stevens P., The 'Shale Gas Revolution': Hype and Reality, 2010

⁹⁶ Zittel W., Unkonventionelles Erdgas, 2010

⁹⁷ Zittel W., Unkonventionelles Erdgas, 2010

⁹⁸ Wood R. et al., Shale gas: a provisional assessment of climate change and environmental impacts, 2011

⁹⁹ Howarth R.W. et al., Methane and the green house-gas footprint of natural gas from shale formations, 2011

¹⁰⁰ IEA, World Energy Outlook 2010, 2010

¹⁰¹ Hubbert M.K., Nuclear Energy and the Fossil Fuels, 1956

¹⁰² Hubbert M.K., The energy resources on the Earth, 1971

¹⁰³ Zittel W. and Schindler J., (eds.), Coal: Resources and future production, 2007

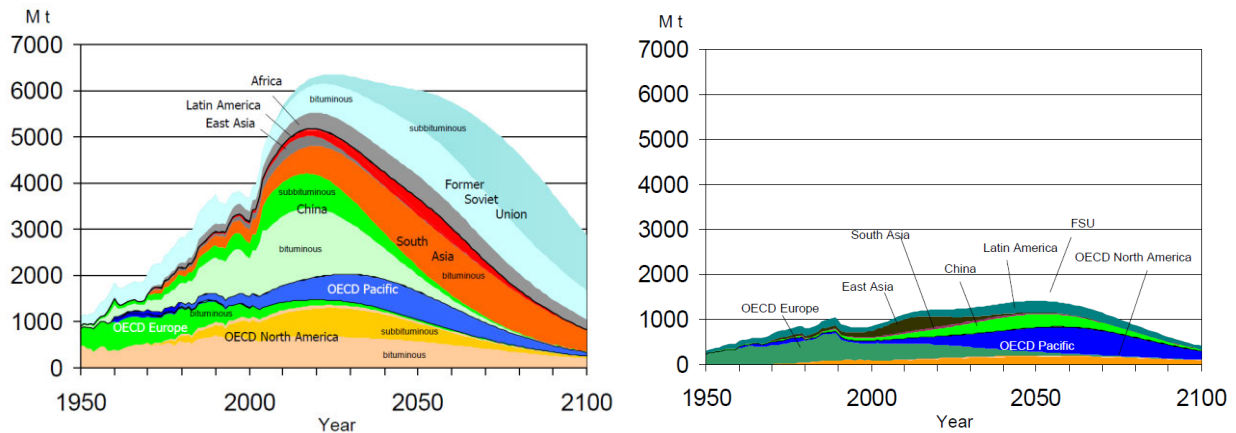


Figure 1.3-5: Global hard (left) and lignite (right) coal production for the years 1950 – 2005 and a projection up to the year 2100.¹⁰⁴ Bituminous and sub-bituminous coal is aggregated to hard coal.

The superposition of hard and lignite coal (Fig. 1.3-5) production might lead to a peak in coal mining around 2030 to 2050, i.e. it might be not enough coal left for firing today's coal power plant fleet during the expected lifetime of about 40 years. The results found by the German Energy Watch Group are fully inline with latest outcome of research on the peak in coal production by Chinese scientists.¹⁰⁵ Lin and Liu point out that China became a net coal importer in the late 2000s and it is very likely that the Chinese coal imports will absorb about 50% of international coal trade by 2030 boosted by fast expansion of coal based power generation. The authors conclude that the economic growth of China would not be sustainable if the dependence on the diminishing global coal resources were such high hence among others they recommend to establish a renewable power generation base. Furthermore, the economic growth of China might be significantly reduced in case of not solving the coal dependence issue.¹⁰⁶ The development of coal consumption in China is highly relevant for the global coal production, since the current global Chinese coal consumption share of about 43% in 2008 is expected to significantly grow to about 50% by end of 2010s.¹⁰⁷

1.3.4 Uranium

About 712 Mtoe uranium were used for energetic needs in total in the world in 2008 and all were used for power generation being equivalent to about 13.5% of global electricity supply.¹⁰⁸ The global capacity of nuclear power plant fleet still in operation has been more or less stable since the late 1980s and is fluctuating between 320 and 370 GW.¹⁰⁹ This is a consequence of the nuclear accident in Harrisburg in 1979 and nuclear melt-down in Chernobyl in 1986 and poor total life cycle cost being not compatible to liberalized power markets.^{110,111} After the nuclear melt-down in Fukushima in 2011 it is very likely that such a unsustainable energy technology will have to phase out at least in participatory societies.

¹⁰⁴ Zittel W. and Schindler J., (eds.), Coal: Resources and future production, 2007

¹⁰⁵ Lin B. and Liu J., Estimating coal production peak and trends of coal imports in China, 2010

¹⁰⁶ Shealy M. and Dorian J.P., Growing Chinese coal use: Dramatic resource and environmental implications, 2010

¹⁰⁷ IEA, World Energy Outlook 2010, 2010

¹⁰⁸ IEA, World Energy Outlook 2010, 2010

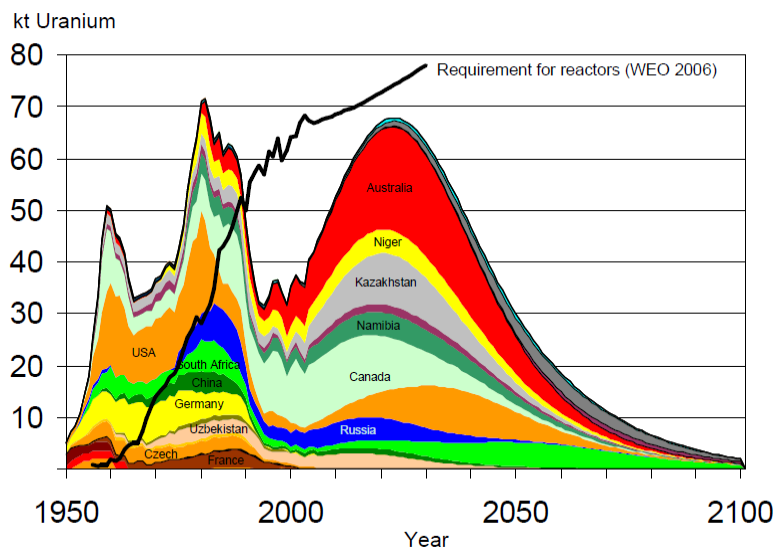
¹⁰⁹ Schneider M. et al., The World Nuclear Industry Status Report 2010-2011, 2011

¹¹⁰ Moody's, Nuclear plant construction poses risks to credit metrics, ratings, 2008

¹¹¹ Roy M. et al., Loan Guarantees for Advanced Nuclear Energy Facilities - Bankers' Comments on DoE Notice of Proposed Rulemaking, 2007

Nuclear fuel supply security can be assessed on the fundamental resource availability similar to the fossil fuels (sections 1.3.1 to 1.3.3). Before doing that three fundamental different nuclear power technologies need to be separated: conventional nuclear fission power, nuclear breeder fission power and nuclear fusion power. The nuclear fusion power has been documented by the hydrogen fusion bomb but up to now it was not possible to generate more electricity than used for the fusion process in a fusion power research reactor under controlled conditions, i.e. despite of many billions of invested public R&D expenditures and decades of research no single prove of concept experiment was successful. Even worse, an optimistic estimate on market availability indicates at least 50 years being much too late for climate change mitigation and fossil fuels peak production adaptation. Cochran et al. summarized the history and status of breeder reactors.¹¹² The nuclear breeder fission power technology was originally suggested for prolonging the limited uranium resources on earth, since only uranium-235 can be used in uranium fission reactors (conventional nuclear power), but 99.3% of uranium is available in uranium-238. However, uranium-238 can be used in plutonium fission reactors, as fast neutrons are used and created in that reactor type and uranium-238 is converted via radioactive decays into plutonium being again available for nuclear fission. But fast neutrons require an adapted cooling medium, typically sodium. Sodium induces several complications, as sodium fires are caused by reaction with water or air, which was typically the reason for the stop of respective breeder programmes in nearly all countries that intended to establish plutonium fission reactors. As a consequence, capital expenditures for plutonium fission reactors are significantly higher than those for uranium reactors, they show very high downtimes due to very difficult maintenance and sodium complications and last but not least a plutonium cycle is precondition for that reactor type. Not to mention plutonium is the most toxic substance known on earth. Summing up, plutonium fission reactors show an even lower security level than uranium fission reactors, hence breeder reactors have to be considered as a failed technology alike conventional uranium fission reactors.

Nuclear power plants in operation need uranium for power generation, thus uranium resource availability is of interest for assessing the future prospects of the technology from the fuel perspective. The global historic uranium production, the demand for nuclear power plants and future mining potentials are illustrated in Figure 1.3-6.



¹¹² Cochran T.B. et al., Fast Breeder Reactor Programs: History and Status, 2010

Figure 1.3-6: Global uranium mining in the past and the commercial potential in future compared to the demand of nuclear power plants.¹¹³ The future uranium mining potential is according to the ‘Reasonably Assured Resources’ (RAR) definition on cost lower than 130 USD/kgU being roughly comparable to ‘probable reserves’. The known reserves fulfilling the RAR < 130 USD/kgU requirement are estimated to be about 3,300 kt, which is equivalent to an exploitable quality of better than 0.01% U₃O₈ in the deposits.

Beginning in early 1950s up to late 1970s global uranium mining has been much higher than the demand of nuclear reactors, caused by military demand and building up respective stocks for assumed high growth rates of new nuclear power plant capacity investments. However, after Harrisburg in 1979 and Chernobyl in 1986 and ongoing cost escalations the rate of new power plant capacity investments sharply declined (Fig. 5.1-9) resulting in low new capacities at late 1980s according a delay of about 6 – 10 years due to the long construction periods (Table 6.1-2). Since the 1990s the annual uranium mining is below the annual nuclear power plant demand (Fig. 1.3-6), which might cause severe price escalations in future. Currently, further uranium quantities are used from material in stock and in particular from cold war weapon sources. However, future demand can only be covered by new mines (Fig. 1.3-6), but the commercially known uranium deposits would be sufficient for the current nuclear power plant capacity – not for further capacities. It remains unclear where the uranium might be exploited which is needed for the build-up of additional 250 GW nuclear power plant capacity until the year 2035 as assumed by International Energy Agency in its ‘New Policies’ scenario.¹¹⁴ Cost of uranium mining does typically not include severe health problems existent around mining sites, i.e. multiple cancer diseases causing many victims.^{115,116}

Ore grades of at least 0.01% U₃O₈ of the known uranium deposits are classified as ‘probable reserves’ or ‘reasonably assured resources’ exploitable for not more than 130 USD/kgU providing access to about 3,300 kt uranium.¹¹⁷ Expected but unexplored uranium resources might increase the commercially minable uranium resources to 4,700 kt.¹¹⁸ This results in the conclusion that the small available resource base classifies uranium fission reactor technology as a negligible technology for fighting against climate change (sub-chapter 1.2) or the replacement of diminishing fossil fuels (sections 1.3.1 to 1.3.3).

The existence of low grade deposits will not prolong existence of nuclear power plants as a consequence of a rapid decline in energetic productivity, i.e. ore grades of less than 0.1% U₃O₈ content induces a fast decline reducing the net generated energy over the entire fuel chain to zero at about 0.01% – 0.02% U₃O₈ content (Fig. 1.3-7).

¹¹³ Zittel W. and Schindler J., (eds.), Uranium Resources and Nuclear Energy, 2006

¹¹⁴ IEA, World Energy Outlook 2010, 2010

¹¹⁵ Meyer C., Der gelbe Fluch, 2010

¹¹⁶ Auth S. et al., Uranium - is it a country? Eine Spurensuche nach der Herkunft von Atomstrom, 2008

¹¹⁷ Zittel W. and Schindler J., (eds.), Uranium Resources and Nuclear Energy, 2006

¹¹⁸ Zittel W. and Schindler J., (eds.), Uranium Resources and Nuclear Energy, 2006

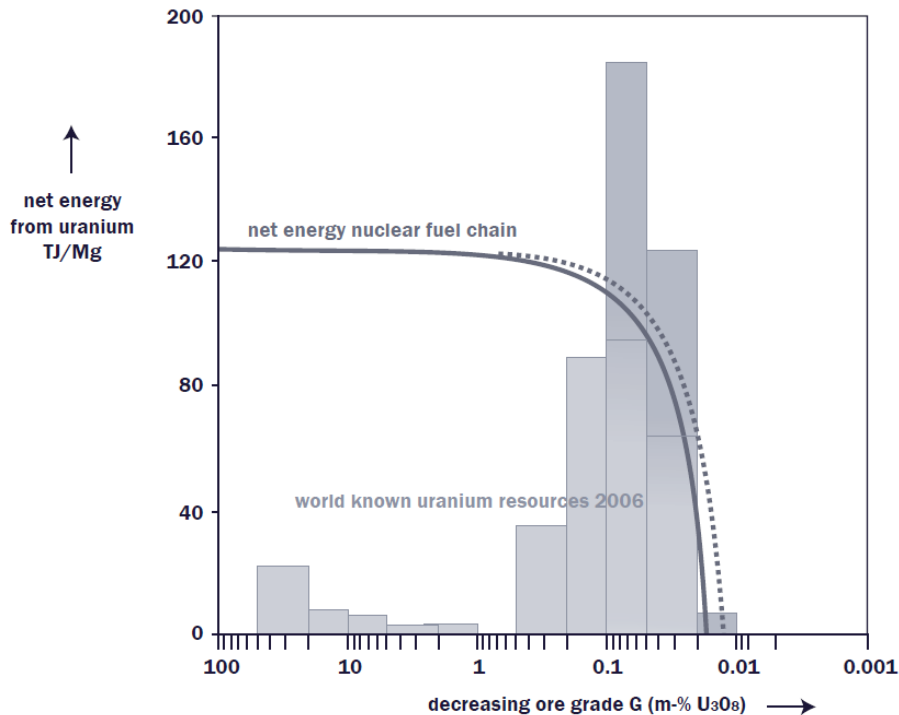


Figure 1.3-7: Net energy of the nuclear fuel chain as a function of uranium ore grade.¹¹⁹ The plotted curve does only include the fuel chain. Further inclusion of power plant construction and dismantling would reduce the net energy by about 35%. The ore grade of about 0.01% U₃O₈ content leading to zero net energy is roughly equivalent to the mining potential curve of Figure 1.3-6. The solid and dashed lines indicate the energy difference of soft and hard ores.

Net energy generated by the nuclear fuel chain is forced to a steep decline for decreasing uranium ore grades (Fig. 1.3-7). Uranium deposits of about 0.01% - 0.02% U₃O₈ content mark the end of the age of nuclear power plants, since energetic productivity would become negative for lower resource qualities, i.e. more energy would be needed than could be provided afterwards by nuclear power plants. This resource induced phase out of nuclear power plants is expected to be around 2050 for the case of having a constant nuclear power supply share and about 2075 for the case of a constant nuclear power plant capacity installed today.¹²⁰ These results obtained by the British Oxford Research Group are fully confirmed by the German Energy Watch Group (Fig. 1.3-6)¹²¹.

On the other side, as a consequence of low energetic productivity, the specific greenhouse gas emissions of nuclear power are subject to a fast increase as a function of decreasing ore grade (Fig. 1.3-8).

¹¹⁹ Barnaby F. and Kemp J., (eds.), *Secure Energy? – Civil Nuclear Power, Security and Global Warming*, 2007

¹²⁰ Barnaby F. and Kemp J., (eds.), *Secure Energy? – Civil Nuclear Power, Security and Global Warming*, 2007

¹²¹ Zittel W. and Schindler J., (eds.), *Uranium Resources and Nuclear Energy*, 2006

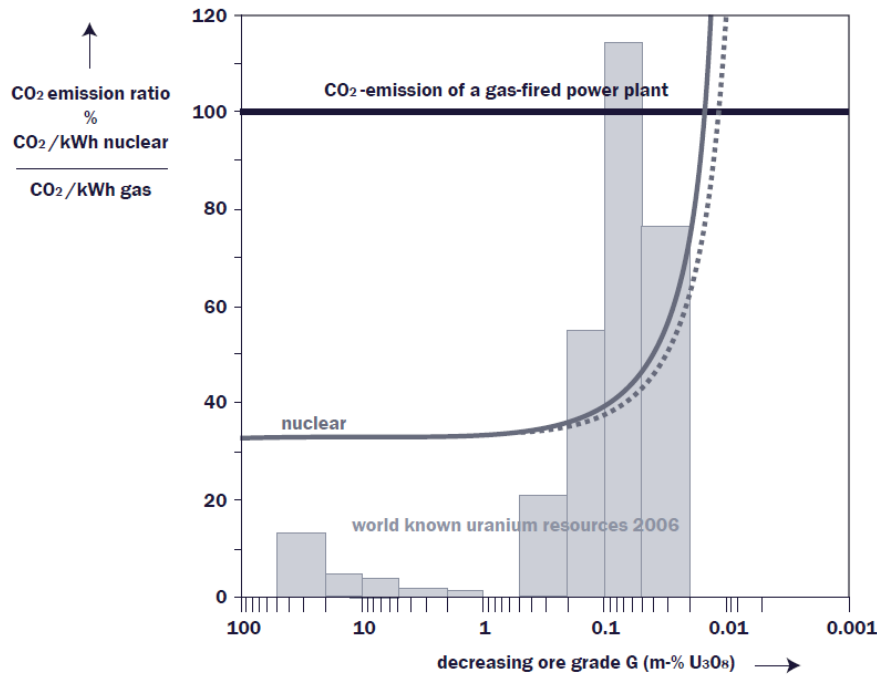


Figure 1.3-8: Specific greenhouse gas emissions of the nuclear power normalized to natural gas fired power plants as a function of uranium ore grade.¹²² The ore grade of about 0.01% U_3O_8 content leading to zero net energy further marks an enormous increase in specific CO_2 emissions. The solid and dashed lines indicate the energy difference of soft and hard ores.

It is often claimed that nuclear power could significantly contribute to climate change mitigation. An energetic analysis of net energy provided by nuclear power indicate a zero net energy for an ore grade of about 0.01% U_3O_8 content (Fig. 1.3-7) which is equivalent to a very steep increase in specific greenhouse gas emissions (Fig. 1.3-8). The enormous increase in specific CO_2 emissions of nuclear power plants is expected to be around 2050 for the case of having a constant nuclear power supply share and about 2075 for the case of a constant nuclear power plant capacity installed today.¹²³ Propagating new nuclear power plants for fighting climate change is fully misleading, since this would further increase CO_2 emissions. Nuclear power is no help in reducing greenhouse gas emissions.

Summing up, the uranium resource availability indicates a global phase out of nuclear power within next four to six decades as a simple consequence of uranium availability, low overall energetic productivity, no other nuclear power technology alternative and poor specific CO_2 emission prospects.

1.4 Energy Injustice

The 19.5 million inhabitants of New York consume in a year roughly the same quantity of electricity, 40 TWh, as the 791 million people of sub-Saharan Africa.¹²⁴ Plenty of such comparisons could be found describing the same, i.e. an enormous difference in energy justice in the world. Access to modern forms of energy, e.g. electricity, is a major prerequisite for sustainable local development, since it is essential for the provision of clean water, sanitation and healthcare, and provides great benefits to development through the provision of reliable

¹²² Barnaby F. and Kemp J., (eds.), *Secure Energy? – Civil Nuclear Power, Security and Global Warming*, 2007

¹²³ Barnaby F. and Kemp J., (eds.), *Secure Energy? – Civil Nuclear Power, Security and Global Warming*, 2007

¹²⁴ IEA, *World Energy Outlook 2010*, 2010, p. 237-271

and efficient lighting, heating, cooking, mechanical power, transport and telecommunication services.¹²⁵ In the late 2000s, there are 1.4 billion people without access to electricity (Fig. 1.4-1) and 2.7 billion people have to rely on traditional biomass cooking.¹²⁶

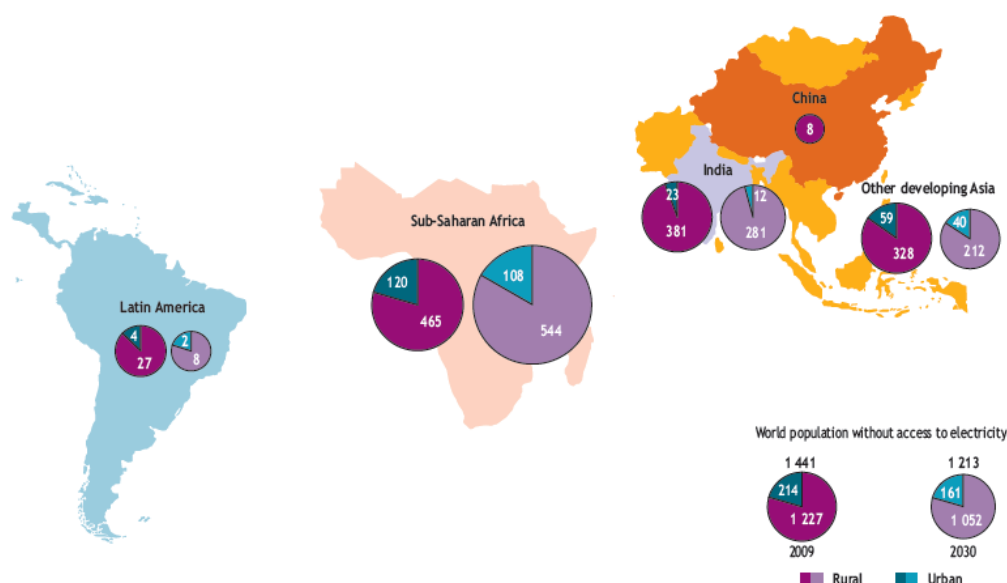


Figure 1.4-1: Global distribution of population without access to electricity in the year 2009 and expected for the year 2030.¹²⁷ Most people live in rural areas in sub-Saharan Africa, India and developing Asia.

Most people without access to electricity live in sub-Saharan Africa, India and developing Asia. The electrification rate in sub-Saharan Africa (excluding South Africa) is 28% and only little progress can be expected. The other developing regions either have already managed the electrification challenge or are on a promising pathway.

In general, the United Nations Millennium Development Goals¹²⁸, e.g. eradicating of extreme poverty and hunger, achieving universal primary education, promoting gender equality, improving health conditions and ensuring environmental sustainability, will not be achieved unless substantial progress is made to improve energy access. For a substantial progress, annual investments would be needed on the level of about 0.06% of global gross domestic product (GDP), i.e. about 40 bnUSD annually.¹²⁹ For the aggressive target of achieving universal access to modern energy services additional 35 bnUSD per year until 2030 would be needed, representing less than 3% of projected global energy investments in the same period. Financing would be available even within the developing countries, as about 250 bnUSD of total fossil fuel subsidies were incurred in developing countries in 2009, and subsidies in countries with low access to modern energy at the household level amounted to about 70 bnUSD, i.e. most developing countries could reach full access to modern energy services on its own.¹³⁰ The incremental generated electricity and the investment needed for achieving the universal modern energy access target is depicted in Figure 1.4-2.

¹²⁵ IEA, World Energy Outlook 2010, 2010, p. 237-271

¹²⁶ IEA, World Energy Outlook 2010, 2010, p. 237-271

¹²⁷ IEA, World Energy Outlook 2010, 2010, p. 237-271

¹²⁸ UN, The Millennium Development Goals Report, 2010

¹²⁹ IEA, World Energy Outlook 2010, 2010, p. 237-271

¹³⁰ IEA, World Energy Outlook 2010, 2010, p. 237-271

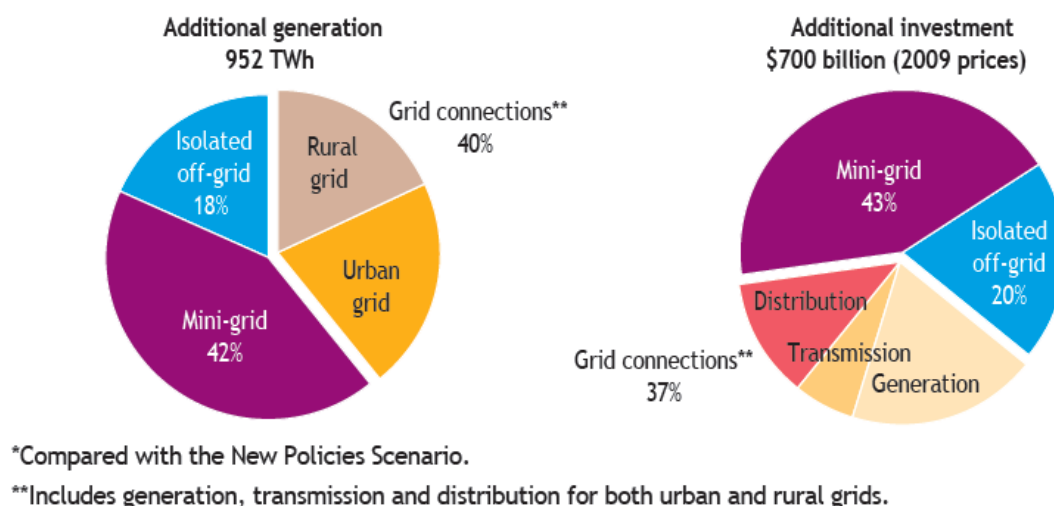


Figure 1.4-2: Incremental electricity generation and capital investment for reaching the universal modern energy access target in the year 2010 – 2030.¹³¹ Isolated off-grid systems would be for instance solar home systems or PV pico-systems (section 3.4.1). The mini-grids would be powered mainly by PV, wind power, hydro power and diesel gensets (section 3.4.2).

The International Energy Agency (IEA)¹³² assumes that a substantial fraction of people without access to electricity could get power by extensions of existing grids (40% of incremental power), furthermore about 40% of additional electricity generation could be provided via mini-grids (section 3.4.2) and 20% of new electricity requirements might be served by isolated off-grid solutions, like solar home systems or PV pico-systems (section 3.4.1). The investments needed for reaching the universal modern energy access target for electricity would require according to Figure 1.4-2 about 260 bnUSD for grid extensions and respective power capacities, about 300 bnUSD for mini-grids and about 140 bnUSD for isolated off-grid solutions. All three categories could be powered mainly by renewable energy sources (sub-chapter 3.4 and chapters 6 and 7).

Access to modern forms of energy services seems to be rather a driver for social progress than the outcome of increase in wealth. This hypothesis is backed by the relation of the human development index (HDI)¹³³ and the energy development index (EDI)¹³⁴ illustrated in Figure 1.4-3. The HDI comprises indicators for life expectancy at birth, adult literacy rate, education rate and GDP per capita, as these output indicators show high rates in case of excellent social conditions.¹³⁵ The EDI is based on energy consumption per capita (residential and commercial), share of modern fuels used in residential sector and share of population with access to electricity, as these output indicators represent the level of energy justice and accessibility of modern forms of energy services for developing countries.¹³⁶ Thus, access to modern forms of energy is a major driver for social progress in developing countries (Fig. 1.4-3), as essential basis for instance for access to lighting, telecommunication, health services, education, labour productivity, agricultural productivity, water supply or sanitation.

¹³¹ IEA, World Energy Outlook 2010, 2010, p. 237-271

¹³² IEA, World Energy Outlook 2010, 2010, p. 237-271

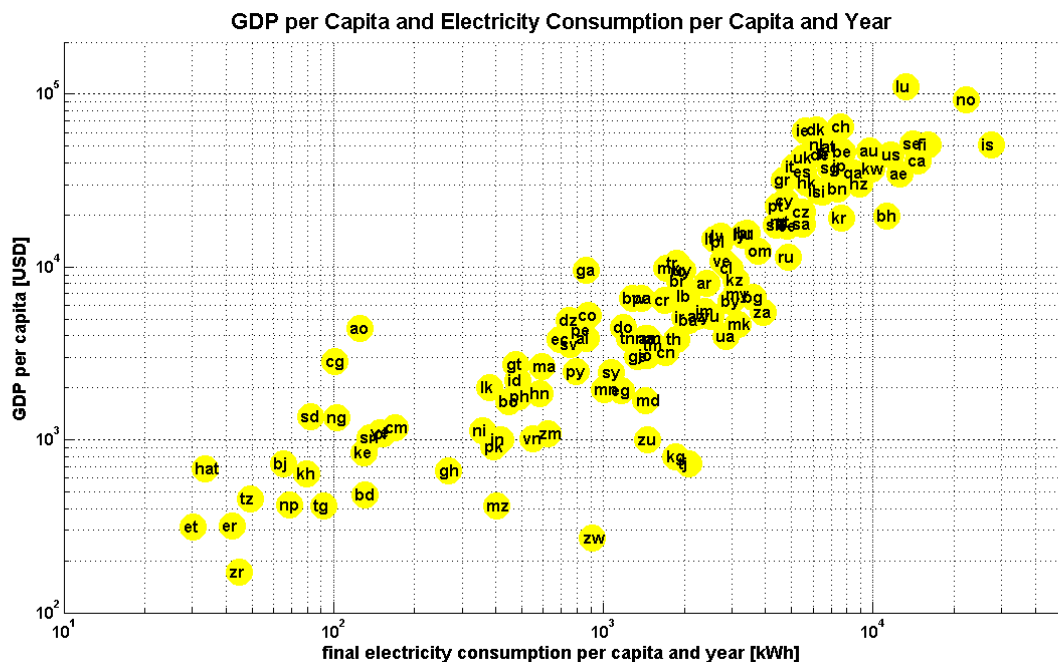
¹³³ UNDP, Human Development Report 2007/2008, 2008

¹³⁴ IEA, World Energy Outlook 2010, 2010, p. 237-271

¹³⁵ UNDP, Human Development Report 2007/2008, 2008

¹³⁶ IEA, World Energy Outlook 2010, 2010, p. 237-271

There is a close relation between GDP per capita and final electricity consumption per capita (Fig. 1.4-4). Due to the relation of HDI and EDI (Fig. 1.4-3) it is very likely that electricity consumption per capita might rather be the major driving force for the GDP per capita than vice versa.



¹⁴¹ IEA, Key World Energy Statistics 2009, 2009

In the following several major aspects for social progress are plotted as a function of final electricity consumption per capita for as many countries as data have been found. The different relations are shown for child per woman, electrification rate, adult illiteracy rate, corruption intensity, undernourishment and access to improved water (Fig. 1.4-5).

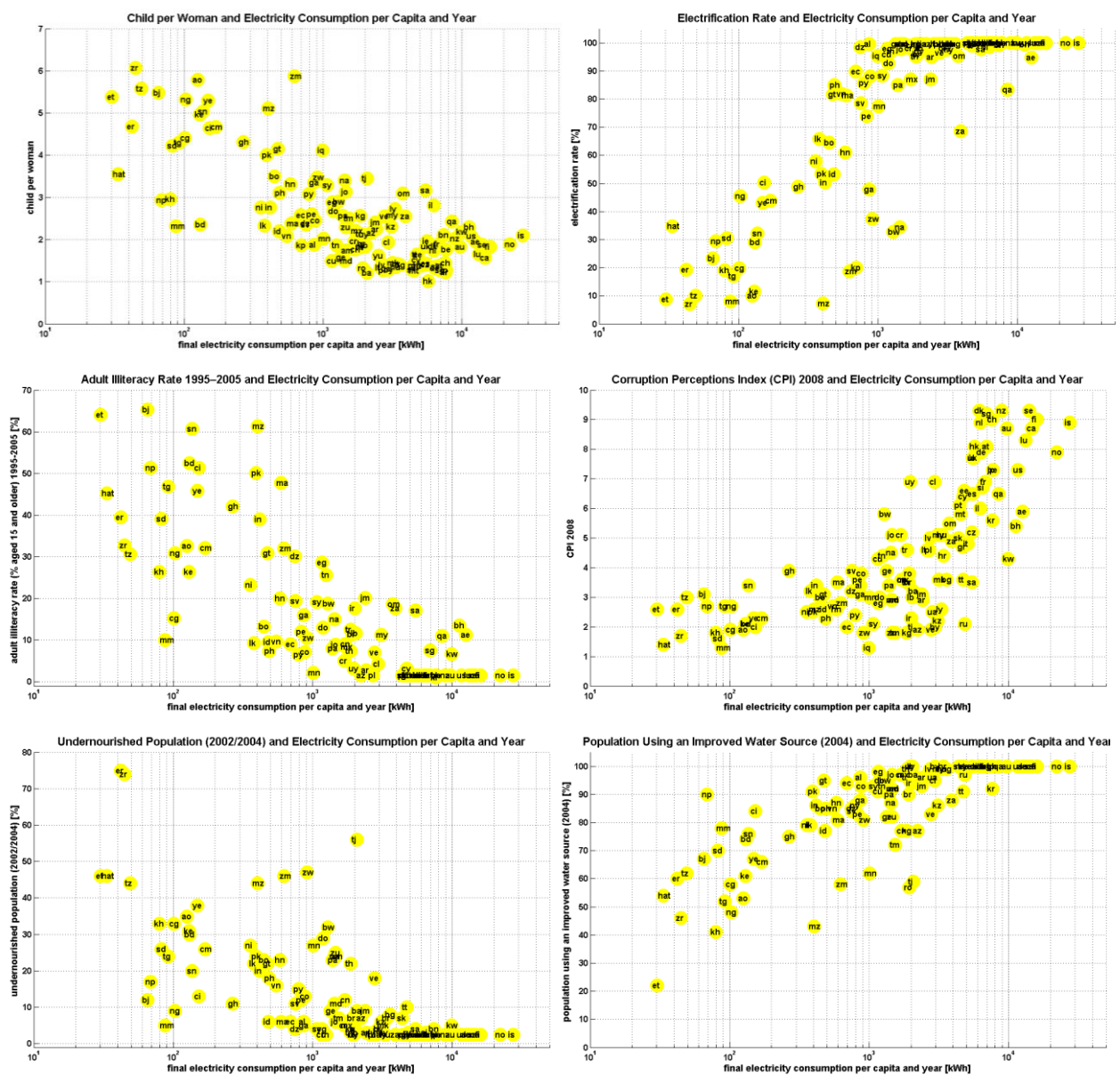


Figure 1.4-5: Major individual aspects indicating social progress in dependence on final electricity consumption per capita for nearly all countries in the world. The aspects are: child per woman (top, left), electrification rate (top, right), adult illiteracy rate (centre, left), corruption perceptions index (centre, right), undernourished population (bottom, left) and population using improved water sources (bottom, right). Countries are named by

their country code of top level web domain (Appendix Table 4). Data are given in Appendix Table 2. Data are taken from United Nations ^{142,143}, Transparency International ¹⁴⁴, World Health Organization ¹⁴⁵ and International Energy Agency ^{146,147}.

The selected major aspects representing social progress show a significant correlation to the final electricity consumption per capita (Fig. 1.4-5). It is very difficult to identify the major driver for social progress. The final electricity consumption per capita might be only one of several key aspects. Data significantly scatter around the trend line indicating the existence of further relevant factors. However, the electricity acts at least as a clear indicator of social progress. Further research is needed to generate a more differentiated view on the interaction of final electricity consumption per capita and social progress. In the following some observations of the correlation of social progress and electricity consumption presented in Figure 1.4-5 are described.

Maybe the most relevant indicator is child per women, since the population explosion is the key driver for the massive overexploitation of the natural resources of our planet.^{148,149} The indicator child per woman is an early indicator representing the trend towards a population equilibrium for 2.1 children per woman. This threshold is reached in many countries for an annual final electricity consumption per capita of about 4,000 kWh (Fig. 1.4-5). The electrification rate is a key indicator for enabling social progress. Two essential thresholds can be observed. No country below 300 kWh/capita of annual final electricity consumption reaches an electrification rate of more than 50%. However, between 1,000 and 2,000 kWh/capita of annual final electricity consumption almost all countries are very close to 100% electrification rate (Fig. 1.4-5). The indicators adult illiteracy and the corruption perception index document the individual and societal threshold for sustainable progress, since either no basis for qualified and well-paid occupations and advanced social interactions or a lack of public services quality is given. The adult illiteracy rate improves significantly for the thresholds of about 500 annual kWh/capita and 2,000 annual kWh/capita (Fig. 1.4-5). The corruption perception index improves significantly for the thresholds of about 1,000 annual kWh/capita and 10,000 annual kWh/capita (Fig. 1.4-5). The indicator for undernourished population represents the level of food supply thus documenting the minimum level of individual existence. The ratio of undernourished people per country improves significantly for the thresholds of about 2,000 annual kWh/capita and 5,000 annual kWh/capita (Fig. 1.4-5). The indicator for improved water sources per country shows the relative level of high quality supply of the population and the reduction of drinking water related disease. The ratio of people using improved water sources per country improves significantly for the thresholds of about 200 annual kWh/capita and 2,000 annual kWh/capita (Fig. 1.4-5).

In total there are two barriers of social progress which can be overcome by an increase in final electricity consumption per capita. The first barrier at about 2,000 annual kWh/capita documents the transition from developing to emerging countries and the second barrier at about 5,000 annual kWh/capita represents the transition from emerging to industrialized countries. The access to electricity seems to be one of the major drivers for social progress in the world. One of the major aspects of this thesis is therefore, whether PV could become a key

¹⁴² UN, World Population Prospects: The 2006 Revision Highlights, 2007

¹⁴³ UNDP, Human Development Report 2007/2008, 2008

¹⁴⁴ TI, Global Corruption Report 2009: Corruption and the Private Sector, 2009

¹⁴⁵ WHO, Progress on Sanitation and Drinking-water: 2010 Update, 2010

¹⁴⁶ IEA, World Energy Outlook 2006, 2006

¹⁴⁷ IEA, Key World Energy Statistics 2009, 2009

¹⁴⁸ Meadows D.H. et al., The limits to growth, 1972

¹⁴⁹ Meadows D.H. et al., Limits to growth: the 30-year update, 2004

source of inexpensive, reliable and worldwide accessible electricity being the fundamental basis for social progress.

1.5 Ecological Footprint

Sustainability requires living within the boundaries of the regenerative capacity of the biosphere. In an attempt to measure the extent to which humanity satisfies this requirement, human demand on the environment translated into area is compared to the area required for the production of food and other goods, together with the absorption of wastes. This comparison indicates that human demand exceeds the biosphere's regenerative capacity since the mid 1970s. This assessment visualises humanity's load corresponded to 70% of the capacity of the global biosphere in early 1960s and grew to 150% in late 2000s (Fig. 1.5-1).^{150,151,152,153}

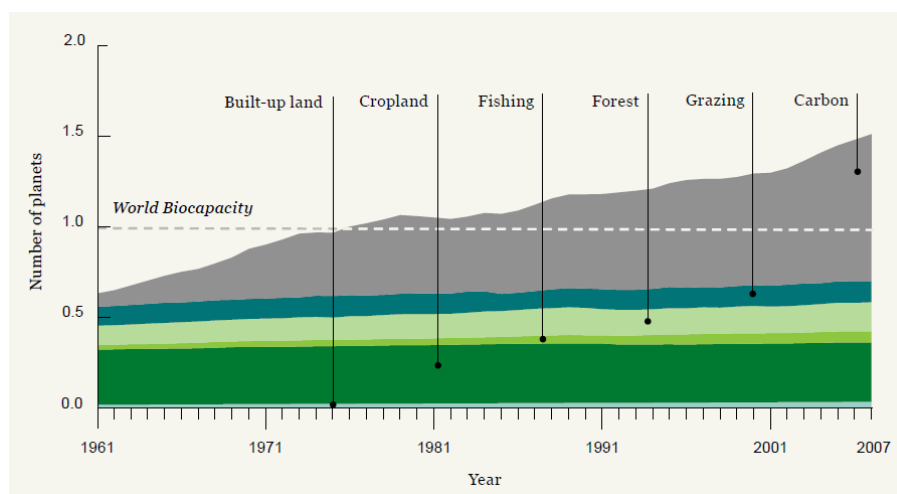


Figure 1.5-1: Development of global ecological footprint by major contributors for the years 1961 – 2007.¹⁵⁴ The major contributor to the ecological footprint is the emission of greenhouse gases representing more than 50% of the total ecological footprint.

The ecological overshoot happened in the mid 1970s, i.e. humanity started to need more biocapacity than being available. This is possible in a status of disequilibrium characterized by absorbing remaining resource stocks and over polluting the surroundings resulting in an aggregation of waste not absorbed by the biocapacity. The major waste aggregation on earth is the rapid increase of greenhouse gas emissions (sub-chapter 1.2) in the atmosphere which will induce a collapse of remaining biocapacity, without a rapid reverse of emission trends, and as a consequence the basis of our global technological society.

In summary, the methodology of the ecological footprint is a metric being able to quantify the overexploitation of the biocapacity of our planet. Since for more than three decades more global biocapacity is needed than available, i.e. the regeneration capacity of the entire planet is reduced, year by year and still accelerating. More than 50% of the total ecological footprint is caused by greenhouse gas emissions. For preventing an even faster degradation of global

¹⁵⁰ Wackernagel M. et al., National natural capital accounting with the ecological footprint concept, 1999

¹⁵¹ Wackernagel M. et al., Tracking the ecological overshoot of the human economy, 2002

¹⁵² Wackernagel M. and Beyers B., Der Ecological Footprint: Die Welt neu vermessen, 2010

¹⁵³ WWF, Living Planet Report 2010: Biodiversity, biocapacity and development, 2010

¹⁵⁴ WWF, Living Planet Report 2010: Biodiversity, biocapacity and development, 2010

biocapacity the need for decarbonising the global energy system is more urgent than ever in human history. Not reacting as fast as possible will very likely end in the collapse of humanity and most of the species currently living on our planet.

Chapter 2

Solar Resources

Energy resource availability is decisive for all power technologies. Basis for all solar energy technologies is the amount and the composition of the **global horizontal irradiation** (sub-chapter 2.1). Different solar system concepts have been developed for optimizing the energy yield. **Solar resources adapted to systems'** requirements are derived (sub-chapter 2.2) and **compared** among each other (sub-chapter 2.2 and 2.4). For assessing solar potentials regional irradiation mean values are calculated. Impact of heterogeneous **population and electricity generation distribution on average irradiation** is analysed (sub-chapter 2.3). Fundamental consequences of solar resource distribution are discussed in context of photovoltaic energy solutions at the end of each section in this chapter.

2.1 Global Horizontal Irradiation as Basis for all Solar Resources

Measurement stations all around the world record solar irradiation on the ground. The irradiance consists of the direct irradiance from the sun, and diffuse irradiance from different sources, e.g. the rest of the hemisphere or ground reflection. Another valuable source of solar irradiation data are meteorological satellites in space. Combining satellite data and ground measurements as reference enables global solar irradiation data. The National Aeronautics and Space Administration (NASA) compiled several global datasets for different meteorological observables, so for global horizontal irradiation (GHI) and its diffuse fraction on global scale for a $1^\circ \times 1^\circ$ mesh, i.e. average data is available for every 1° step of latitude and longitude, respectively. In this chapter NASA Surface meteorology and Solar Energy (SSE) 6.0 dataset is taken for all calculations.^{1,2}

In general, meteorology and solar radiation for SSE Release 6.0 were obtained from the NASA Science Mission Directorate's satellite and re-analysis research programmes. Parameters based upon the solar and/ or meteorology data were derived and validated based on recommendations from partners in the energy industry. Release 6.0 extends the temporal coverage of the solar and meteorological data from approximately 11 years to 22 plus years (e.g. July 1983 through June 2005) with improved NASA data, and includes new parameters and validation studies.

The underlying solar and cloud related data are obtained from the Surface Radiation Budget (SRB) portion of NASA's Global Energy and Water Cycle Experiment. The current SRB archive is Release 3.0. The cloud parameters and top of atmosphere radiances are from the International Satellite Cloud Climatology Project (ISCCP). The ISCCP project provides global 3-hourly snapshots of the clouds and the top of atmosphere radiance compiled from an array of satellite platforms (i.e. GMS-1 through 8; METEOSAT-2 through 5; NOAA-7 through 14). Within the SRB project, the ISCCP data are augmented by data from the Earth Radiation Budget Energy, the Clouds and the Earth's Radiant Energy System and Multi-angle Imaging Spectro-Radiometer. The current ISCCP data covers the time period July 1, 1983 – June 30, 2005. The underlying meteorological data are obtained from NASA's Global Model and Assimilation Office (GMAO), Goddard Earth Observing System model version 4 (GEOS-4), and precipitation parameters are obtained from the Global Precipitation Climate Project and the Tropical Rainfall Measurement

¹ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

² Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

Mission. The wind data are based upon the NASA/ GMAO GEOS version 1 (GEOS-1).³

SSE estimates have been compared to ground site data on a global basis. Radiation parameters were compared to data from the Baseline Surface Radiation Network (39 stations). Meteorological parameters were compared to data from the National Climate Data Center (1,140 and 2,704 stations in 1987 and 2004, respectively).

Relevant definitions for solar resource calculations are summarized in the following:⁴

- **Irradiation** [kWh/m² or J/m²]: The incident energy per unit area on a surface, found by integration of irradiance over a specified time, usually a year, a day or an hour.
- **Insolation** [kWh/m² or J/m²]: This term is applied specifically to solar energy irradiation. The symbol H is used for insolation for a day. The symbol I is used for insolation for an hour or year. The symbols H and I can represent beam, diffuse or global and can be on surfaces of any orientation.
- **Irradiance** [W/m²]: The rate at which radiant energy is incident on a surface per unit area of surface. The symbol G is used for solar irradiance, with appropriate subscripts for beam, diffuse or spectral radiation.
- **Beam radiation**: The solar radiation received from the sun without having been scattered by the atmosphere. Beam radiation is often referred to as direct solar radiation.
- **Diffuse radiation**: The solar radiation received from the sun after its direction has been changed by scattering in the atmosphere.
- **Global radiation**: The sum of the beam and the diffuse solar radiation on a surface. Global radiation is often referred to as total solar radiation. The most common measurements of solar radiation are global radiation on a horizontal surface, referred to as global horizontal radiation.
- Subscripts for radiation classification are 0 for radiation above the earth's atmosphere (extraterrestrial radiation), b for beam radiation, d for diffuse radiation and T for radiation on a tilted plane.

Core solar resource data are the beam and diffuse fraction of global horizontal irradiation in this chapter. All further solar resources discussed in this chapter and used in following chapters are based on global horizontal irradiation (GHI) depicted in Figure 2.1-1. Key driver for beneficial yield results of tracking systems (sections 2.2.3 to 2.2.9) is the diffuse fraction of GHI (Fig. 2.1-2) besides geographic location of the site and overall solar irradiation.

³ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

⁴ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

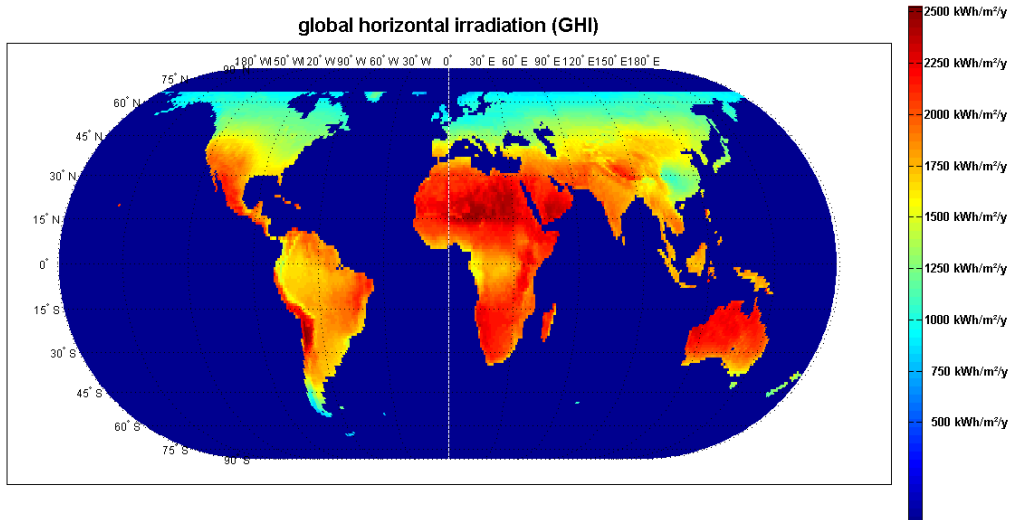


Figure 2.1-1: Annual global horizontal irradiation (GHI). GHI input data are provided by NASA SSE 6.0⁵ and used in a 1°x1° mesh of latitude and longitude.

GHI is composed by direct horizontal irradiation (DHI) and diffuse horizontal irradiation (DIF). Absolute and relative DIF is plotted in Figures 2.1-2 and 2.1-3. Relation of GHI, DHI and DIF is summarized in Equation 2.1-1.

$$GHI = DHI + DIF \quad (\text{Eq. 2.1-1})$$

Equation 2.1-1: Composition of GHI. Abbreviations stand for: global horizontal irradiation (*GHI*), direct horizontal irradiation (*DHI*) and diffuse horizontal irradiation (*DIF*).

Global horizontal irradiation is more or less homogeneously distributed on earth. Variations of GHI for most populated regions in the world are typically within a range of a factor of two, e.g. Central Europe (~ 1,100 kWh/m²/y) and Arabian Peninsula (~ 2,200 kWh/m²/y). GHI is best in Atacama desert and in Sahara desert. Excellent and very good solar conditions of more than 1,700 kWh/m²/y are available all around the world. Tropical regions near to the equator show good but not excellent solar conditions despite of best geographic location for solar exposure. Local climate conditions, mainly daily or seasonal cloud patterns, can have enormous impact on GHI. Besides tropical regions near the equator, this can be found for monsoon effects in India and South-East China as a consequence of regional topography and Pacific clouds.

⁵ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

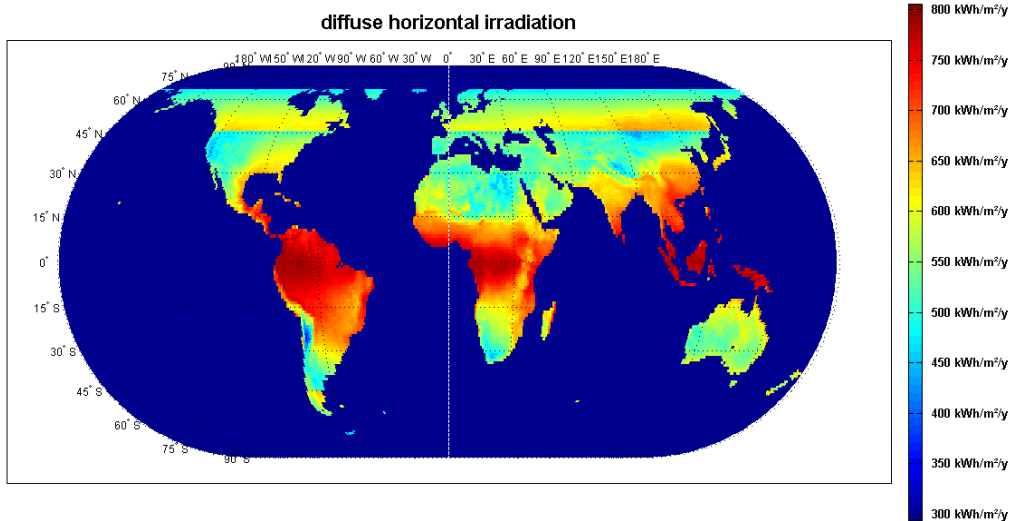


Figure 2.1-2: Diffuse horizontal irradiation (DIF). Input data is provided by NASA SSE 6.0 ⁶ and used in a 1°x1° mesh of latitude and longitude. Changes of diffuse irradiation at 45°N and 45°S are due to data combinations of different satellites.

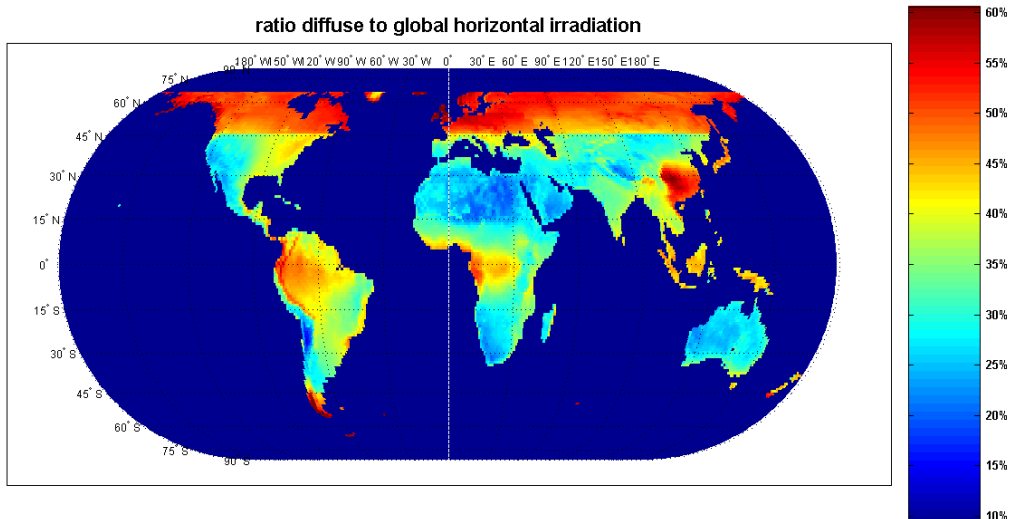


Figure 2.1-3: Ratio of diffuse to global annual horizontal irradiation. Input data are provided by NASA SSE 6.0 ⁷ and used in a 1°x1° mesh of latitude and longitude. Changes of ratio at 45°N and 45°S are due to data combinations of different satellites.

Absolute and relative diffuse irradiation is strongly coupled to regional climatic conditions, in particular to daily and seasonal occurrence of clouds. Tropical regions near the equator show these effects, e.g. Amazonas rim, Central Africa and South-East Asia, but also India. Most deserts on earth are located between 15° and 40° N/S. Diffuse irradiation in deserts is quite low and ranges typically between 15% and 30%. Diffuse irradiation is lost for solar power technologies only capable to convert direct solar irradiation, thus sites of low diffuse irradiation are most appropriate for these technologies. Solar system technologies increasing insolation on active surface by tracking the sun's position are most beneficial for lower diffuse irradiation.

⁶ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

⁷ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

2.2 Resources Adapted for Basic Solar System Concepts

A broad discussion of specific advantages of different PV systems is not the intention of this chapter. Nevertheless, a short overview might be helpful for further considerations.

2.2.1 Overview on Solar System Concepts

Best possible, i.e. lowest cost, configuration of PV systems in general and PV power plants in particular is needed for an optimised cost structure which enables fast growing markets for PV systems. Different PV system applications have been developed over the decades, especially in the field of PV tracking systems.⁸ Fixed tilted, 1-axis and 2-axes tracking module surfaces receive different total irradiation over the year. Different PV tracking or non-tracking system solutions might be best suited for a specific site, depending on geographic, climatic and PV system cost structure. In this chapter it is not intended to discuss consequences of different irradiation levels of various tracking and non-tracking PV systems on levelized cost of electricity (LCOE). PV LCOE of various system technologies are discussed in section 3.2. An overview on different solar power technologies and their respective solar resources is depicted in Figure 2.2-1.

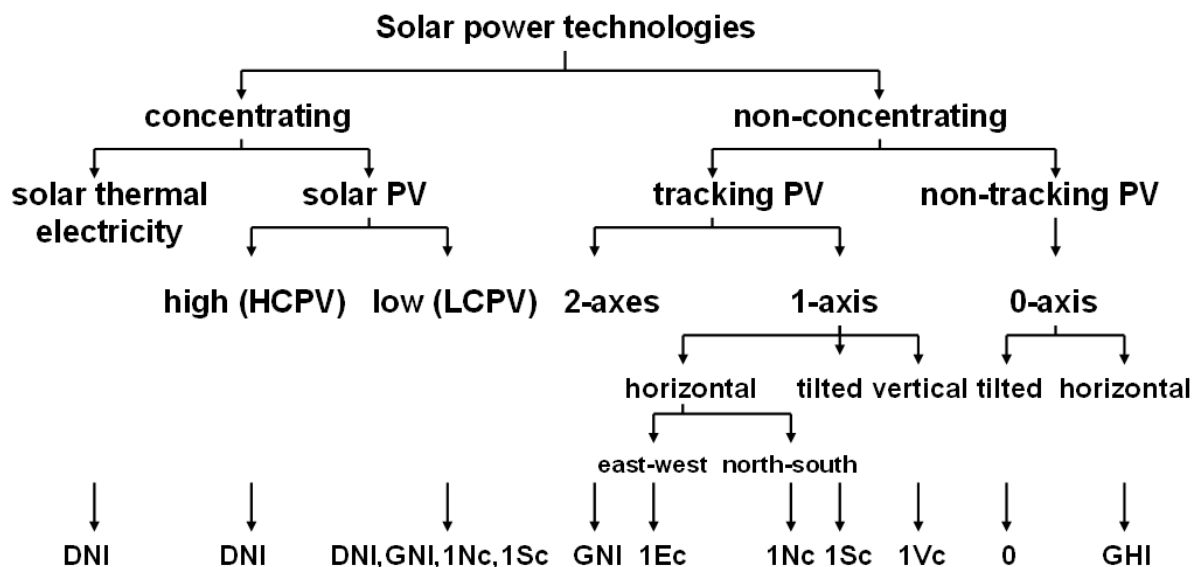


Figure 2.2-1: Overview on different solar power technologies and their respective solar resources. Abbreviations stand for: high concentrating PV (HCPV), low concentrating PV (LCPV), global horizontal irradiation (GHI), irradiation on fixed optimally tilted surfaces (0), irradiation on 1-axis horizontal east-west continuous tracking surfaces (1Ec), irradiation on 1-axis horizontal north-south continuous tracking surfaces (1Nc), irradiation on 1-axis optimally tilted north-south continuous tracking surfaces (1Sc), irradiation on 1-axis vertical optimally tilted continuous tracking surfaces (1Vc), irradiation on 2-axes non-concentrating continuous tracking surfaces (GNI, for global normal irradiation) and irradiation on 2-axes concentrating continuous tracking surfaces (DNI, for direct normal irradiation).

Major advantage of solar PV technology is the need for no moving parts; this is still the case for fixed optimally tilted systems. To give up such a great advantage very good reasons are needed, this might be given for specific tracking systems. 1-axis east-west horizontal tracking

⁸ Siemer J., Trackers Survey: An industry in transition, 2009

systems are best adapted for regions of large seasonal deviation of daily zenith angles. Advantage of horizontal tracking and fixed tilted systems is shading in only one direction, which significantly reduces necessary minimum site area thus balance of system related cost are kept at a lowest possible level. 1-axis north-south horizontal continuous tracking systems follow the sun over the day. 1-axis north-south optimally tilted tracking systems are better adapted to respective site latitude but need a larger plant area than fixed optimally tilted or 1-axis north-south horizontal continuous tracking due to two directional shading. 1-axis vertical optimally tilted systems also need a larger plant ground as a consequence of two directional shading. PV system of highest annual irradiation is 2-axes non-concentrating tracking system. Large plant area is needed due to two directional shading effects and a higher mechanical stress and cost is effective due to more moving parts and engines. 2-axes concentrating tracking variation is only needed for high concentrating PV (HCPV) systems and solar thermal electricity generation (STEG). A derivation and discussion of all mentioned systems in respect to their respective solar resource is given in the following sections.

2.2.2 Methodology for Solar Resource Calculations

GHI needs to be transferred to irradiation data received by a tilted PV module. For well adapted calculation of direct and diffuse irradiation Hay and Davis introduced a model peer-reviewed published by Hay and McKay⁹ which takes into account the circumsolar diffuse and horizon-brightening diffuse components of diffuse irradiation on a tilted surface. Reindl et al.¹⁰ practically improved the horizon-brightening part after suggestion of Klucher¹¹. This standard model for describing direct and all relevant diffuse parts of solar irradiance on a tilted surface is called **Hay-Davis-Klucher-Reindl (HDKR) model** (Eqs. 2.2-1 and 2.2-2 and Fig. 2.2-2) comprehensively discussed in Duffie and Beckmann.¹² Great advantage of the HDKR model are good output results using only very limited input data, i.e. monthly data for global horizontal irradiation, diffuse horizontal irradiation, geographic coordinates and system geometry.

$$I_T = \underbrace{(I_b + I_d \cdot A_i) \cdot R_b}_{= \text{direct and circumsolar diffuse}} + \underbrace{I \cdot \rho_g \cdot \left(\frac{1 - \cos \beta}{2} \right)}_{= \text{ground reflected}} + \underbrace{I_d \cdot (1 - A_i) \cdot \left(\frac{1 + \cos \beta}{2} \right) \cdot \left[1 + f \cdot \sin^3 \left(\frac{\beta}{2} \right) \right]}_{= \text{diffuse sky and horizon}} \quad (\text{Eq. 2.2-1a})$$

$$A_i = \frac{I_b}{I_0} \quad f = \sqrt{\frac{I_b}{I}} \quad (\text{Eq. 2.2-1b,c})$$

$$I_0 = \frac{12 \cdot 3600}{\pi} \cdot G_{sc} \cdot \left(1 + 0.033 \cos \frac{360 \cdot n}{365} \right) \cdot \left(\cos \phi \cos \delta \cdot (\sin \omega_2 - \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} \sin \phi \sin \delta \right) \quad (\text{Eq. 2.2-1d})$$

Equation 2.2-1: Total radiation on a tilted surface according to Hay-Davis-Klucher-Reindl (HDKR) model. Abbreviations stand for: irradiance tilted surface (I_T), irradiance beam horizontal (I_b), irradiance diffuse horizontal (I_d), anisotropy index (A_i), geometric factor (function of time, position of sun and surface) (R_b), irradiance global horizontal (I), reflection of ground (ρ_g), tilt angle (β), modulating factor (f) and extraterrestrial irradiance (I_0), solar constant (G_{sc}), day of the year (n), latitude (ϕ), declination of earth axis (δ) and hour angle of specific time 1 and 2 ($\omega_{1,2}$).

⁹ Hay J.E. and McKay D.C., Estimating Solar Irradiance on Inclined Surfaces, 1985

¹⁰ Reindl D.T. et al., Evaluation of Hourly Tilted Surface Radiation Models, 1990

¹¹ Klucher T.M., Evaluation of Models to predict Insolation on tilted Surfaces, 1979

¹² Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

Equation 2.2-1 is nearly free of geometric considerations, which are summarized in the geometric factor (R_b). Geometric information comprises site location, tilt angle of module, day of the year and time of the day. This geometric set of information is summarized in **general for all tracking and non-tracking** variations in Equations 2.2-2.¹³

$$R_b = \frac{\cos \theta}{\cos \theta_z} \quad (\text{Eq. 2.2-2a})$$

$$\cos \theta_z = \cos \phi \cdot \cos \delta \cdot \cos \omega + \sin \phi \cdot \sin \delta \quad (\text{Eq. 2.2-2b})$$

$$\gamma_s = \text{sign}(\omega) \cdot \left| \arccos \left(\frac{\cos \theta_z \cdot \sin \phi - \sin \delta}{\sin \theta_z \cdot \cos \phi} \right) \right| \quad (\text{Eq. 2.2-2c})$$

$$\omega = (t_{sol} - 12) \cdot 15 \frac{^\circ}{h} \quad (\text{Eq. 2.2-2d})$$

$$\delta = 23.45 \cdot \sin \left(360 \frac{284 + n}{365} \right) \quad (\text{Eq. 2.2-2e})$$

Equation 2.2-2: Geometric factor and its contributing functions. Abbreviations stand for: geometric factor (function of time, position of sun and surface) (R_b), angle of incidence (beam and surface normal) (θ), zenith angle (θ_z), latitude (ϕ), declination of earth axis (δ), hour angle (ω), solar azimuth angle (γ_s), solar time (t_{sol}) and day of the year (n).

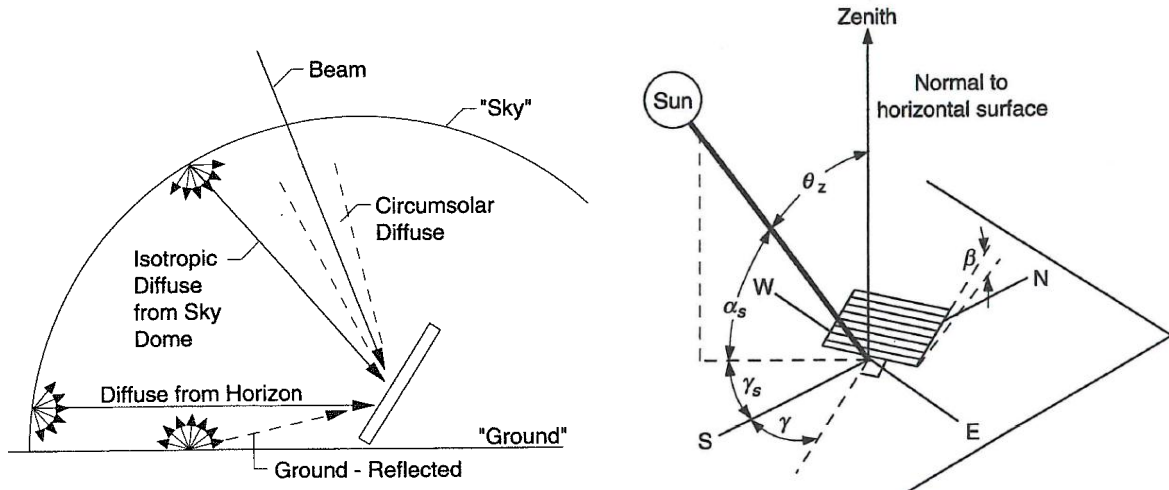


Figure 2.2-2: Components of irradiation on tilted surfaces (left) and geometric composition of coordinate systems of earth, sun and PV module (right).¹⁴ Abbreviations stand for: zenith angle (θ_z), solar altitude angle (α_s), solar azimuth angle (γ_s), surface azimuth angle (γ), tilt angle (β), north (N), east (E), south (S) and west (W).

Data source of NASA SSE 6.0 is available for all coordinates on earth in a $1^\circ \times 1^\circ$ mesh of latitude and longitude and a time resolution of every so-called mean day of all months of the year.^{15,16} A respective mean day best describes the entire month. The dataset comprises the mean values for 22 years from July 1, 1983 through June 30, 2005, i.e. climatologic and not meteorological weather conditions, which is important for best averaged future estimates.¹⁷ Description of transformation of mean average day to hourly data (Eqs. 2.2-3) is discussed in

¹³ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

¹⁴ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

¹⁵ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

¹⁶ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

¹⁷ Hay J.E. and McKay D.C., Estimating Solar Irradiance on Inclined Surfaces, 1985

Duffie and Beckmann¹⁸ and is based on Liu and Jordan¹⁹ and improvements of Collares-Pereira and Rabl²⁰.

$$I_{t,d} = r_{t,d} \cdot H_{t,d} \quad (\text{Eq. 2.2-3a})$$

$$I_b = I_t - I_d \quad (\text{Eq. 2.2-3b})$$

$$r_t = \frac{\pi}{24} \cdot (a + b \cdot \cos \omega) \cdot \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi \omega_s}{180} \cos \omega_s} \quad (\text{Eq. 2.2-3c})$$

$$a = 0.409 + 0.5016 \cdot \sin(\omega_s - 60) \quad (\text{Eq. 2.2-3d})$$

$$b = 0.6609 + 0.4767 \cdot \sin(\omega_s - 60) \quad (\text{Eq. 2.2-3e})$$

$$r_d = \frac{\pi}{24} \cdot \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - \frac{\pi \omega_s}{180} \cos \omega_s} \quad (\text{Eq. 2.2-3f})$$

$$\omega_s = \arccos(-\tan \varphi \cdot \tan \delta) \quad (\text{Eq. 2.2-3g})$$

Equation 2.2-3: Decomposition of daily into hourly irradiation data. Abbreviations stand for: hourly irradiation total horizontal (I_t), hourly irradiation beam horizontal (I_b), hourly irradiation diffuse horizontal (I_d), daily irradiation total horizontal (H_t), daily irradiation diffuse horizontal (H_d), ratio of hourly total to daily total irradiation (r_t), ratio of hourly diffuse to daily diffuse irradiation (r_d), hour angle (ω), sunrise/ sunset hour angle (ω_s), latitude (φ) and declination of earth axis (δ).

Annual aggregated monthly global horizontal irradiation (GHI) (Fig. 2.1-1) and annual aggregated monthly diffuse horizontal irradiation (Fig. 2.1-2) are used to calculate best possible irradiation on module surface for all discussed fixed tilted, 1-axis and 2-axes PV systems by applying the HDKR model. Due to complex interaction of formulas all incident irradiation results are calculated for tilt angles between 0° and 90°, i.e. horizontal and perpendicular position of the module, in tilt angle steps of 1°. This routine is necessary for all tilt angle optimised PV systems, like fixed tilted, 1-axis north-south tilted and 1-axis vertical tilted. Annual incident irradiation on these tilted module surfaces of respective PV systems is evaluated as a function of module tilt angle. Tilt angle of highest annual irradiation is defined as optimum tilt angle which optimises the incident irradiance over the entire year. All other tracking PV systems do not need this routine. For efficient calculations, proper handling of the comprehensive data and flexible adaptable illustrations the mathematical programming language Matlab was chosen.²¹

Results of optimised annual irradiation are shown for fixed optimally tilted (section 2.2.3), 1-axis horizontal east-west continuous tracking (section 2.2.4), 1-axis horizontal north-south continuous tracking (section 2.2.5), 1-axis vertical optimally tilted continuous tracking (section 2.2.6), 1-axis optimally tilted north-south continuous tracking (section 2.2.7), 2-axes non-concentrating continuous tracking (section 2.2.8) and 2-axes concentrating continuous tracking (section 2.2.9) PV systems.

¹⁸ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

¹⁹ Liu B.Y.H. and Jordan R.C., The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation, 1960

²⁰ Collares-Pereira M. and Rabl A., The Average Distribution of Solar Radiation – Correlations Between Diffuse and Hemispherical and Between Daily and Hourly Insolation Values, 1979

²¹ The MathWorks Inc., Matlab 7.1 (R 14SP3), 2005

2.2.3 Fixed Optimally Tilted Systems

The fixed optimally tilted PV system is the typical PV power plant system and is used as reference system for the various tracking systems. Therefore, considerations for fixed optimally tilted PV systems are presented in a more comprehensive way than other PV systems.

In this section general geometric considerations in Equations 2.2-1 to 2.2-3 are expanded by Equations 2.2-4 for fixed optimally tilted non-tracking PV systems:²²

$$\cos \theta = \cos \theta_z \cdot \cos \beta + \sin \theta_z \cdot \sin \beta \cdot \cos(\gamma_s - \gamma) \quad (\text{Eq. 2.2-4a})$$

$$\beta = \text{const.} \quad (\text{Eq. 2.2-4b})$$

$$\gamma = \begin{cases} +90^\circ & \text{if } \gamma_s > 0 \\ -90^\circ & \text{if } \gamma_s \leq 0 \end{cases} \quad (\text{Eq. 2.2-4c})$$

Equation 2.2-4: Specific geometric considerations for fixed optimally tilted non-tracking PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (θ), zenith angle (θ_z), tilt angle (β), solar azimuth angle (γ_s) and surface azimuth angle (γ).

Major cost components of PV power plants are PV modules, inverters, further so-called balance of system (BOS) components and a site for placing the plant. A large fraction of BOS cost is dependent on the total area needed for the plant, which is a driver for placing rows of modules very close to each other. However, the solar energy source, the sun, shines only for a short time of annual sunshine hours perpendicular to ground. Therefore, modules are tilted for optimized annual irradiation on the modules' surface. Standard textbook knowledge suggests tilt angle should be equal to latitude of specific site of a PV system for optimising annual irradiation on module.^{23,24} Nevertheless, optimised tilt angles and lowest possible area demand for a PV plant form an inherent trade-off.

Annual incident irradiation on tilted module surface has been evaluated as a function of module tilt angle. Tilt angle of highest annual irradiation is defined as optimum tilt angle (Fig. 2.2-5), which optimises the irradiance on module surface over the entire year. An optimised tilt angle increases annual irradiation on module surface up to 500 kWh/m²/y and 35% (Fig. 2.2-4). Latitudes near equator cannot be significantly improved by tilt angles, whereas for latitudes lower than 30°S and higher than 30°N partly significant increase in irradiation on module surface can be expected. Usually, one assumes optimum tilt angle to be the latitude of the site of interest as a rule of thumb. Some parts in the world, e.g. Central and North Europe, Tibet and Thailand, deviate by about 10° and more from this educated guess (Fig. 2.2-5 and 2.2-6), which is mainly driven by a different occurrence of clouds.

Notably, solar resource is very homogeneously available for nearly all people in the world (Fig. 2.2-3). This is a significant contrast to all other sources of energy. There is only a maximal factor of about 2.5 between highest and lowest irradiation sites in the world, in particular where the people live (Fig. 2.3-1). More or less even availability of solar resource triggers a very important social impact of photovoltaic as the most democratic energy technology.

²² Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

²³ Green M.S., Solar Cells: Operating Principles, Technology and System Applications, 1998, p. 231

²⁴ NREL, PVWatts, 2010

Solar irradiation is mainly determined by latitude and weather conditions (Fig. 2.2-3), which can be observed for tropic regions in South America, Africa and South Asia, but also for special weather conditions like in India (monsoon) or South East China.

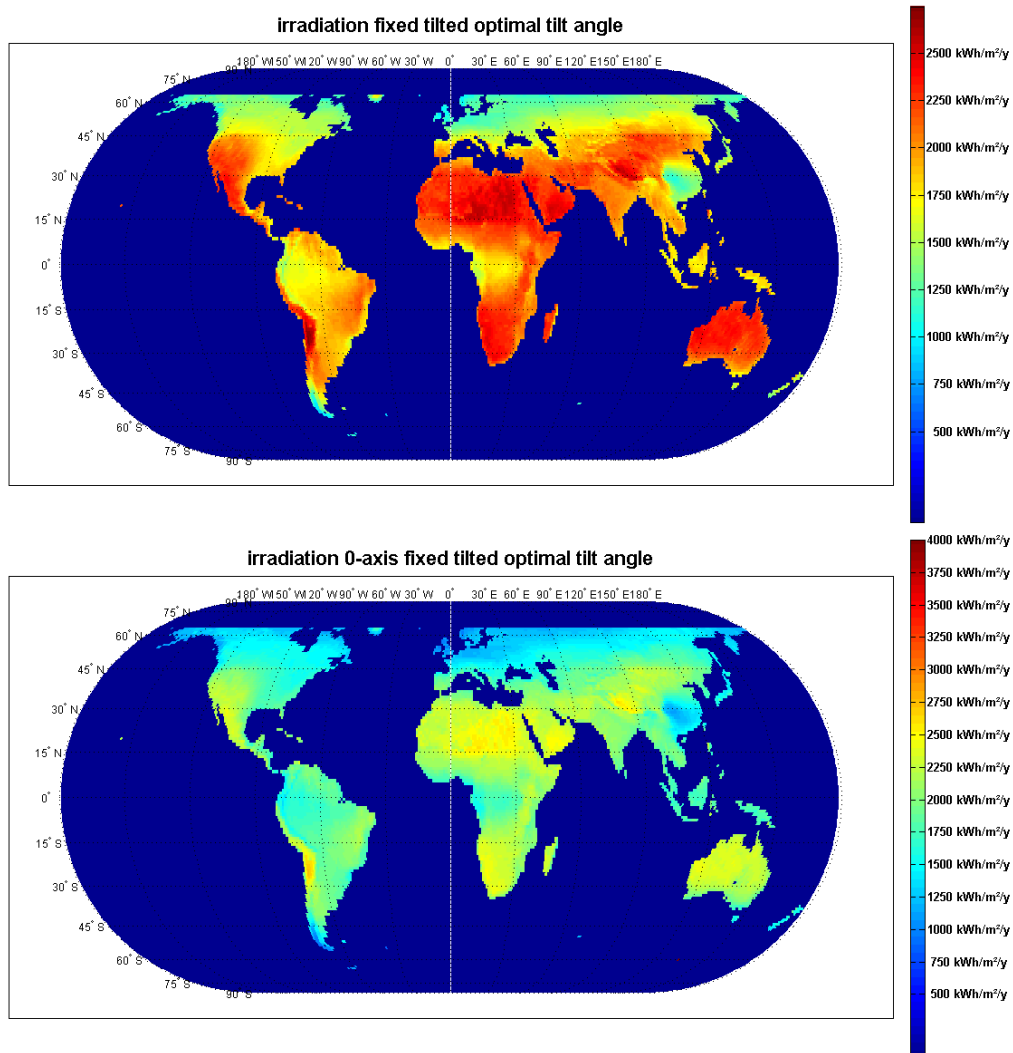


Figure 2.2-3: Annual irradiation on module surface of fixed optimally tilted PV systems at tilt angle for optimised irradiation (top and bottom visualization are identical except colour coding for subsequent comparison reasons). Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately optimised for maximum annual irradiation on module. HDKR model is performed by calculating each month of the year and selecting the tilt angle of maximum annual irradiation (section 2.2.2).

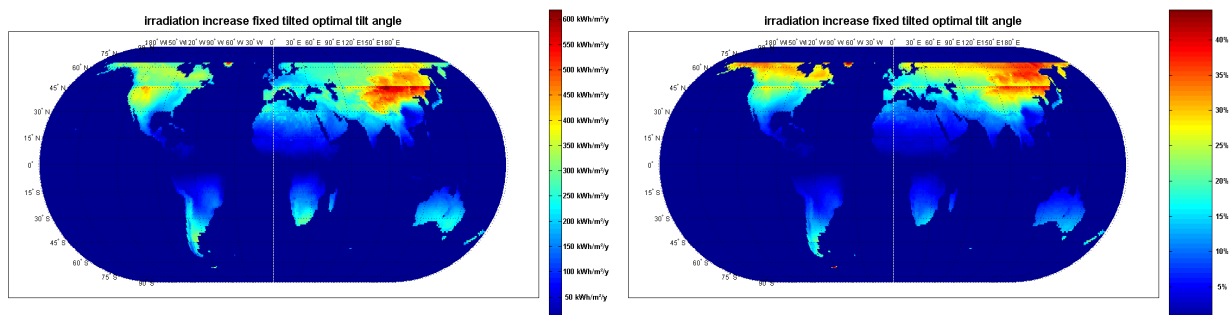


Figure 2.2-4: Annual increased irradiation on module surface of fixed optimally tilted PV systems at tilt angle for optimised irradiation versus global horizontal irradiation in absolute (left) and relative (right) numbers.

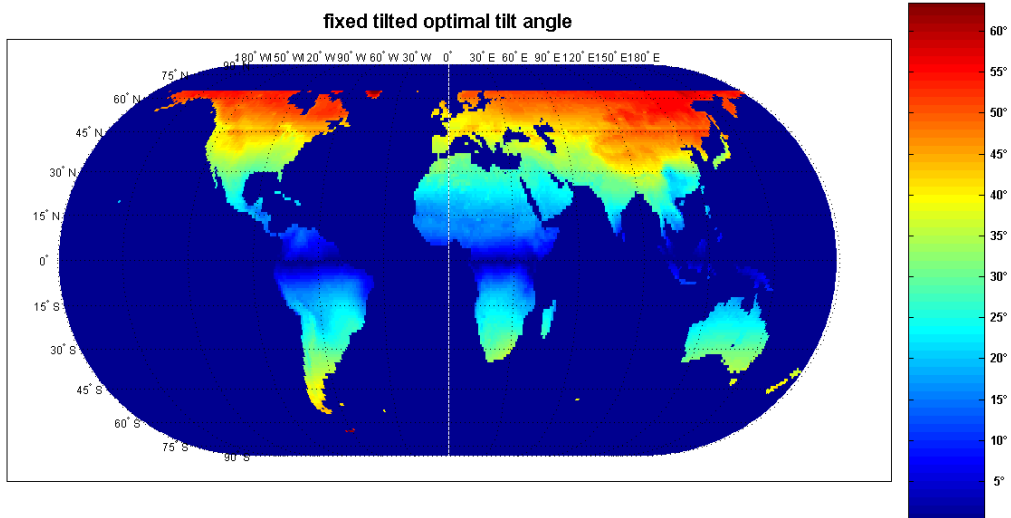


Figure 2.2-5: Optimal tilt angles for fixed tilted PV systems for optimised irradiation on module surface. Roughly, irradiation optimised tilt angles are dependent on latitude, but impact of local climate conditions on tilt angles can be observed.

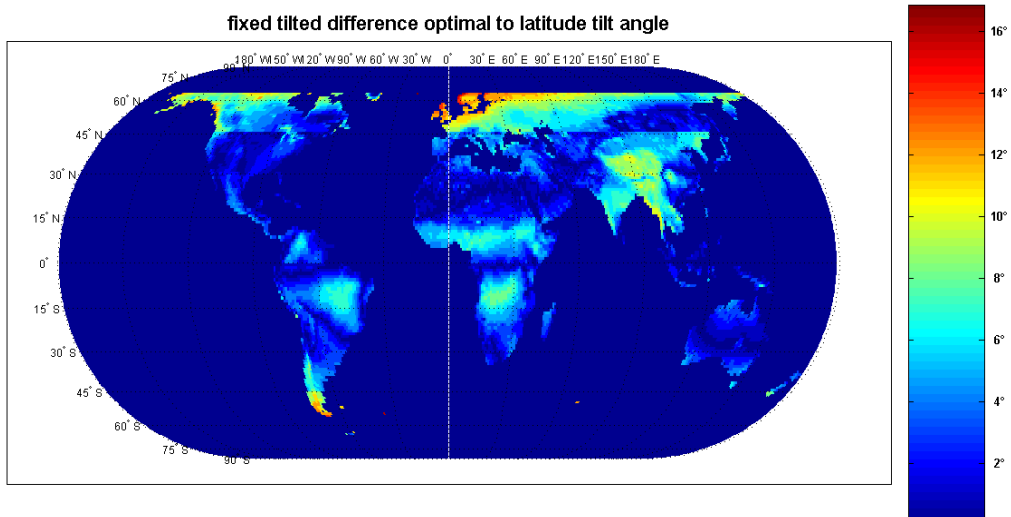


Figure 2.2-6: Deviation of irradiation optimised to latitude tilt angle of fixed tilted PV systems. Roughly, irradiation optimised tilt angles are dependent on latitude, but impact of local climate conditions on tilt angles can be observed. Major deviation is given for example for Europe, due to a large fraction of diffuse irradiation as a consequence of cloudy conditions.

An annual irradiation profile of a fixed optimally tilted PV system in hourly and monthly time resolution is shown in Figure 2.2-7 for an example in Sahara desert. Irradiation profile is calculated according to Equations 2.2-1 to 2.2-4. Reduced irradiation during summer time is a consequence of optimal tilt angle and declination of earth axis, i.e. sun's position is behind the module. Nevertheless annual irradiation on module surface of fixed optimally tilted PV system is maximised for this system configuration.

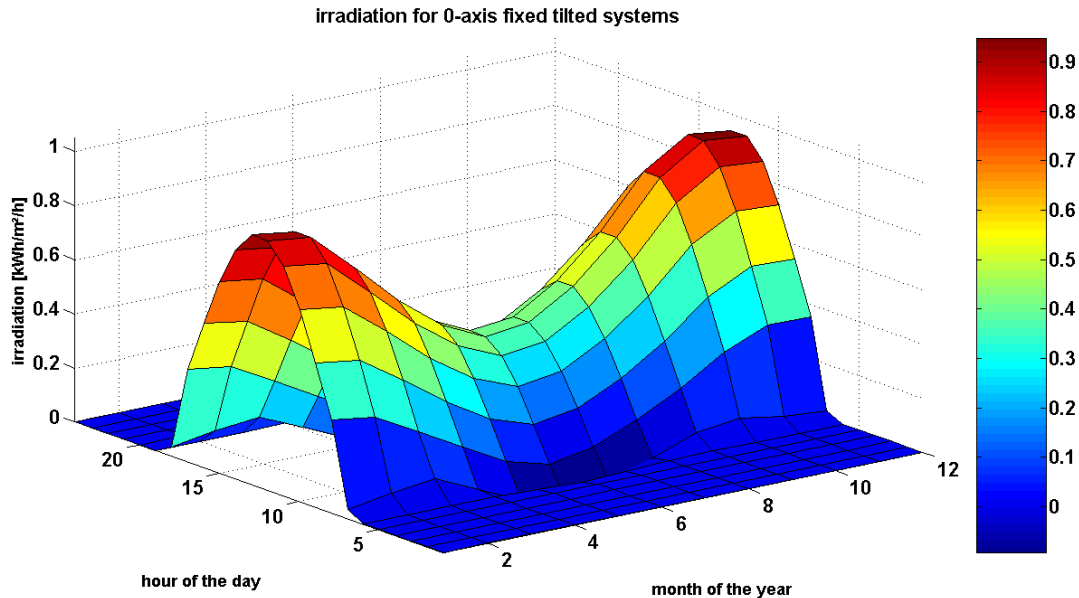


Figure 2.2-7: Hourly irradiation on module profile of fixed optimally tilted PV systems. Coordinate for this example is 20.5°N/ 15.5°E in Sahara desert, optimal tilt angle is 21°, annual GHI is about 2,390 kWh/m²/y and annual irradiation on module of fixed optimally tilted PV system is about 2,520 kWh/m²/y, thus optimal tilted PV systems receive about 5% more irradiation on module surface. Mean day of the month data are used for all days of respective months.

By applying HDKR model good irradiation values are obtained for further computation. In the end cost per generated energy needs to be minimized. PV generation costs are calculated by the **levelized cost of electricity (LCOE) method** (section 3.2.1). It has to be mentioned, that no subsidies for PV are taken in to account, i.e. real PV costs are regarded. Using the LCOE method (Eqs. 3.2-1) one can easily transform the cost/Wp numbers usually used in PV industry into the more decisive cost/kWh category of the power industry.

The input parameters for LCOE formula are mainly dependent on circumstances in geography, time, energy and financial markets. Net generated energy is a function of local solar irradiance, which is given by latitude and annual aggregated average monthly weather conditions of a specific site (Fig. 2.2-3), and performance of all components for local conditions, summarized in the performance ratio. Capital expenditures for PV systems are cost for PV modules, inverters, mounting structure, cabling, grid connection, civil works, project engineering, project development and cost for plant area. Except modules and inverters, all the other cost components are defined as balance of system (BOS) cost. Cost for inverters, project engineering, project development and grid connection are dependent on the power output of the PV plant. Cost for mounting structure, cabling and civil works are dependent on area of modules and distance of adjacent module rows, which reflects shading considerations. Module area needed for a specific power output is mainly determined by the module efficiency. Today's commercially available modules convert 6% to 20% of incident solar irradiance (Fig. 3.1-26).²⁵ Commercial PV systems have to be designed for minimum LCOE, hence a trade-off between maximum irradiation and minimum overall cost and in particular BOS cost has to be optimised.

Local solar irradiation is a very important factor for LCOE (Eqs. 3.2-1). PV systems need to minimize electricity generation cost, measured in cost/kWh by LCOE method. As a consequence tilt angles of optimised economics further deviate from those of optimised

²⁵ Kreutzman A. and Siemer J., Market survey on solar modules 2010: Smooth sailing, 2010

annual irradiation (Fig. 2.2-8 and 2.2-9). A large fraction of BOS cost is dependent on the ground cover ratio (GCR) of the PV system, i.e. ratio of entire module surface to site area, hence a higher GCR reduces BOS cost and maybe LCOE, whereas annual irradiation on module surface might be decreased by shading effects as well.

The economic model is based on true cost in German PV power plant market. In 2010, effective PV power plant capital expenditures are about 2.40 €/Wp. The German market takes over a global price setting function due to the sheer size of the German market (section 3.1.4). System price assumptions are based on consensus view of several financial PV industry analysts all published in 2010 and discussed in more detail in sub-chapter 3.3. Module price is assumed to be about 1.50 €/Wp, hence 0.90 €/Wp is for inverter and all other BOS cost including small profit for construction and development of PV power plant. Major part of BOS cost is dependent on module area and area of PV power plant size. Module efficiencies are set to values below 15%.

PV system performance ratio is assumed to be 80%, which is conservative for large-scale installations, in particular for moderate temperature conditions. Weighted average cost of capital is set to 6.8%, result of 6% debt financing cost, 10% return on equity and a ratio of debt to equity of 80 to 20. Annual PV power plant operation and maintenance expenditures (Opex) are estimated by 1.0% of PV system capital expenditures (Capex). Degradation of modules is expected to stay at 0.4% p.a. PV system lifetime is set to 25 years, which is assumed to be conservative (section 3.1.6).

Row to row shading is considered by rules described by Duffie and Beckmann²⁶ and Narvarte and Lorenzo²⁷. The tilt angle of modules is directly joined to the distance of adjacent rows, which is the driving factor for ground cover ratio and total PV power plant area. Electrical consequence of partial shading of rows is calculated by method of Narvarte and Lorenzo.²⁸ Module arrangement per row is assumed to be in parallel association for three or four lines, each made up of series association of a certain number of PV modules. Thus, each time one line of a row gets shaded output, power reduces by one third or a quarter, respectively.

LCOE optimised method for finding best suited tilt angles is quite similar to irradiation optimised method. All coordinates run through the same routine, which applies the tilt angle dependent irradiation and computes the LCOE model of Equation 3.2-1 by using all numbers mentioned before. LCOE optimised tilt angle is defined by lowest LCOE of all applied tilt angles between 0° and 90°, calculated in 1° steps. The tilt angle directly influences incident irradiation on module surface (Eqs. 2.2-1 to 2.2-4), cost for PV power plant area due to coupling to ground cover ratio and power losses due to shading effects.

Results for LCOE optimised tilt angles are depicted in Figure 2.2-8. Deviation of LCOE optimised to latitude tilt angles is plotted in Figure 2.2-9. Nearly all regions in the world confirm the rule of thumb, i.e. ideal tilt angle should be latitude angle. Larger deviations are given for regions of latitude higher than 45°N or lower than 45°S. Modelling results of LCOE optimised tilt angles match to tilt angles of PV power plants built in Europe, which are usually constructed by applying tilt angles of about 25° – 30°.

Results are again influenced by weather conditions, e.g. tilt angles in Central and North Europe are lower than those of South Europe contradictory to the rule of thumb, but a

²⁶ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

²⁷ Narvarte L. and Lorenzo E., Tracking and Ground Cover Ratio, 2008

²⁸ Narvarte L. and Lorenzo E., Tracking and Ground Cover Ratio, 2008

consequence of significant more clouds, hence more diffuse irradiation which is best captured by flat tilted modules which additionally minimize area related PV power plant cost.

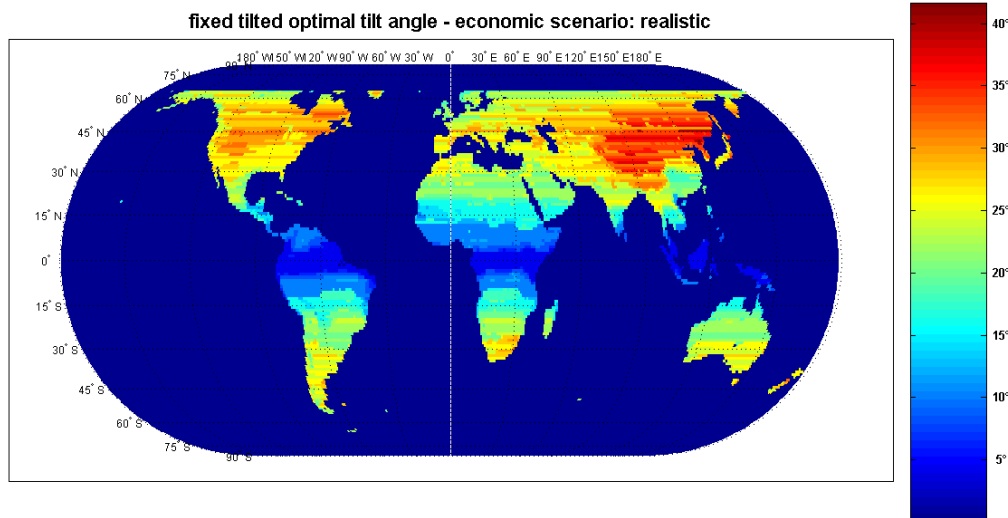


Figure 2.2-8: Optimal tilt angles for fixed tilted PV systems for minimising LCOE. Minimising cost/kWh gives pressure for a higher ground cover ratio, hence for reducing row to row shading effects in PV power plants and respective tilt angles have to be lowered. PV power plant cost structure of German market in 2010 is assumed (Table 3.2-1).

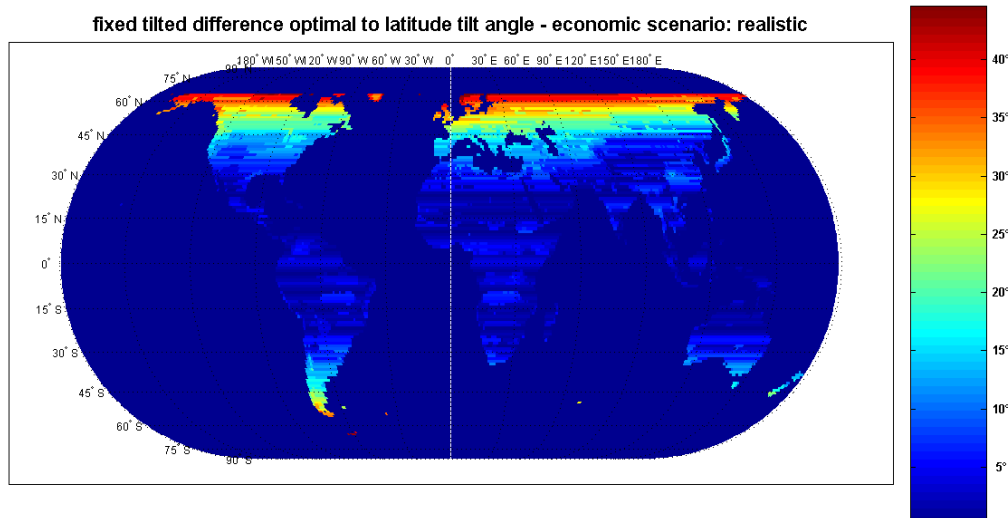


Figure 2.2-9: Deviation of levelized cost of electricity (LCOE) optimised to latitude tilt angle of fixed tilted PV systems. Deviation for latitudes near equator is not significantly high, whereas for latitudes lower than 45°S and higher than 45°N partly significant deviations in LCOE optimised tilted to latitude tilted PV systems are computed.

Different assumed and applied optimised tilt angles can be depicted for each coordinate, explicitly depicted for 50.5°N/ 11.5°E in Southern Germany (North Bavaria) (Fig. 2.2-10). Tilt angles are for latitude assumed, irradiation optimised and LCOE optimised considerations 50.5°, 41° and 25°, respectively. Annual irradiation on module surface is 1,294 kWh/m²/y (latitude assumed), 1,304 kWh/m²/y (irradiation optimised) and 1,271 kWh/m²/y (LCOE optimised). Thus, despite of significant deviations in applied tilt angles differences in annual irradiation are not significant for that region but might differ more in other regions.

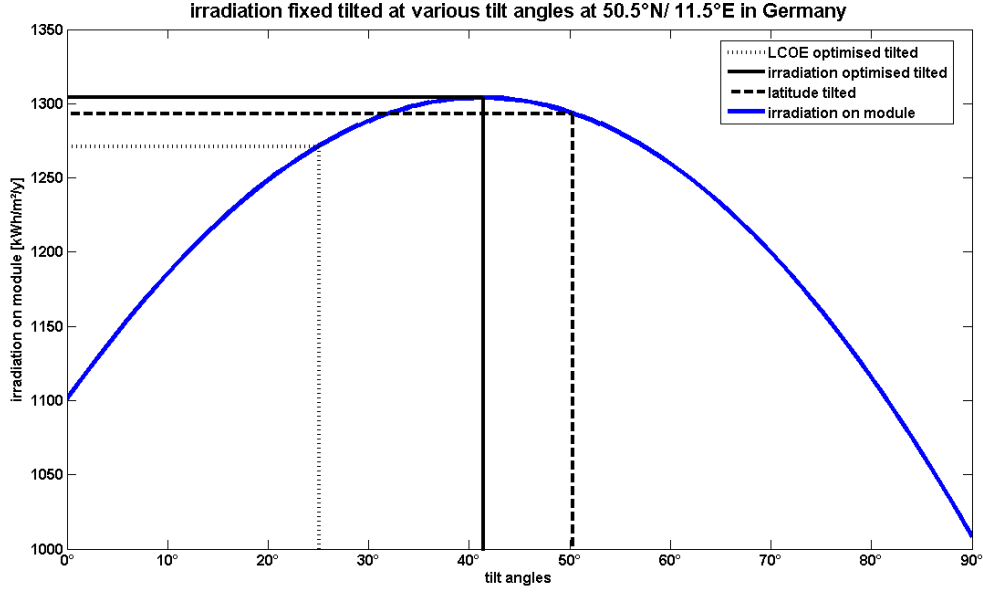


Figure 2.2-10: Tilt angle dependence of annual irradiation on module surface for a site in Southern Germany. Impact of latitude assumed, irradiation optimised and LCOE optimised tilt angle on annual irradiation ranges within a low single digit percentage. Rows of modules in PV power plants are usually tilted by about 25° - 30° in Germany.

In general, rule of thumb that latitude should be taken for module tilt angle can be confirmed. For site latitudes higher 45°N and lower 45°S deviation from rule of thumb has been found. Nevertheless, it can be stated that significant deviations in optimal tilt angles for a single site might be given for different assumptions and optimisation approaches, whereas deviation in annual irradiation should stay within a low single digit percentage.

2.2.4 1-axis Horizontal East-West Continuous Tracking System

Horizontal continuous tracking PV systems address one disadvantage of fixed optimally tilted systems of the previous section. Depending on the orientation of the axis the PV system allows to follow the daily or seasonal position of the sun but shading effects occur in only one direction, identical to fixed optimally tilted systems. Nevertheless, higher irradiation on module surface is achieved by accepting moving parts for the tracking system which result in slightly higher capital but also operational expenditures.

In this section general geometric considerations in Equations 2.2-1 to 2.2-3 are expanded by Equations 2.2-5 for 1-axis horizontal east-west continuous tracking PV systems.²⁹

$$\cos \vartheta = \sqrt{1 - \cos^2 \delta \cdot \sin^2 \omega} \quad (\text{Eq. 2.2-5a})$$

$$\beta = \arctan(\tan \vartheta_z \cdot |\cos \gamma_s|) \quad (\text{Eq. 2.2-5b})$$

$$\gamma = \begin{cases} 0^\circ & \text{if } |\gamma_s| < 90 \\ 180^\circ & \text{if } |\gamma_s| \geq 90 \end{cases} \quad (\text{Eq. 2.2-5c})$$

Equation 2.2-5: Specific geometric considerations for 1-axis horizontal east-west continuous tracking PV

²⁹ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

systems. Abbreviations stand for: angle of incidence (beam and surface normal) (θ), declination of earth axis (δ), hour angle (ω), tilt angle (β), zenith angle (θ_z), solar azimuth angle (γ_s) and surface azimuth angle (γ).

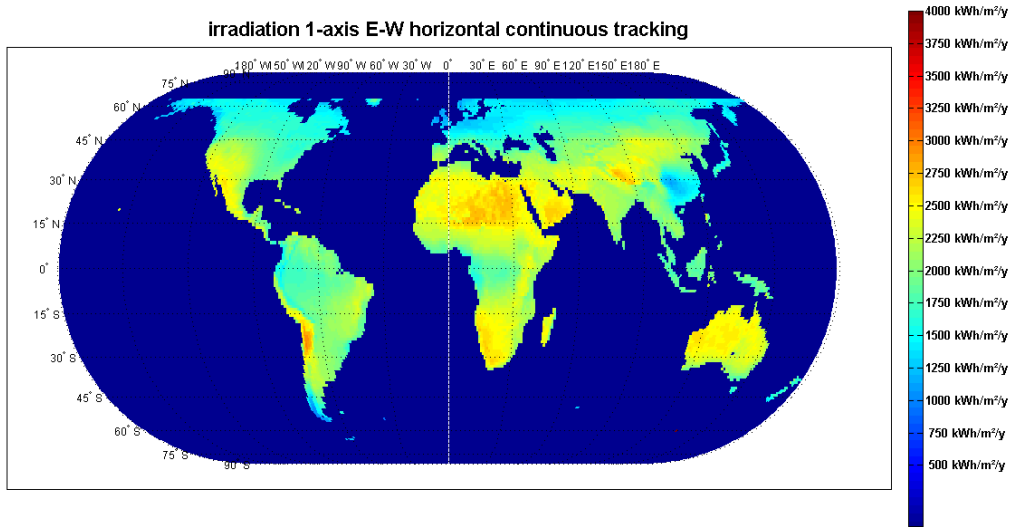


Figure 2.2-11: Annual irradiation on module surface of 1-axis horizontal east-west continuous tracking PV systems. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately optimised for maximum annual irradiation on module surface. HDKR model is performed by calculating each month of the year for maximum annual irradiation (section 2.2.2).

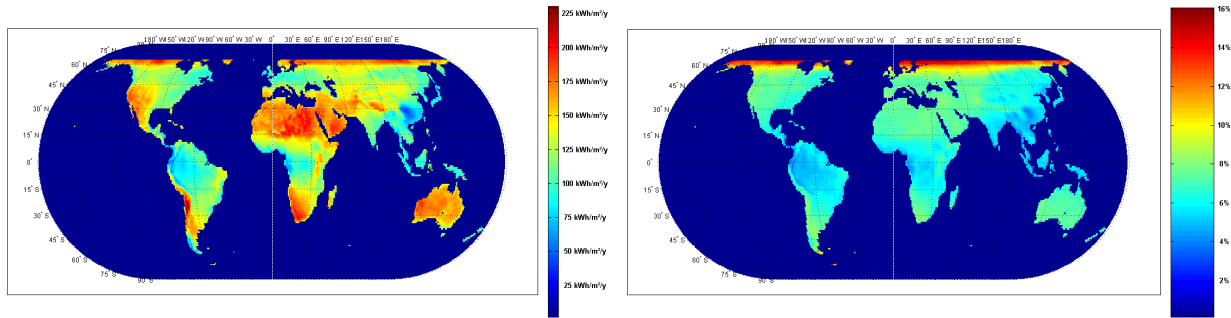


Figure 2.2-12: Annual increased irradiation on module surface of 1-axis horizontal east-west continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute (left) and relative (right) numbers.

For all regions in the world irradiation on module surface is increased by 1-axis horizontal east-west continuously tracking PV systems in reference to fixed optimally tilted systems (Fig. 2.2-11 and 2.2-12). Nevertheless, absolute irradiation increase is limited to 100 – 200 $\text{kWh/m}^2/\text{y}$ for most regions in the world. This translates to a relative increase of about 6% - 9% for most regions. Relative increase is higher for sites in the far north and south, i.e. higher than 50°N and lower than 50°S , as a consequence of strong changes in solar zenith angle (Fig. 2.2-2) over the year.

An annual irradiation profile of a 1-axis horizontal east-west continuous tracking PV system in hourly and monthly time resolution is shown in Figure 2.2-13 for an example in Sahara desert. Irradiation profile is calculated according to Equations 2.2-1 to 2.2-3 and 2.2-5. Regarding the irradiation on module received additionally by 1-axis horizontal east-west continuous tracking versus fixed optimally tilted PV systems (Fig. 2.2-13), advantageous effect of continuously optimized tilt angle is obvious, in particular during those months which show the largest deviation of monthly to annual optimized tilt angle (Fig. 2.2-7).

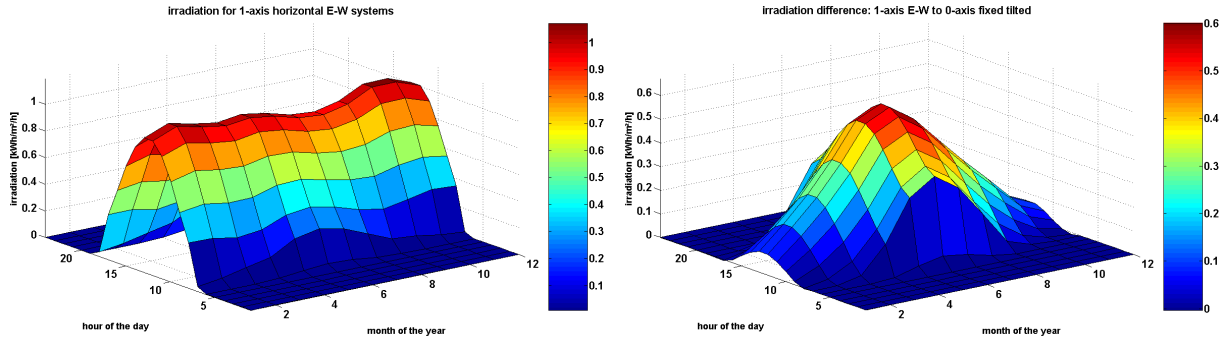


Figure 2.2-13: Hourly irradiation on module profile of 1-axis horizontal east-west continuous tracking PV systems (left) and irradiation increase in reference to fixed optimally tilted PV systems (right). Coordinate for this example is 20.5°N/ 15.5°E in Sahara desert, annual GHI is about 2,390 kWh/m²/y, annual irradiation on module of 1-axis horizontal east-west continuous tracking PV system is about 2,710 kWh/m²/y, annual irradiation on module of fixed optimally tilted PV system is about 2,520 kWh/m²/y, thus an irradiation improvement of about 8% in reference to fixed optimally tilted PV systems. Mean day of the month data are used for all days of respective months.

Summarizing the results of this section, it seems to be unlikely that the relative small increase in irradiation on module surface justifies the higher complexity in PV system technology. Advantage of no moving parts is valuable and causes less capital and operational expenditures for PV systems, which might not be compensated by relative small higher irradiation.

2.2.5 1-axis Horizontal North-South Continuous Tracking System

Identical horizontal continuous tracking PV systems can be built either in east-west (previous section) or in north-south direction of axis. East-west axis systems optimise the module's orientation to the zenith angle of the sun, thus it is adapted to seasonal variations of the position of the sun. In contrary north-south axis systems follow the position of the sun over the day and therefore optimise irradiation on a daily basis.

In this section general geometric considerations in Equations 2.2-1 to 2.2-3 are expanded by Equations 2.2-6 for 1-axis horizontal north-south continuous tracking PV systems:³⁰

$$\cos \vartheta = \sqrt{\cos^2 \vartheta_z + \cos^2 \delta \cdot \sin^2 \omega} \quad (\text{Eq. 2.2-6a})$$

$$\beta = \arctan(\tan \vartheta_z \cdot |\cos(\gamma - \gamma_s)|) \quad (\text{Eq. 2.2-6b})$$

$$\gamma = \begin{cases} +90^\circ & \text{if } \gamma_s > 0 \\ -90^\circ & \text{if } \gamma_s \leq 0 \end{cases} \quad (\text{Eq. 2.2-6c})$$

Equation 2.2-6: Specific geometric considerations for 1-axis horizontal north-south continuous tracking PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (ϑ), zenith angle (ϑ_z), declination of earth axis (δ), hour angle (ω), tilt angle (β), surface azimuth angle (γ) and solar azimuth angle (γ_s).

³⁰ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

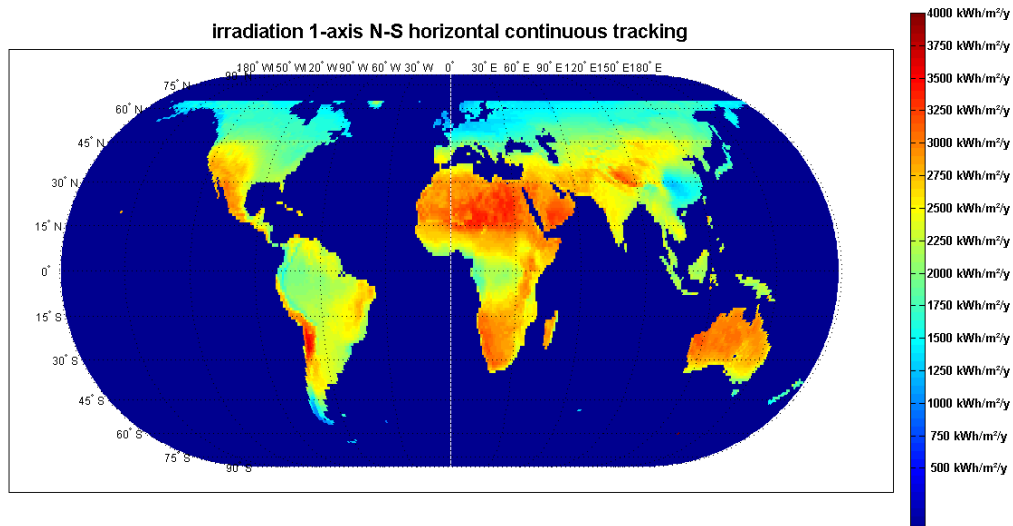


Figure 2.2-14: Annual irradiation on module surface of 1-axis horizontal north-south continuous tracking PV systems. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately optimised for maximum annual irradiation on module surface. HDKR model is performed by calculating each month of the year for maximum annual irradiation (section 2.2.2).

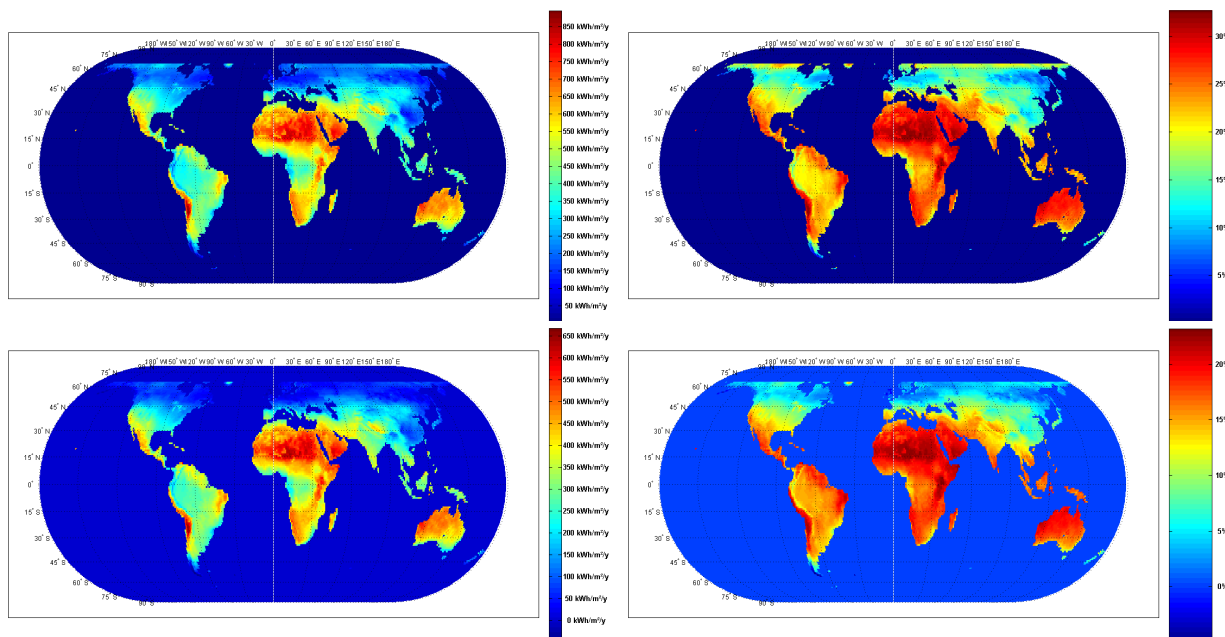


Figure 2.2-15: Annual increased irradiation on module surface of 1-axis horizontal north-south continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute (top, left) and relative (top, right) numbers and versus 1-axis horizontal east-west continuous tracking PV systems in absolute (bottom, left) and relative (bottom, right) numbers.

For all regions in the world irradiation on module surface is increased by 1-axis horizontal north-south continuously tracking PV systems in reference to fixed optimally tilted systems (Fig. 2.2-14 and 2.2-15). Absolute irradiation increase reaches $500 - 800 \text{ kWh/m}^2/\text{y}$ for regions of good and excellent solar conditions, whereas regions of moderate solar conditions achieve higher irradiation of $100 - 300 \text{ kWh/m}^2/\text{y}$. This translates to a relative increase of about $20\% - 30\%$ for the sunny regions and $10\% - 20\%$ for the regions of moderate GHI. Absolute and relative increase is highest for sites of excellent solar conditions and low level

of diffuse insolation (Fig. 2.1-2 and 2.1-3), hence irradiation increasing effect of tracking is maximized.

An annual irradiation profile of a 1-axis horizontal north-south continuous tracking PV system in hourly and monthly time resolution is shown in Figure 2.2-16 for an example in Sahara desert. Irradiation profile is calculated according to Equations 2.2-1 to 2.2-3 and 2.2-6. Regarding the irradiation on module received additionally by 1-axis horizontal north-south continuous tracking versus fixed optimally tilted PV systems (Fig. 2.2-16), the irradiation increase is highest during the morning and afternoon hours, in particular for the months of lower irradiation on module surface of fixed optimally tilted PV systems. These results are a consequence of continuously tracking the position of the sun over the day. Comparing 1-axis horizontal north-south to 1-axis horizontal east-west continuously tracking PV systems, the former show a more distinct yield characteristic than the previous one (Fig. 2.2-16). Increase of irradiation in the morning and afternoon hours is still achieved, but the noon hours are worse for most months of the year, however in total annual irradiation is increased by about 20% for sites of excellent solar conditions like in the chosen example.

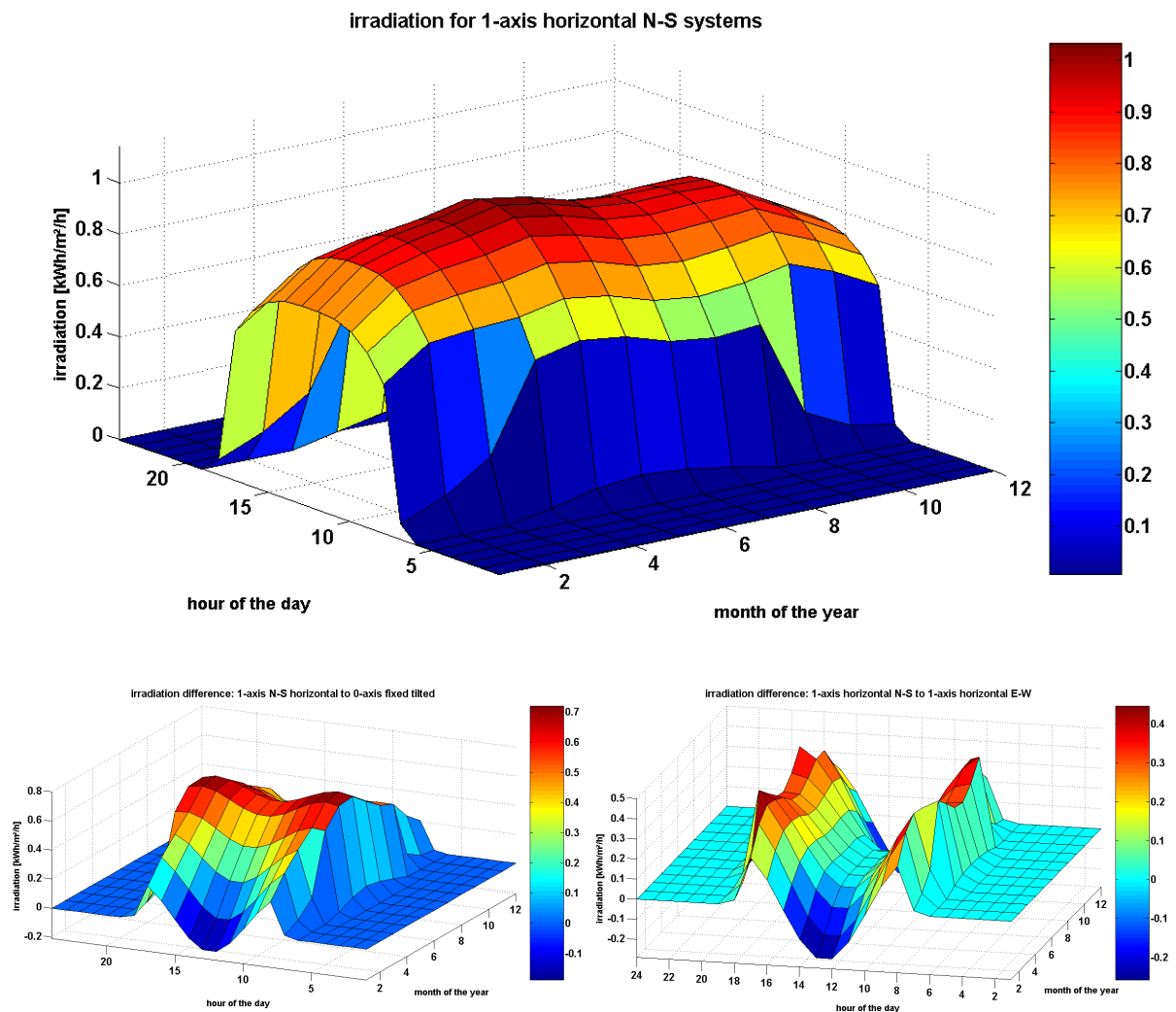


Figure 2.2-16: Hourly irradiation on module profile of 1-axis horizontal north-south continuous tracking PV systems (top), irradiation increase in reference to fixed optimally tilted PV systems (bottom, left) and irradiation increase in reference to 1-axis horizontal east-west continuous tracking PV systems (bottom, right). Coordinate for this example is 20.5°N/ 15.5°E in Sahara desert, annual GHI is about 2,390 kWh/m²/y, annual irradiation on module of 1-axis horizontal north-south continuous tracking PV system is about 3,305 kWh/m²/y, annual irradiation on module of 1-axis horizontal east-west continuous tracking PV system is about 2,710 kWh/m²/y and

annual irradiation on module of fixed optimally tilted PV system is about 2,520 kWh/m²/y. An irradiation improvement of about 31% and 22% can be achieved in reference to fixed optimally tilted and 1-axis horizontal east-west continuous tracking PV systems, respectively. Mean day of the month data are used for all days of respective months.

Summarizing the results of this section, 1-axis horizontal north-south continuous tracking PV systems might be competitive to fixed optimally tilted and 1-axis horizontal east-west continuous tracking PV systems. An increase in irradiation of 20% - 30% for sunny and very sunny regions might justify higher capital and operational expenditures, especially for plant operators achieving further advantages of more full load hours of the PV plant.

2.2.6 1-axis Vertical Optimally Tilted Continuous Tracking System

Vertical axis optimally tilted continuous tracking PV systems are widely used. Key characteristic is a site adapted optimised tilt angle and continuous tracking over the day, whereas the tracking axis is in vertical orientation. However, shading effects occur in two directions due to tilt angle and vertical axis configuration. Consequently, respective PV power plants need a lower ground cover ratio for minimizing shading effects, resulting in higher area related capital and operational expenditures.

In this section general geometric considerations in Equations 2.2-1 to 2.2-3 are expanded by Equations 2.2-7 for 1-axis vertical optimally tilted continuous tracking PV systems:³¹

$$\cos \vartheta = \cos \vartheta_z \cdot \cos \beta + \sin \vartheta_z \cdot \sin \beta \quad (\text{Eq. 2.2-7a})$$

$$\beta = \text{const.} \quad (\text{Eq. 2.2-7b})$$

$$\gamma = \gamma_s \quad (\text{Eq. 2.2-7c})$$

Equation 2.2-7: Specific geometric considerations for 1-axis vertical optimally tilted continuous tracking PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (ϑ), zenith angle (ϑ_z), tilt angle (β), surface azimuth angle (γ) and solar azimuth angle (γ_s).

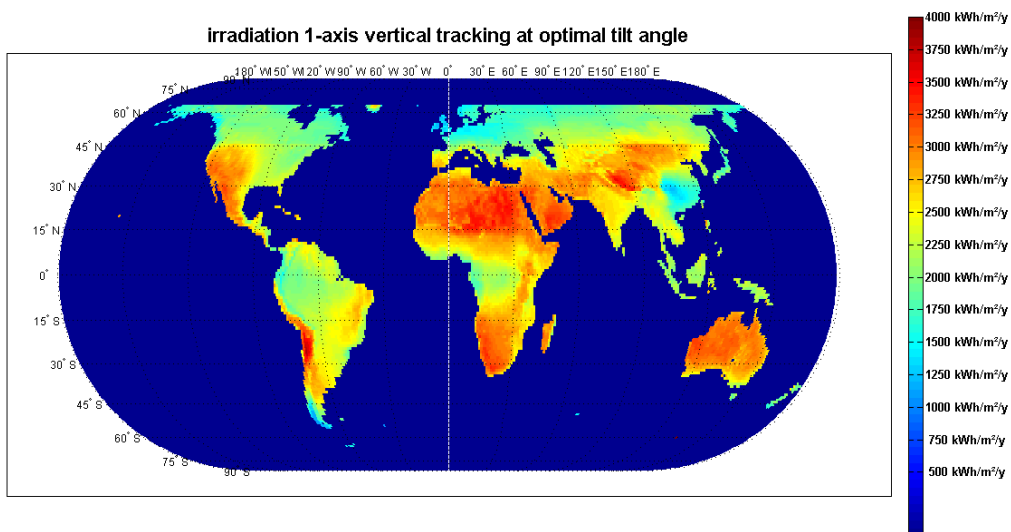


Figure 2.2-17: Annual irradiation on module surface of 1-axis vertical optimally tilted continuous tracking PV systems. Every coordinate of a 1°x1° mesh of latitude and longitude within 65°S and 65°N is separately

³¹ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

optimised for maximum annual irradiation on module surface. HDKR model is performed by calculating each month of the year for maximum annual irradiation (section 2.2.2).

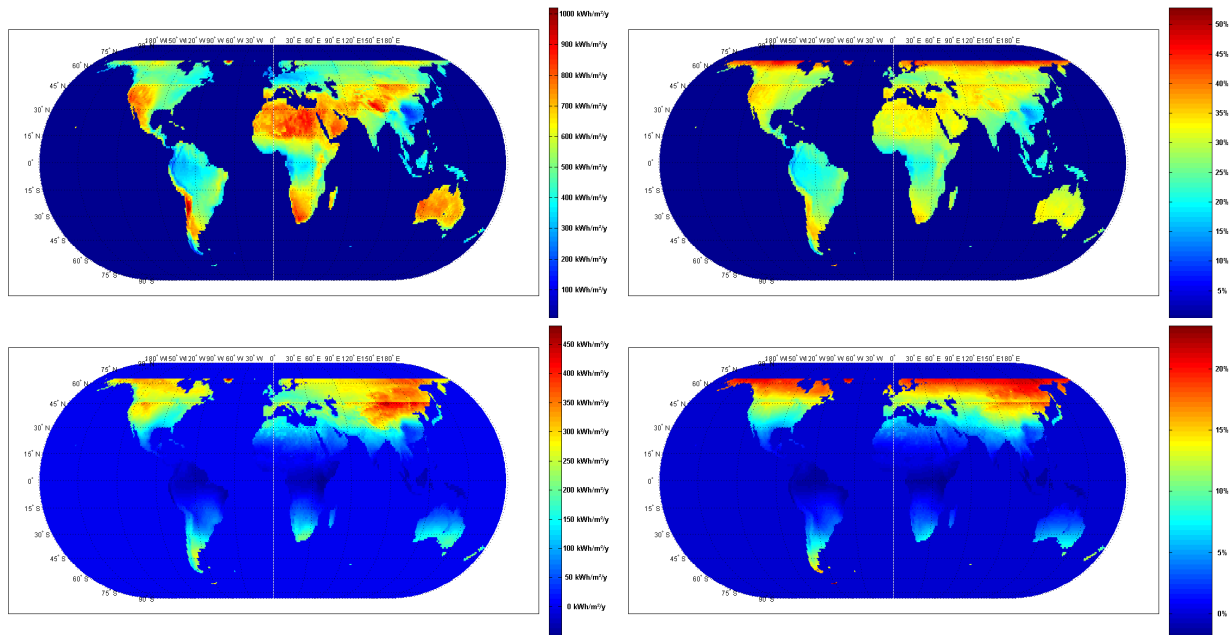


Figure 2.2-18: Annual increased irradiation on module surface of 1-axis vertical optimally tilted continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute (top, left) and relative (top, right) numbers and versus 1-axis horizontal north-south continuous tracking PV systems in absolute (bottom, left) and relative (bottom, right) numbers.

Annual incident irradiation on 1-axis vertical tilted continuously tracking module surface has been evaluated as a function of module tilt angle. Tilt angle of highest annual irradiation is defined as optimum tilt angle, which optimises the irradiance on module surface over the entire year (Fig. 2.2-17). For all regions in the world irradiation on module surface is increased by 1-axis vertical optimally tilted continuously tracking PV systems in reference to fixed optimally tilted systems (Fig. 2.2-17 and 2.2-18). Absolute irradiation increase reaches 500 - 800 kWh/m²/y for regions of good and excellent solar conditions, whereas regions of moderate solar conditions achieve higher irradiation of 200 – 400 kWh/m²/y (Fig. 2.2-18). This translates to a relative increase of about 25% - 35% for the sunny regions and 15% - 25% for the regions of moderate GHI. Moreover, relative irradiation increase is also high for sites higher than 30°N and lower than 30°S, as a consequence of tilted modules and vertical tracking. Absolute and relative increase is highest for sites of excellent solar conditions and low level of diffuse insolation (Fig. 2.1-2 and 2.1-3), hence irradiation increasing effect of tracking is maximized.

An annual irradiation profile of a 1-axis vertical optimally tilted continuous tracking PV system in hourly and monthly time resolution is shown in Figure 2.2-19 for an example in Sahara desert. Irradiation profile is calculated according to Equations 2.2-1 to 2.2-3 and 2.2-7. Regarding the irradiation on module received additionally by 1-axis vertical optimally tilted continuous tracking versus fixed optimally tilted PV systems (Fig. 2.2-19), the irradiation increase is highest during the morning and afternoon hours, in particular for the months of lower irradiation on module surface of fixed optimally tilted PV systems. These results are a consequence of continuously tracking the position of the sun over the day. Comparing 1-axis vertical optimally tilted to 1-axis horizontal north-south continuously tracking PV systems, the latter show a more distinct yield characteristic than the previous one (Fig. 2.2-19). Increase of irradiation over the hours of the day in the winter months is achieved, but the noon

hours are worse for most months of the year, however in total annual irradiation is slightly increased by about 1% for sites of excellent solar conditions like in the chosen example.

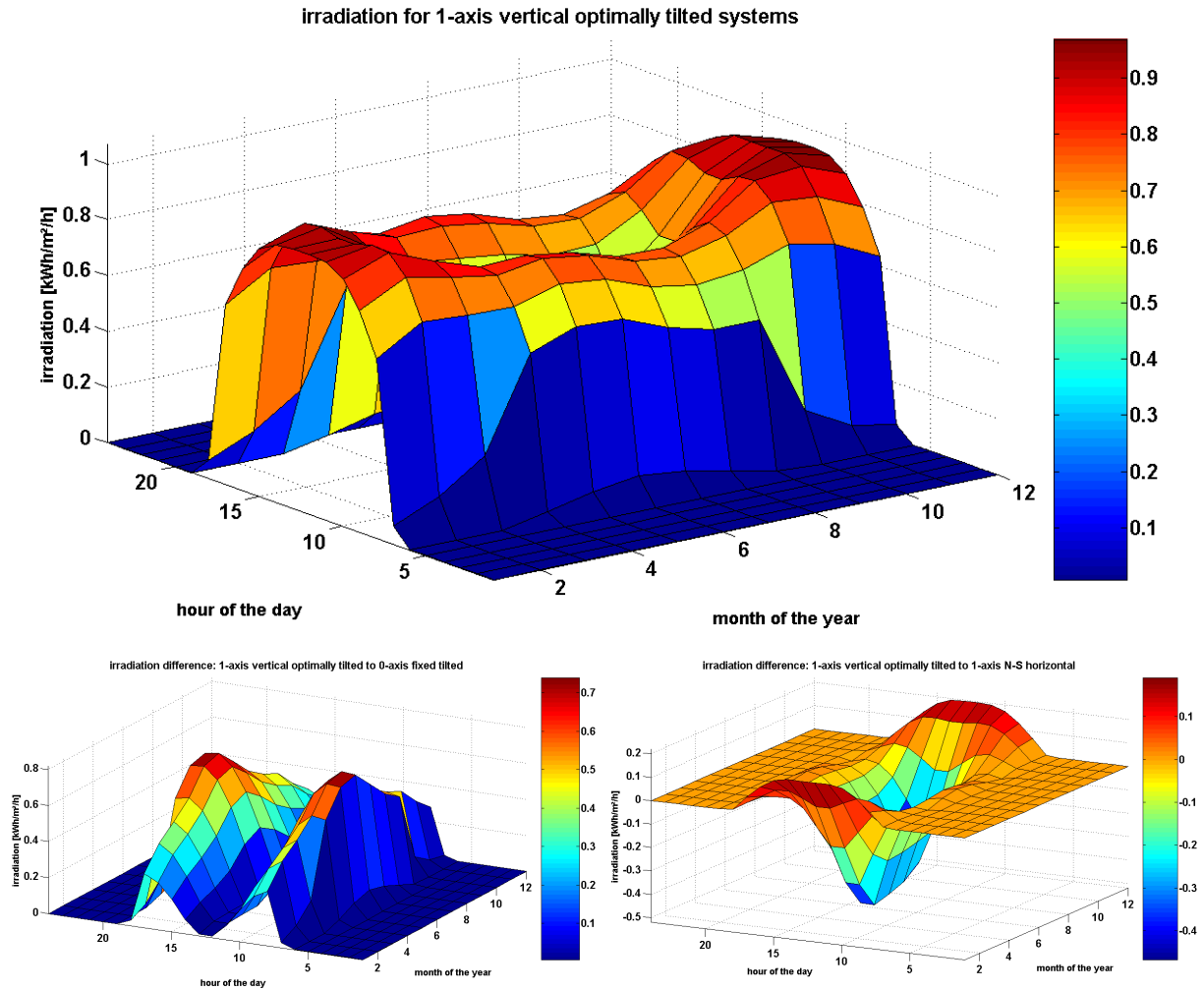


Figure 2.2-19: Hourly irradiation on module profile of 1-axis vertical optimally tilted continuous tracking PV systems (top), irradiation increase in reference to fixed optimally tilted PV systems (bottom, left) and irradiation increase in reference to 1-axis horizontal north-south continuous tracking PV systems (bottom, right). Coordinate for this example is 20.5°N/ 15.5°E in Sahara desert, optimal tilt angle is 48°, annual GHI is about 2,390 kWh/m²/y, annual irradiation on module of 1-axis vertical optimally tilted continuous tracking PV system is about 3,350 kWh/m²/y, annual irradiation on module of 1-axis horizontal north-south continuous tracking PV system is about 3,305 kWh/m²/y and annual irradiation on module of fixed optimally tilted PV system is about 2,520 kWh/m²/y. An irradiation improvement of about 33% and 1% can be achieved in reference to fixed optimally tilted and 1-axis horizontal north-south continuous tracking PV systems, respectively. Mean day of the month data are used for all days of respective months.

Summarizing the results of this section, 1-axis vertical optimally tilted continuous tracking PV systems might be competitive to fixed optimally tilted but rather not to 1-axis horizontal north-south continuous tracking PV systems. An increase in irradiation of 25% - 35% for sunny and very sunny regions might justify higher capital and operational expenditures, especially for plant operators achieving further advantages of more full load hours of the PV plant. Moreover, irradiation increase up to 35% is also achieved in regions of higher than 30°N and lower than 30°S. However, disadvantageous might be shading effects in two directions resulting in higher capital expenditures (Capex) and operational expenditures (Opex).

2.2.7 1-axis Optimally Tilted North-South Continuous Tracking System

Fixed optimally tilted PV systems maximize annual irradiation by one single optimal tilt angle over the year. 1-axis horizontal north-south continuous tracking PV systems maximize annual irradiation by tracking the sun over the day. These two irradiation optimising strategies are combined by 1-axis optimally tilted north-south continuous tracking PV systems. However, advantageous one directional shading is changed to shading effects in two directions resulting in higher Capex and Opex.

In this section general geometric considerations in Equations 2.2-1 to 2.2-3 are expanded by Equations 2.2-8 for 1-axis optimally tilted north-south continuous tracking PV systems described by Braun and Mitchell:³²

$$\cos \vartheta = \cos \vartheta_z \cdot \cos \beta + \sin \vartheta_z \cdot \sin \beta \cdot \cos(\gamma_s - \gamma) \quad (\text{Eq. 2.2-8a})$$

$$\beta = \beta'_0 + \sigma'_{\beta} \cdot 180^\circ \quad (\text{Eq. 2.2-8b})$$

$$\beta'_0 = \arctan \frac{\tan \beta'}{\cos(\gamma - \gamma')} \quad \sigma'_{\beta} = \begin{cases} 0 & \text{if } \beta'_0 \geq 0 \\ 1 & \text{otherwise} \end{cases} \quad (\text{Eq. 2.2-8c,d})$$

$$\gamma = \gamma_0 + \sigma_{\gamma_1} \cdot \sigma_{\gamma_2} \cdot 180^\circ \quad (\text{Eq. 2.2-8e})$$

$$\gamma_0 = \gamma' + \arctan \frac{\sin \vartheta_z \cdot \sin(\gamma_s - \gamma')}{\cos \vartheta \cdot \sin \beta'} \quad (\text{Eq. 2.2-8f})$$

$$\sigma_{\gamma_1} = \begin{cases} 0 & \text{if } (\gamma_0 - \gamma')(\gamma_s - \gamma') \geq 0 \\ 1 & \text{otherwise} \end{cases} \quad \sigma_{\gamma_2} = \begin{cases} 1 & \text{if } (\gamma_s - \gamma') \geq 0 \\ -1 & \text{otherwise} \end{cases} \quad (\text{Eq. 2.2-8g,h})$$

Equation 2.2-8: Specific geometric considerations for 1-axis optimally tilted north-south continuous tracking PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (ϑ), zenith angle (ϑ_z), tilt angle of surface (β), solar azimuth angle (γ_s), surface azimuth angle (γ), slope angle of the tracking axis (β'), azimuth angle of the tracking axis (γ') and some variables only needed for calculations (β'_0 , σ'_{β} , γ_0 , σ_{γ_1} , σ_{γ_2} and γ).

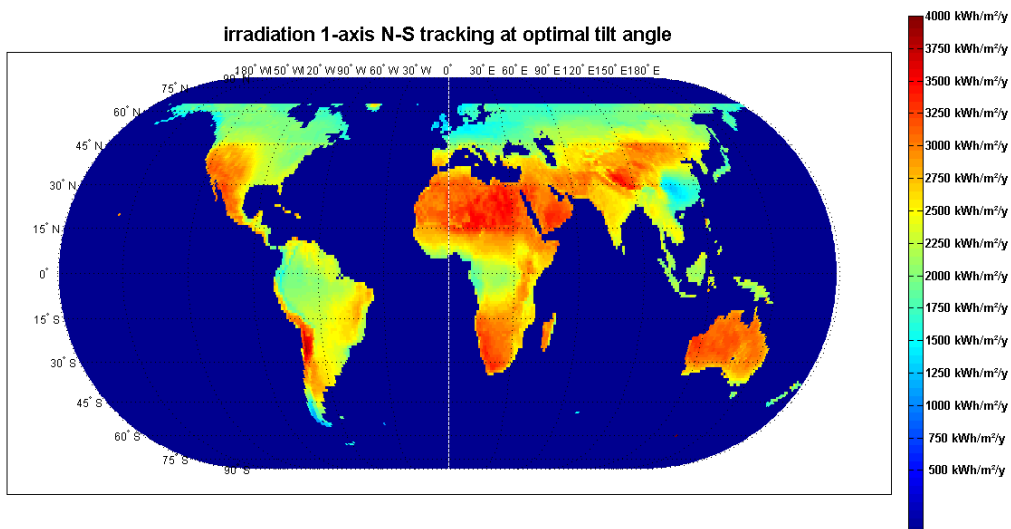


Figure 2.2-20: Annual irradiation on module surface of 1-axis optimally tilted north-south continuous tracking PV systems. Every coordinate of a 1°x1° mesh of latitude and longitude within 65°S and 65°N is separately

³² Braun J.E. and Mitchell J.C., Solar Geometry for Fixed and Tracking Surfaces, 1983

optimised for maximum annual irradiation on module surface. HDKR model is performed by calculating each month of the year for maximum annual irradiation (section 2.2.2).

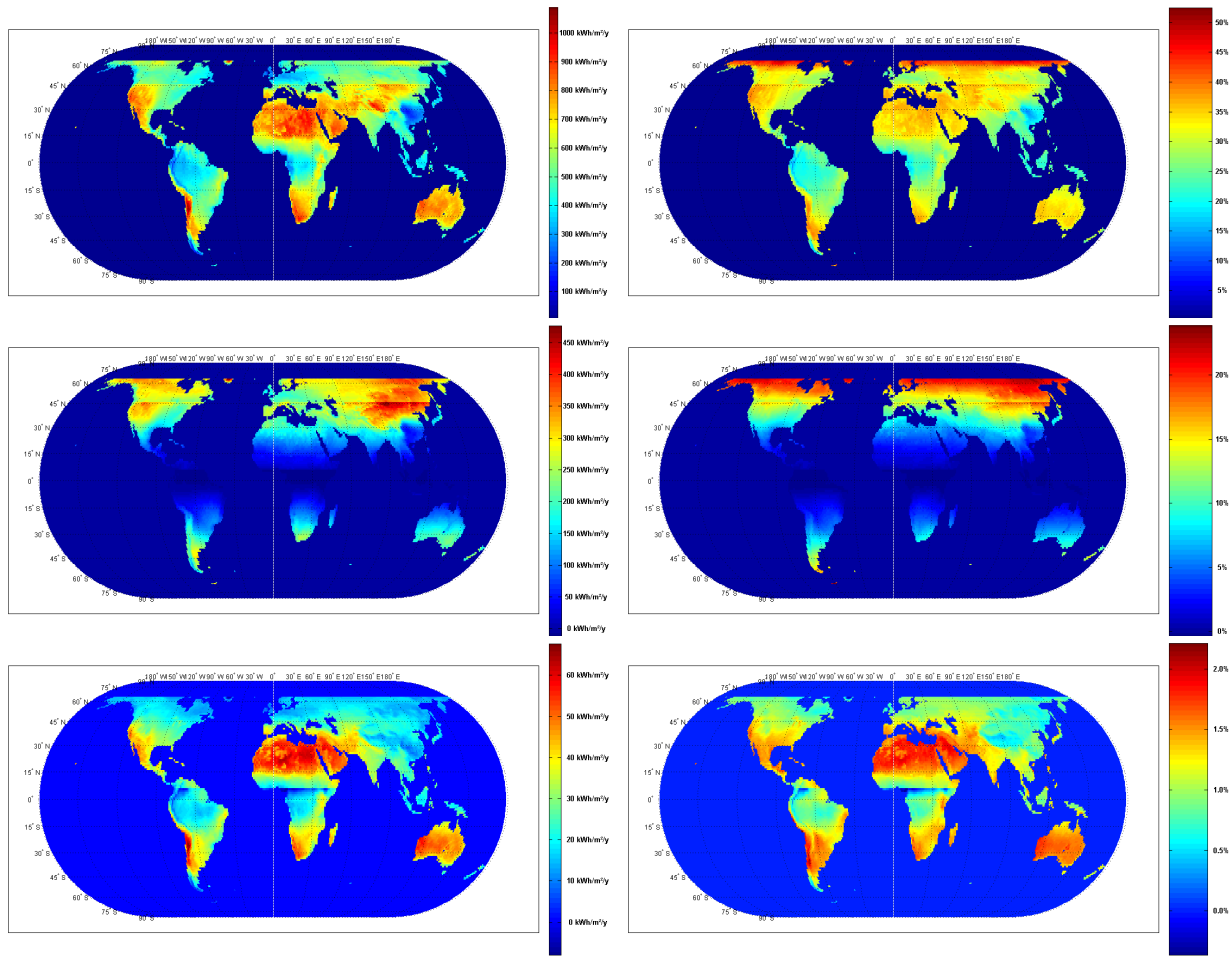


Figure 2.2-21: Annual increased irradiation on module surface of 1-axis optimally tilted north-south continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute (top, left) and relative (top, right) numbers, versus 1-axis horizontal north-south continuous tracking PV systems in absolute (centre, left) and relative (centre, right) numbers and versus 1-axis vertical optimally tilted continuous tracking PV systems in absolute (bottom, left) and relative (bottom, right) numbers.

Annual incident irradiation on 1-axis optimally tilted north-south continuous tracking module surface has been evaluated as a function of module slope angle. Slope angle of highest annual irradiation is defined as optimum tilt angle, which optimises the irradiance on module surface over the entire year (Fig. 2.2-20). For all regions in the world irradiation on module surface is increased by 1-axis optimally tilted north-south continuous tracking PV systems in reference to fixed optimally tilted systems (Fig. 2.2-20 and 2.2-21). Absolute irradiation increase reaches 500 - 900 kWh/m²/y for most regions in the world, whereas regions of high absolute and relative diffuse horizontal irradiation achieve higher irradiation of only 200 – 400 kWh/m²/y. This translates to a relative increase of about 25% - 35% for nearly all regions in the world and 15% - 20% for regions of high absolute diffuse horizontal irradiation. Absolute and relative increase is highest for sites of excellent solar conditions but still high for regions of moderate GHI except those of high absolute diffuse horizontal irradiation.

Comparing 1-axis optimally tilted north-south to 1-axis horizontal north-south continuous tracking PV systems (Fig. 2.2-21), only regions higher than 30°N and 30°S receive significantly more irradiation on module surface and reach 10% to 20% more irradiation

which is similar to fixed optimally tilted PV systems versus GHI and also a consequence of tilt angle advantage of higher absolute latitude sites. Furthermore 1-axis optimally tilted north-south continuous tracking PV systems receive more irradiation on module surface than 1-axis vertical optimally tilted continuous tracking PV systems. However, this increase is limited to only up to 50 kWh/m²/y for best sites in the world (Fig. 2.2-21).

An annual irradiation profile of a 1-axis optimally tilted north-south continuous tracking PV system in hourly and monthly time resolution is shown in Figure 2.2-22 for an example in Sahara desert. Irradiation profile is calculated according to Equations 2.2-1 to 2.2-3 and 2.2-8. Regarding the irradiation on module received additionally by 1-axis optimally tilted north-south continuous tracking versus fixed optimally tilted PV systems (Fig. 2.2-22), the irradiation increase is highest during the morning and afternoon hours, in particular for the months of lower irradiation on module surface of fixed optimally tilted PV systems. These results are a consequence of continuously tracking the position of the sun over the day.

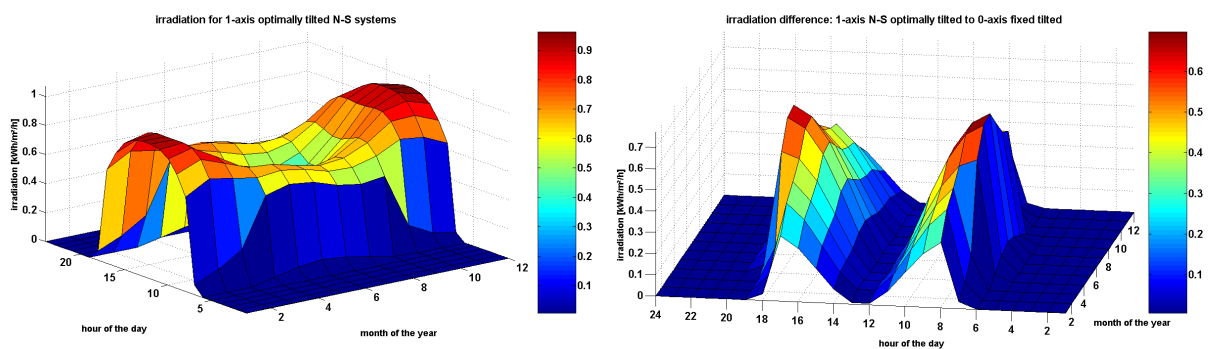


Figure 2.2-22: Hourly irradiation on module profile of 1-axis optimally tilted north-south continuous tracking PV systems (left) and irradiation increase in reference to fixed optimally tilted PV systems (right). Coordinate for this example is 20.5°N/ 15.5°E in Sahara desert, optimal tilt angle is about 21°, annual GHI is about 2,390 kWh/m²/y, annual irradiation on module of 1-axis optimally tilted north-south continuous tracking PV system is about 3,410 kWh/m²/y and annual irradiation on module of fixed optimally tilted PV system is about 2,520 kWh/m²/y. An irradiation improvement of about 35% can be achieved in reference to fixed optimally tilted PV systems. Mean day of the month data are used for all days of respective months.

Summarizing the results of this section, 1-axis optimally tilted north-south continuous tracking PV systems might be competitive to fixed optimally tilted, 1-axis horizontal north-south continuous tracking and 1-axis vertical optimally tilted continuous tracking PV systems. An increase in irradiation of 25% - 35% for most regions in the world might justify higher capital and operational expenditures, especially for plant operators achieving further advantages of more full load hours of the PV plant.

2.2.8 2-axes Non-concentrating Continuous Tracking System: Global Normal Irradiation

Highest possible irradiation on modules can be achieved by 2-axes non-concentrating tracking, hence module surface is always perpendicular to direct radiant beam of the sun, but for non-concentrating systems additional diffuse irradiance can be converted. This highest possible solar resource is defined as global normal irradiation (GNI).

In this section general geometric considerations in Equations 2.2-1 to 2.2-3 are expanded by

Equations 2.2-9 for 2-axes non-concentrating continuous tracking PV systems:³³

$$\cos \vartheta = 1 \quad (\text{Eq. 2.2-9a})$$

$$\beta = \vartheta_z \quad (\text{Eq. 2.2-9b})$$

$$\gamma = \gamma_s \quad (\text{Eq. 2.2-9c})$$

Equation 2.2-9: Specific geometric considerations for 2-axes non-concentrating continuous tracking PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (ϑ), tilt angle (β), zenith angle (ϑ_z), surface azimuth angle (γ) and solar azimuth angle (γ_s).

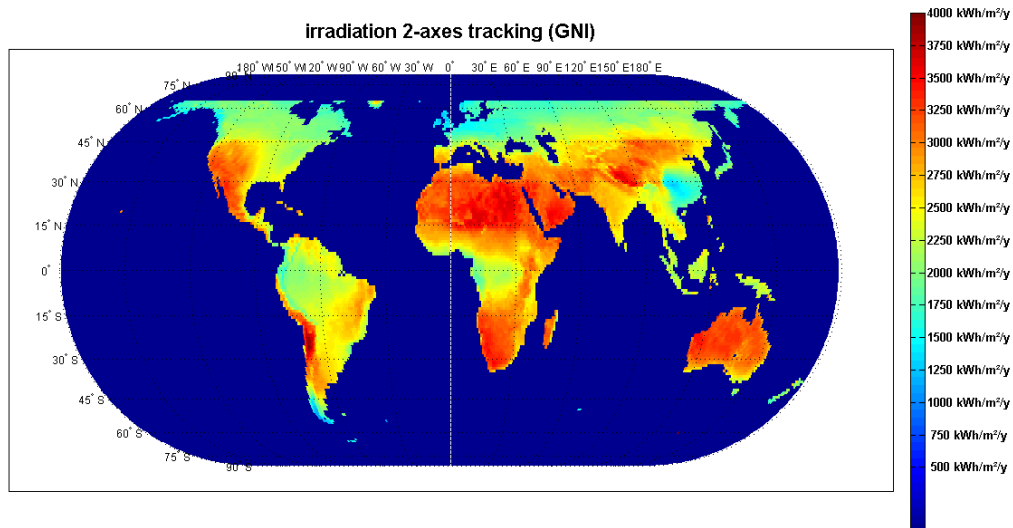
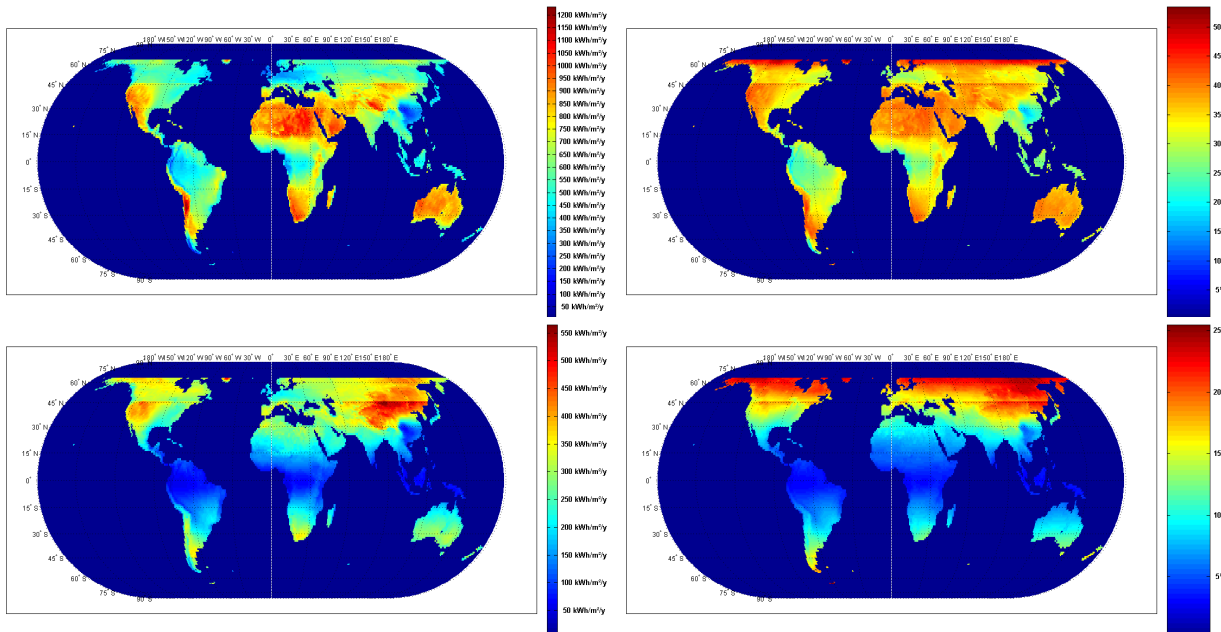


Figure 2.2-23: Annual irradiation on module surface of 2-axes non-concentrating continuous tracking PV systems. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately optimised for maximum annual irradiation on module surface. This solar resource is identical to global normal irradiation (GNI). HDKR model is performed by calculating each month of the year for maximum annual irradiation (section 2.2.2).



³³ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

Figure 2.2-24: Annual increased irradiation on module surface of 2-axes non-concentrating continuous tracking (GNI) PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute (top, left) and relative (top, right) numbers and versus 1-axis horizontal north-south continuous tracking PV systems in absolute (bottom, left) and relative (bottom, right) numbers.

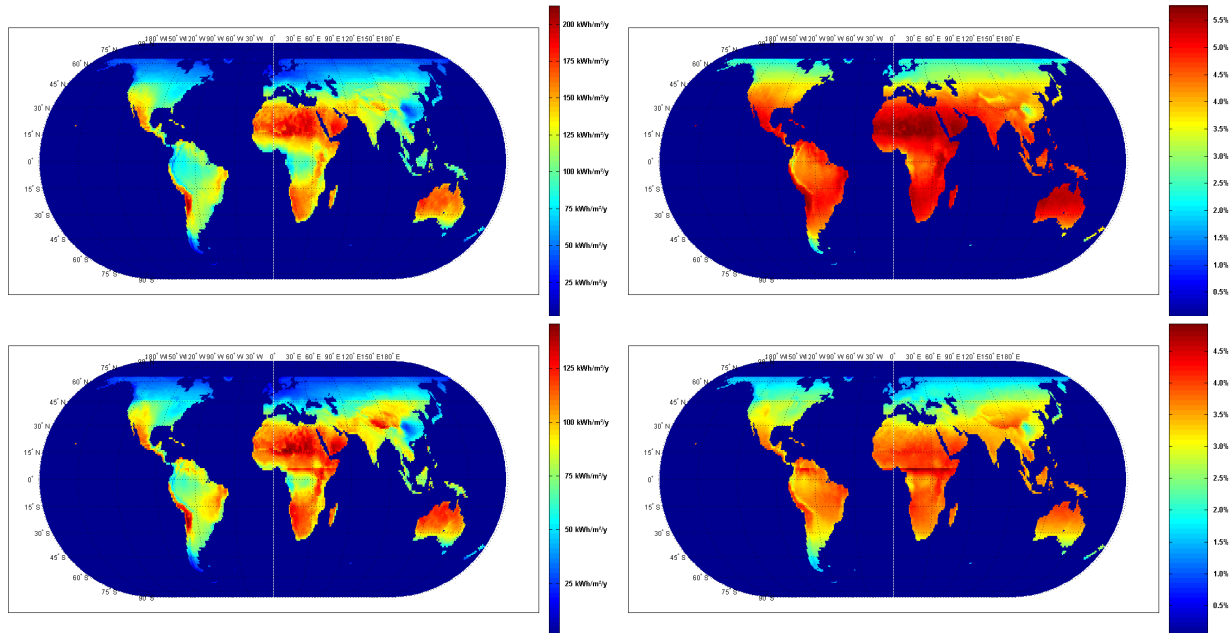


Figure 2.2-25: Annual increased irradiation on module surface of 2-axes non-concentrating continuous tracking (GNI) PV systems versus 1-axis vertical optimally tilted continuous tracking PV systems in absolute (top, left) and relative (top, right) numbers and versus 1-axis optimally tilted north-south continuous tracking PV systems in absolute (bottom, left) and relative (bottom, right) numbers.

For all regions in the world irradiation on module surface is increased by 2-axes non-concentrating continuous tracking (GNI) PV systems in reference to fixed optimally tilted systems (Fig. 2.2-23 to 2.2-25). Absolute irradiation increase reaches 600 - 1000 kWh/m²/y for most regions in the world, whereas regions of high absolute and relative diffuse horizontal irradiation achieve higher irradiation of only 200 – 400 kWh/m²/y. This translates to a relative increase of about 30% - 45% for nearly all regions in the world and 15% - 25% for regions of high absolute diffuse horizontal irradiation. Absolute and relative increase is highest for sites of excellent solar conditions but still high for regions of moderate GHI except those of high absolute diffuse horizontal irradiation.

Comparing 2-axes non-concentrating to 1-axis horizontal north-south continuous tracking PV systems (Fig. 2.2-24), only regions higher than 30°N and 30°S receive significantly more irradiation on module surface and reach 10% - 20% more irradiation which is similar to fixed optimally tilted PV systems versus GHI and also a consequence of tilt angle advantage of higher absolute latitude sites. Furthermore 2-axes non-concentrating continuous tracking PV systems receive more irradiation on module surface than 1-axis vertical optimally tilted PV systems. However, this increase is limited to only 100 - 200 kWh/m²/y for absolute latitudes within 45°N/S (Fig. 2.2-25). 2-axes non-concentrating continuous tracking also improves 1-axis optimally tilted north-south continuous tracking PV systems, but this effect is rather low, as only 70 – 130 kWh/m²/y more irradiation can be realised (Fig. 2.2-25).

An annual irradiation profile of a 2-axes non-concentrating continuous tracking (GNI) PV system in hourly and monthly time resolution is shown in Figure 2.2-26 for an example in Sahara desert. Irradiation profile is calculated according to Equations 2.2-1 to 2.2-3 and 2.2-9.

Regarding the irradiation on module received additionally by 2-axes non-concentrating continuous tracking versus fixed optimally tilted PV systems (Fig. 2.2-26), the irradiation increase is highest during the morning and afternoon hours, in particular for the months of lower irradiation on module surface of fixed optimally tilted PV systems. These results are a consequence of continuously tracking the position of the sun over the day. At latitudes close to the equator 1-axis horizontal north-south continuous tracking PV systems show excellent irradiation optimization characteristics, as 2-axes non-concentrating systems can only slightly improve a few months in the year.

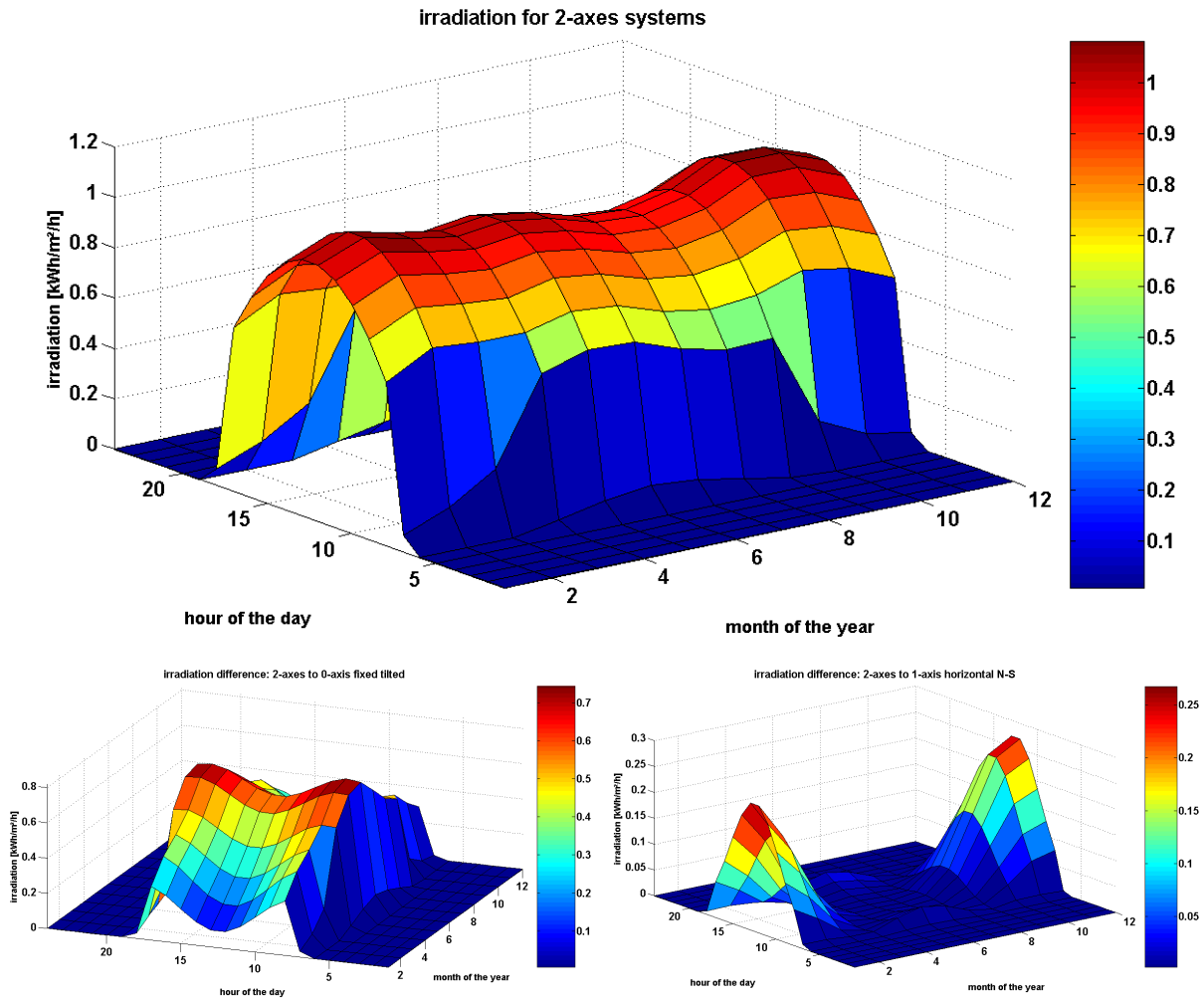


Figure 2.2-26: Hourly irradiation on module profile of 2-axes non-concentrating continuous tracking (GNI) PV systems (top), irradiation increase in reference to fixed optimally tilted PV systems (bottom, left) and irradiation increase in reference to 1-axis horizontal north-south continuous tracking PV systems (bottom, right). Coordinate for this example is 20.5°N/ 15.5°E in Sahara desert, annual GHI is about 2,390 kWh/m²/y, annual irradiation on module of 2-axes non-concentrating continuous tracking PV system is about 3,540 kWh/m²/y, annual irradiation on module of 1-axis horizontal north-south continuous tracking PV system is about 3,305 kWh/m²/y and annual irradiation on module of fixed optimally tilted PV system is about 2,520 kWh/m²/y. An irradiation improvement of about 41% and 7% can be achieved in reference to fixed optimally tilted and 1-axis horizontal north-south continuous tracking PV systems, respectively. Mean day of the month data are used for all days of respective months.

Summarizing the results of this section, 2-axes non-concentrating continuous tracking (GNI) is the best solar resource available on earth in terms of irradiation as a consequence of optimum tracking modus and maximal irradiation, in particular including diffuse irradiation. Nevertheless, 2-axes non-concentrating continuous tracking (GNI) PV systems might not be

competitive to 1-axis horizontal north-south, 1-axis vertical optimally tilted and 1-axis optimally tilted north-south continuous tracking PV systems as a consequence of very limited additional irradiation on module surface. 2-axes tracking is more complex in its technical realization due to one additional axis resulting in more Capex and Opex.

2.2.9 2-axes Concentrating Continuous Tracking System: Direct Normal Irradiation

Concentrating solar power technologies are specially adapted for converting direct solar irradiation. For optimising insolation 2-axes continuous tracking systems are applied, or at least quasi 2-axes systems, e.g. long rows of 1-axis horizontal north-south continuous tracking systems using a one dimensional focal line. As a consequence of 2-axes tracking and direct solar irradiation, solar resource for concentrating solar power technologies is called direct normal irradiation (DNI).

In this section general geometric considerations in Equations 2.2-1 to 2.2-3 are adapted and expanded, as diffuse part of solar resource cannot be converted. Tracking formulas are identical to 2-axes non-concentrating PV systems and are summarized for 2-axes non-concentrating continuous tracking PV systems in Equations 2.2-10:³⁴

$$I_T = I_b \cdot R_b \quad (\text{Eq. 2.2-10a})$$

$$\cos \vartheta = 1 \quad (\text{Eq. 2.2-10b})$$

$$\beta = \vartheta_z \quad (\text{Eq. 2.2-10c})$$

$$\gamma = \gamma_s \quad (\text{Eq. 2.2-10d})$$

Equation 2.2-10: Total radiation on a tilted concentrating surface according to Hay-Davis-Klucher-Reindl (HDKR) model and specific geometric considerations for 2-axes concentrating continuous tracking PV systems. Abbreviations stand for: irradiance tilted surface (I_T), irradiance beam horizontal (I_b), geometric factor (R_b), angle of incidence (beam and surface normal) (ϑ), tilt angle (β), zenith angle (ϑ_z), surface azimuth angle (γ) and solar azimuth angle (γ_s).

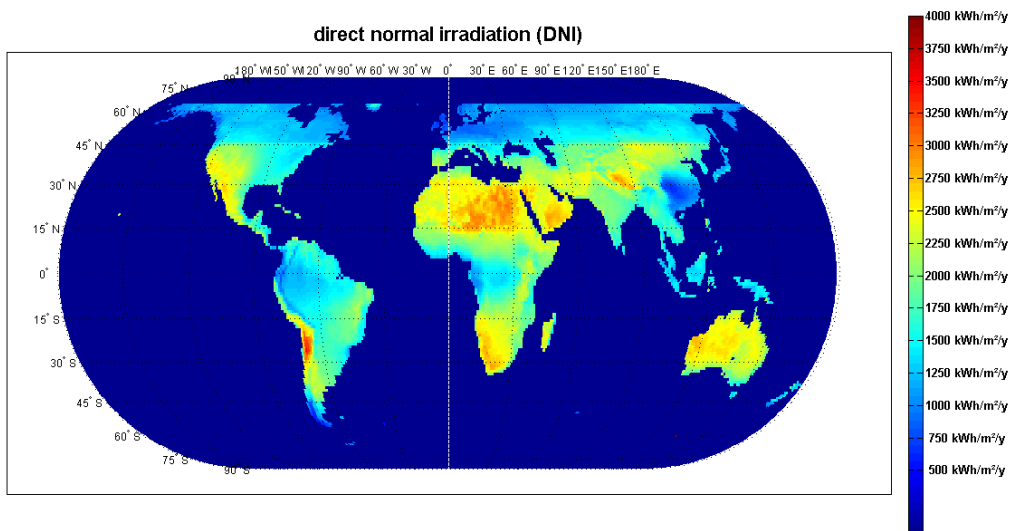


Figure 2.2-27: Annual irradiation on module surface of 2-axes concentrating continuous tracking PV systems. Every coordinate of a 1°x1° mesh of latitude and longitude within 65°S and 65°N is separately optimised for

³⁴ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

maximum annual irradiation on module surface. This solar resource is identical to direct normal irradiation (DNI). HDKR model is performed by calculating each month of the year for maximum annual irradiation (section 2.2.2).

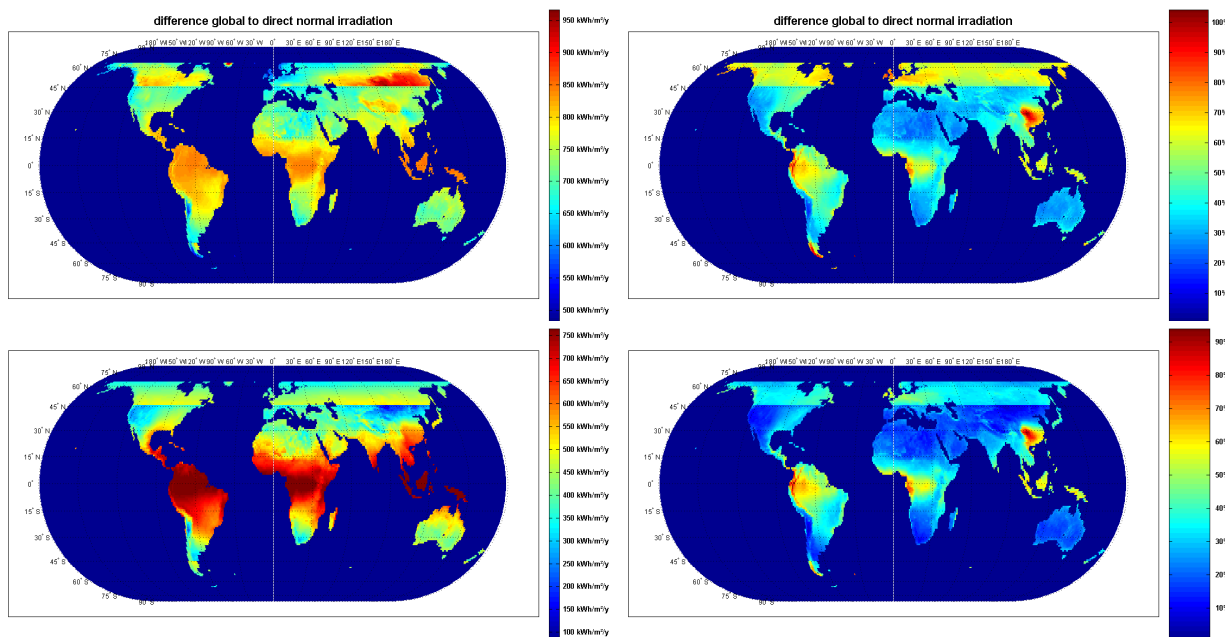


Figure 2.2-28: Annual irradiation loss on module surface of 2-axes concentrating continuous tracking (DNI) PV systems versus 2-axes non-concentrating continuous tracking (GNI) PV systems in absolute (top, left) and relative (top, right) numbers and versus 1-axis horizontal north-south continuous tracking PV systems in absolute (bottom, left) and relative (bottom, right) numbers.

For all regions in the world irradiation on module surface is decreased by 2-axes concentrating continuously tracking (DNI) PV systems in reference to 2-axes non-concentrating and 1-axis horizontal north-south continuous tracking PV systems (Fig. 2.2-27 and 2.2-28). Absolute irradiation decrease reaches 550 - 750 kWh/m²/y for most sunny and very sunny regions in the world, whereas regions of low absolute and relative diffuse horizontal irradiation achieve lowest irradiation losses. This translates to a relative decrease of about 10% - 30% for regions of good and very good solar conditions.

2-axes concentrating solar power technologies need to overcome aforementioned irradiation loss and furthermore higher Capex and Opex for active sun tracking and the necessity for 2-axes tracking have to be additionally compensated. Both factors are best addressed by higher power conversion efficiency of respective solar power systems. High concentrating PV (HCPV) achieve currently maximum DC-efficiencies of up to 26%³⁵, compared to measured string efficiencies of about 15% to 18% of respective low- and non-concentrating PV systems³⁶. These numbers are best illustrated for the standard exemplary site of this chapter in Sahara desert. GNI and DNI are 3,400 and 2,650 kWh/m²/y, respectively, hence GNI is 750 kWh/m²/y higher than DNI, i.e. slightly more than 20% irradiation is lost for concentrating solar power systems. Currently highest power conversion efficiencies of non-concentrating and concentration PV technologies are about 16% and 26% for entire PV systems accounted for string power. Assuming a low ground cover ratio of 20%, the 2-axes non-concentrating and the 2-axes concentrating PV systems are able to generate about 110 and 150

³⁵ Gombert A. et al., Analysis of Long Term Operation Data of Flatcon CPV Systems, 2010

³⁶ Judkins Z.S. et al., Performance Results of a Low-concentration Photovoltaic System Based on High Efficiency Back Contact Cells, 2010

$\text{GWh}_{\text{el}}/\text{km}^2/\text{y}$, i.e. HCPV systems generate about 35% more electricity than conventional PV systems. Therefore concentrating PV systems might be competitive to non-concentrating PV systems if Capex and Opex increases were less than 35%.

In theory the irradiance at standard test conditions are assumed to be 1000 W/m^2 for non-concentrating and 850 W/m^2 for concentrating PV systems, as a consequence of lost diffuse irradiance.³⁷ However, in practice concentrating irradiance (DNI) reaches up to 94% of non-concentrating irradiance (GNI) and 1000 W/m^2 direct normal irradiance is the standard operation condition.³⁸ Due to that fact the first manufacturers of HCPV modules label their panels for 1000 W/m^2 , e.g. Soitec CPV (former Concentrix Solar). Up to now the deviation of practical measurements and theory cannot be explained properly, but it is a further push for HCPV systems.

Summarizing the results of this section, solar resource for 2-axes concentrating continuous tracking (DNI) PV systems is about 10% - 30% lower than for comparable 2-axes non-concentrating continuous tracking PV systems, which can use GNI. However, significantly higher power conversion efficiencies of HCPV in reference to non-concentrating PV systems result in about 35% higher electricity generation potential per area unit. Higher cost of HCPV systems due to more complex technology and necessity to use 2-axes tracking have to be below 35% for being competitive in very sunny regions of low diffuse irradiation.

2.3 Weighted Irradiation

Besides different irradiation potentials of respective tracking and non-tracking PV systems, there is a lack of available data for averaged solar resource data per country and region. The purpose of this sub-chapter is a global overview on population and area weighted mean irradiation on fixed tilted, 1-axis and 2-axes tracking module surfaces for all major regions in the world (section 2.3.1) and for estimates concerning transformation pathways of the global power system also values for electricity generation weighted irradiation (section 2.3.2). A detailed database has been published comprising all countries in the world by applying a methodology identical to this sub-chapter.³⁹

2.3.1 Population and Area Weighted Irradiation

Mean irradiation values for countries and regions can be derived by population and area weighted procedures. Calculated mean irradiation values for countries, continents and regions can be very helpful for further cost analyses or for first order estimates of solar resource potentials. Population weighted mean value is very relevant for PV, as highly modular PV technology can be directly and decentralized used at the place of electricity demand, where the people live.

Mathematical description for population and area weighted mean irradiation values for all considered geographic entities is given in Equations 2.3-1:

³⁷ Gueymard C.A. et al., Proposed Reference Irradiance Spectra for Solar Energy Systems Testing, 2002

³⁸ Lerchenmüller H., DNI Values in good CPV Sites, 2011

³⁹ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation: global Overview on Solar Resource Conditions for fixed tilted, 1-axis and 2-axes PV Systems, 2010

$$irrad_{pop,entity} = \frac{\sum_{\forall lat, lon \in entity} irrad_{annual}(lat, lon) \cdot population(lat, lon)}{\sum_{\forall lat, lon \in entity} population(lat, lon)} \quad (\text{Eq. 2.3-1a})$$

$$irrad_{area,entity} = \frac{\sum_{\forall lat, lon \in entity} irrad_{annual}(lat, lon) \cdot area(lat, lon)}{\sum_{\forall lat, lon \in entity} area(lat, lon)} \quad (\text{Eq. 2.3-1b})$$

Equation 2.3-1: Population and area weighted irradiation values per considered entity. Abbreviations stand for: irradiation (of respective PV system) (*irrad*), population (*pop*), latitude of respective coordinate (*lat*), longitude of respective coordinate (*lon*) and area (*area*).

Commercial PV systems have to be designed for minimum levelized cost of electricity (section 3.2.1), hence a trade-off between maximum irradiation and minimum PV system cost has to be optimised. Calculations performed in much detail for fixed optimally tilted PV systems clearly show for Central European conditions, that LCOE optimised and irradiation optimised tilt angles significantly deviate whereas irradiation values differ only by a few percent (section 2.2.3). Therefore, irradiation optimised population and area weighted mean values for irradiation of respective PV systems are a good first order approximation for investigated entities.

Fundamental datasets used for all calculations in this sub-chapter are for the GHI the NASA SSE 6.0 data ^{40,41}, which are also basis for all solar resource calculations of the previous sub-chapters (sub-chapter 2.1 and 2.2) and for the global population density the CIESIN GWPv3 data ⁴². CIESIN GWPv3 dataset comprises expected population data for the year 2010 and is provided by the Center for International Earth Science Information Network (CIESIN) of Columbia University in New York. Global distribution of population density is shown in Figure 2.3-1.

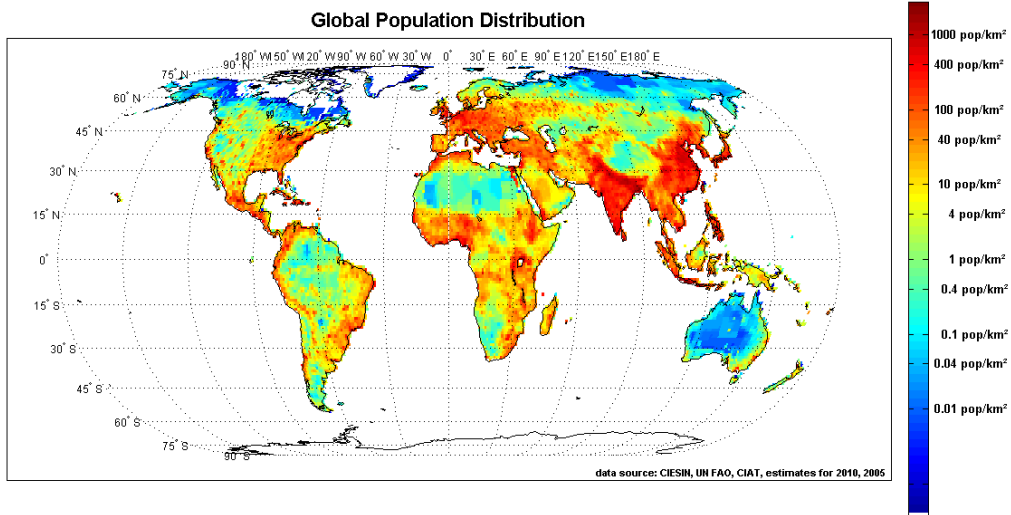


Figure 2.3-1: Global population density for the year 2010. Areas coloured red show a high and dark red a very high population density. The unit for population density is persons/km². Population input data are used in a 1°x1° mesh. Data are provided by Center for International Earth Science Information Network (CIESIN).⁴³

⁴⁰ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

⁴¹ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

⁴² Balk D. and Yetman G., The Global Distribution of Population: Gridded Population of the World, 2005

⁴³ Balk D. and Yetman G., The Global Distribution of Population: Gridded Population of the World, 2005

Detailed analysis of georeferenced location of world population (Fig. 2.3-1), location of land masses and local irradiation on module surface of fixed optimally tilted PV systems (Fig. 2.2-3) shows global solar resource quality on land and relative solar resource quality according to the distribution of the world population depicted in Figure 2.3-2.

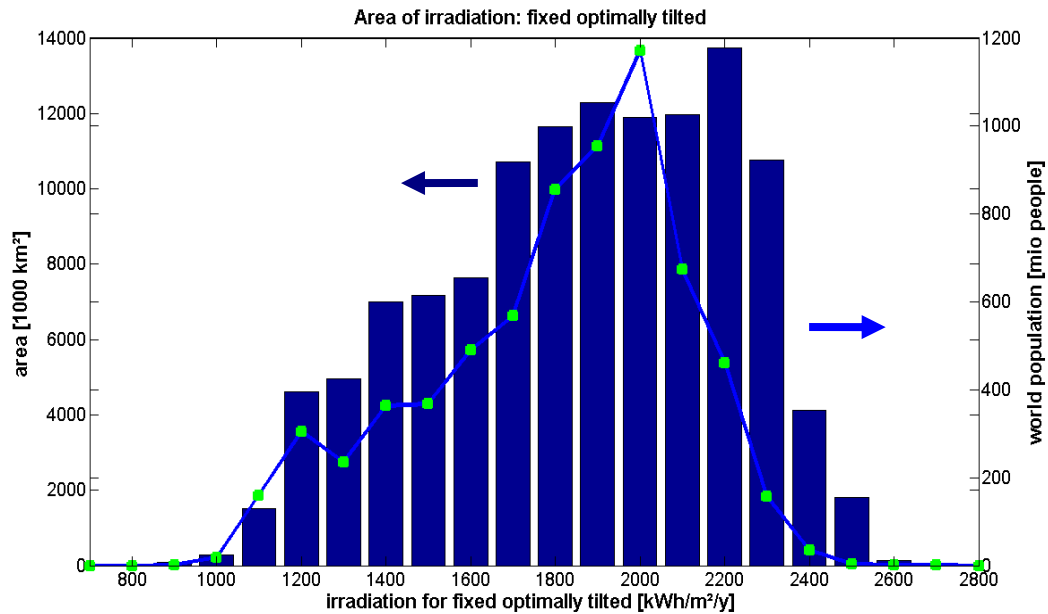


Figure 2.3-2: Distribution of world population and land masses on earth in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to right axis and represents distribution of world population. The bars are referred to left axis and represent land masses.

Both results for world population and for land mass confirms very good solar resource availability for most regions in the world and the large majority of world population as only a minor fraction is located at a irradiation of less than 1,600 kWh/m²/y on fixed optimally tilted module surface.

All relevant countries, continents and major regions in the world are analysed by population (Fig. 2.3-1) and area weighted mean irradiation according to Equations 2.3-1 plus maximum and minimum of any coordinate within the geographic extent of respective geographic entity. Results for major regions in the world are summarized in Table 2.3-1. Corresponding data for all countries in the world have been published.⁴⁴

Solar Resource		World	EU	Europe	MENA	Europe-MENA	Africa	Asia-Pacific	India	China	North America	Latin America	South America
Population	[mio. people]	6,908	503	835	453	1,288	1,031	4,103	1,214	1,362	356	191	393
Area	[1000 km ²]	135,952	4,333	26,141	12,008	38,149	30,317	39,350	3,287	9,598	19,623	2,698	17,834
GHI													
Population	[kWh/m ² /y]	1677	1181	1221	1880	1466	1985	1643	1848	1414	1533	1973	1802
Area	[kWh/m ² /y]	1608	1229	918	2043	1257	2078	1426	1856	1577	1143	2020	1799
max	[kWh/m ² /y]	2546	2261	2261	2465	2465	2492	2465	2232	2185	2326	2327	2546
min	[kWh/m ² /y]	666	813	666	1316	666	1505	822	1433	1052	863	1505	792
fixed tilted													
Population	[kWh/m ² /y]	1846	1391	1448	2086	1685	2067	1834	2032	1631	1776	2087	1890

⁴⁴ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation: global Overview on Solar Resource Conditions for fixed tilted, 1-axis and 2-axes PV Systems, 2010

Area	[kWh/m ² /y]	1776	1450	1140	2232	1468	2178	1640	2027	1911	1382	2149	1881
max	[kWh/m ² /y]	2769	2479	2479	2621	2621	2599	2621	2446	2615	2442	2530	2769
min	[kWh/m ² /y]	772	975	772	1520	772	1517	1012	1615	1087	1067	1523	916
1-horiz. E-W													
Population	[kWh/m ² /y]	1961	1502	1565	2243	1817	2201	1943	2150	1723	1900	2221	2006
Area	[kWh/m ² /y]	1901	1575	1245	2400	1592	2326	1756	2144	2027	1495	2293	1996
max	[kWh/m ² /y]	3001	2672	2672	2830	2830	2801	2830	2610	2798	2628	2731	3001
min	[kWh/m ² /y]	902	1070	902	1626	902	1581	1126	1702	1126	1163	1584	990
1-horiz. N-S													
Population	[kWh/m ² /y]	2217	1591	1671	2618	2023	2599	2170	2450	1849	2108	2603	2321
Area	[kWh/m ² /y]	2175	1711	1320	2843	1779	2768	1960	2454	2203	1622	2704	2315
max	[kWh/m ² /y]	3672	3206	3206	3418	3418	3446	3418	3086	3237	3208	3243	3672
min	[kWh/m ² /y]	862	1047	862	1763	862	1771	1191	1816	1191	1119	1776	940
1-vertical													
Population	[kWh/m ² /y]	2331	1789	1878	2765	2208	2629	2300	2559	2009	2298	2656	2363
Area	[kWh/m ² /y]	2294	1914	1522	2965	1956	2808	2122	2552	2447	1825	2768	2354
max	[kWh/m ² /y]	3797	3341	3341	3557	3557	3481	3557	3206	3557	3249	3437	3797
min	[kWh/m ² /y]	1022	1199	1022	1938	1022	1766	1223	1940	1223	1312	1770	1079
1-tilted N-S													
Population	[kWh/m ² /y]	2358	1808	1899	2810	2238	2660	2325	2591	2026	2327	2693	2391
Area	[kWh/m ² /y]	2323	1937	1538	3015	1981	2846	2146	2583	2466	1845	2810	2381
max	[kWh/m ² /y]	3866	3399	3399	3619	3619	3543	3619	3251	3580	3308	3494	3866
min	[kWh/m ² /y]	1027	1206	1027	1961	1027	1763	1230	1955	1230	1320	1785	1084
2-GNI													
Population	[kWh/m ² /y]	2434	1842	1938	2895	2293	2759	2400	2680	2087	2391	2790	2475
Area	[kWh/m ² /y]	2397	1977	1568	3114	2033	2953	2209	2672	2545	1889	2910	2463
max	[kWh/m ² /y]	4012	3516	3516	3749	3749	3676	3749	3371	3710	3434	3609	4012
min	[kWh/m ² /y]	1038	1222	1038	2006	2006	1832	1254	2021	1254	1341	1837	1100
2-DNI													
Population	[kWh/m ² /y]	1685	1182	1260	2184	1603	1975	1651	1918	1359	1673	2008	1683
Area	[kWh/m ² /y]	1695	1342	1016	2407	1435	2191	1524	1905	1787	1271	2148	1676
max	[kWh/m ² /y]	3480	2856	2856	3137	3137	3042	3137	2674	2982	2733	2980	3480
min	[kWh/m ² /y]	562	657	573	1333	573	1020	611	1272	611	745	1029	562

Table 2.3-1: Solar resources for all major regions in the world. Derivation of solar resources according to sub-chapter 2.2 and population and area weighted calculation by performing Equation 2.3-1. Fundamental GHI data and population distribution data are taken from NASA SSE 6.0^{45,46} and CIESIN GPWv3⁴⁷. Abbreviations stand for: European Union (*EU*), Middle East North Africa (*MENA*), global horizontal irradiation (*GHI*), fixed optimally tilted (*fixed tilted*), 1-axis horizontal east-west continuous tracking (*1-horiz. E-W*), 1-axis horizontal north-south continuous tracking (*1-horiz. N-S*), 1-axis vertical optimally tilted continuous tracking (*1-vertical*), 1-axis optimally tilted north-south continuous tracking (*1-tilted N-S*), 2-axes non-concentrating continuous tracking/ global normal irradiation (*2-GNI*) and 2-axes concentrating continuous tracking/ direct normal irradiation (*2-DNI*).

Major result of this section is the database itself which can be used for various estimates. There are specific outcomes like global population weighted mean irradiation, i.e. mean irradiation in the world where the people live, of about 1,850 kWh/m²/y, whereas the area weighted mean irradiation is about 1,780 kWh/m²/y for fixed optimally tilted PV systems (Table 2.3-1). Africa, MENA and Latin America show irradiation of more than 2,050 kWh/m²/y for fixed optimally tilted PV systems. Best ten countries in the world sorted by their maximum irradiation for fixed optimally tilted PV systems are: Chile, Bolivia,

⁴⁵ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

⁴⁶ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

⁴⁷ Balk D. and Yetman G., The Global Distribution of Population: Gridded Population of the World, 2005

Argentina, Saudi Arabia, China, Niger, Chad, Egypt, Libya and Sudan.⁴⁸ Usually, population and area weighted mean irradiation is quite similar, except countries of special extreme climate conditions, like Algeria (area weighted irradiation is significantly higher than population one, as most people do not live in desert regions) or Chile (population weighted irradiation is significantly higher than area one, as most people do not live in cold parts of the country).

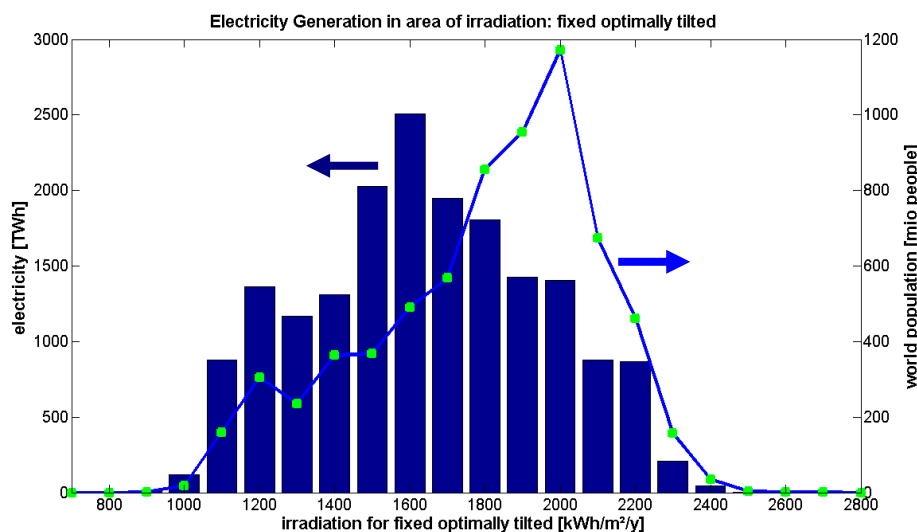
Global maximum solar irradiation is given for Atacama desert by about 2,770 kWh/m²/y for fixed optimally tilted PV systems up to 4,010 kWh/m²/y for 2-axes non-concentrating PV systems (GNI).

It is still unclear whether high concentrating PV (HCPV) might gain large market shares, as non-concentrating 2-axes PV systems receive at least 20%, but often 35% - 40% more solar radiation, even in very sunny countries like Algeria. This disadvantage of HCPV systems need to be compensated by higher overall system efficiency at identical cost structure or even higher system efficiency for the case of higher Capex and Opex of concentrating versus non-concentrating PV systems. However, rough estimates in section 2.2.9 lead to the conclusion that HCPV might be competitive for the case of optimised cost structures.

2.3.2 Electricity Generation Weighted Irradiation

For global estimates of the PV market potential it might be of interest to know the global electricity generation weighted average fixed optimally tilted irradiation. For calculating this, population weighted fixed optimally tilted irradiation per country is weighted by electricity generation per country.⁴⁹ Current global electricity generation weighted average fixed optimally tilted irradiation is computed to about 1,690 kWh/m²/y.

Detailed analysis of georeferenced location of world population (Fig. 2.3-1), location of generated electricity and local irradiation on module surface of fixed optimally tilted PV systems (Fig. 2.2-3) clearly shows a global imbalance of generated electricity and world population depicted in Figure 2.3-3.



⁴⁸ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation: global Overview on Solar Resource Conditions for fixed tilted, 1-axis and 2-axes PV Systems, 2010

⁴⁹ IEA, Key World Energy Statistics, 2009

Figure 2.3-3: Global electricity generation in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to right axis and represents distribution of world population. The bars are referred to left axis and represent electricity generation.

Despite of diminishing conventional energy resources (sub-chapter 1.3) poor and developing regions largely have access to good and excellent domestic solar resources and thus may catch up with industrialized regions by tapping most abundant energy source on earth, the sun.

Results of this sub-chapter enables estimates based on mean irradiation of countries, continents, regions and the world. In several following chapters these irradiation mean data are used for estimating photovoltaic power generation and respective cost of electricity and furthermore global PV capacity potential estimate is derived on basis of this sub-chapter.

2.4 Comparing Solar Resources

It is impossible to evaluate most appropriate solar resource for solar power generation without economic assessment of the respective systems. This key objective of this thesis is discussed in sub-chapter 3.2. Nevertheless, all major solar resources are discussed in sub-chapter 2.2 and absolute and relative irradiation increases in reference to most relevant other solar resources are mentioned. Intention of this sub-chapter is a comparison of all solar resources presented in sub-chapter 2.2 for two countries and two coordinates.

A broad discussion of specific advantages of different PV systems is not the intention of this sub-chapter. However, a short overview might be helpful for further considerations. Major advantage of solar PV technology is the need for no moving parts; this is still the case for fixed optimally tilted systems. To give up such a great advantage needs very good reasons, this might be given for specific tracking systems. 1-axis horizontal east-west continuous tracking systems are best adapted for regions of large seasonal deviation of daily zenith angles, which is the case for sites in far north and south latitudes. Advantage of 1-axis horizontal tracking and fixed tilted systems are shading effects in only one direction which significantly reduces necessary minimum site area thus BOS related cost are kept at a lowest possible level. 1-axis horizontal north-south continuous tracking systems follow the sun over the day. These systems show high additional annual irradiation in reference to fixed optimally tilted systems (Tables 2.3-1 and 2.4-1 and Fig. 2.2-15). 1-axis optimally tilted north-south continuous tracking systems are better adapted to respective site latitude but need a larger plant area than fixed optimally tilted or 1-axis horizontal north-south continuous tracking due to two directional shading. 1-axis vertical optimally tilted systems also need a larger plant ground as a consequence of two directional shading. PV system of highest annual irradiation is 2-axes non-concentrating tracking system. Larger plant area is needed as well due to two directional shading effects and a higher mechanical stress and cost is effective due to more moving parts and engines. 2-axes concentrating tracking variation is needed for HCPV systems.

Impact of different tracking and non-tracking PV systems on achievable respective annual irradiation is shown in Table 2.4-1 for two exemplarily weighted countries for moderate and excellent solar conditions in Germany and Egypt, respectively. Relative irradiation differences of PV systems in these two countries indicate the type of PV system best adapted to respective solar conditions.

	GHI	fixed tilted	1-axis horiz. E-W	1-axis horiz. N-S	1-axis vertical	1-axis tilted N-S	2-axes (GNI)	2-axes (DNI)
	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]
Germany	1,046	1,222	1,320	1,356	1,534	1,548	1,573	926
increase abs GHI		176	274	310	488	502	527	-120
increase rel GHI		16.8%	26.2%	29.6%	46.7%	48.0%	50.4%	-11.5%
increase abs fixed			98	134	312	326	351	-296
increase rel fixed			8.0%	11.0%	25.5%	26.7%	28.7%	-24.2%
Egypt	2,054	2,242	2,412	2,871	2,993	3,047	3,143	2,443
increase abs GHI		188	358	817	939	993	1,089	389
increase rel GHI		9.2%	17.4%	39.8%	45.7%	48.3%	53.0%	18.9%
increase abs fixed			170	629	751	805	901	201
increase rel fixed			7.6%	28.1%	33.5%	35.9%	40.2%	9.0%
EG vs DE								
increase abs	1,008	1,020	1,092	1,515	1,459	1,499	1,570	1,517
increase rel	96.4%	83.5%	82.7%	111.7%	95.1%	96.8%	99.8%	163.8%

Table 2.4-1: Various population weighted solar resources for moderate (Germany) and excellent (Egypt) solar conditions. Relative diffuse fraction of global horizontal irradiation is 55% and 25% for Germany and Egypt, respectively. Solar resource for 2-axes GNI tracking provides 70% and 29% more irradiation than 2-axes DNI for Germany and Egypt, respectively. Calculations are performed under assumption of only one single PV system. Shading losses need to be considered for PV power plants in the order of 3 – 10% in dependence of PV system technology and ground cover ratio, i.e. ratio of module area to total plant area. Abbreviations stand for: global horizontal irradiation (*GHI*), global normal irradiation (*GNI*), direct normal irradiation (*DNI*), absolute (*abs*) and relative (*rel*).

Solar resources in Egypt are roughly twice as good as in Germany, only DNI is even better in Egypt due to high diffuse irradiation in Germany. As a consequence of high relative diffuse irradiation in Germany tracking systems do not receive as much additional irradiation than respective systems in Egypt. For optimising irradiation on module surface it can be expected about 500 kWh/m²/y (equals ~27% increase to fixed tilted PV systems) in Germany for 1-axis vertical optimally tilted (section 2.2.6), 1-axis optimally tilted north-south (section 2.2.7) and 2-axes non-concentrating (section 2.2.8) continuous tracking PV systems. In Egypt well adapted tracking systems receive 800 – 1000 kWh/m²/y more irradiation on module surface, as it is the case for 1-axis horizontal north-south (section 2.2.5), 1-axis vertical optimally tilted (section 2.2.6), 1-axis optimally tilted north-south (section 2.2.7) and 2-axes non-concentrating (section 2.2.8) continuous tracking PV systems. 1-axis horizontal north-south continuous tracking might be the favoured tracking system for sunny regions due to maximized irradiation, minimised specific space requirement and lowest additional technical complexity. Technologies dependent on direct solar resource (DNI) need to be placed in areas of high GHI and low diffuse fraction of it, as the latter cannot be converted into electricity. However, these technologies have to compete with non-concentrating 2-axes (GNI) or 1-axis continuous tracking systems which can use diffuse solar resource as well.

Absolute and relative solar resource quality of respective PV system options is highly dependent on GHI quality and in particular on its diffuse fraction. Typical characteristics of sites of low diffuse but also of high diffuse GHI fraction are depicted in Figure 2.4-1.

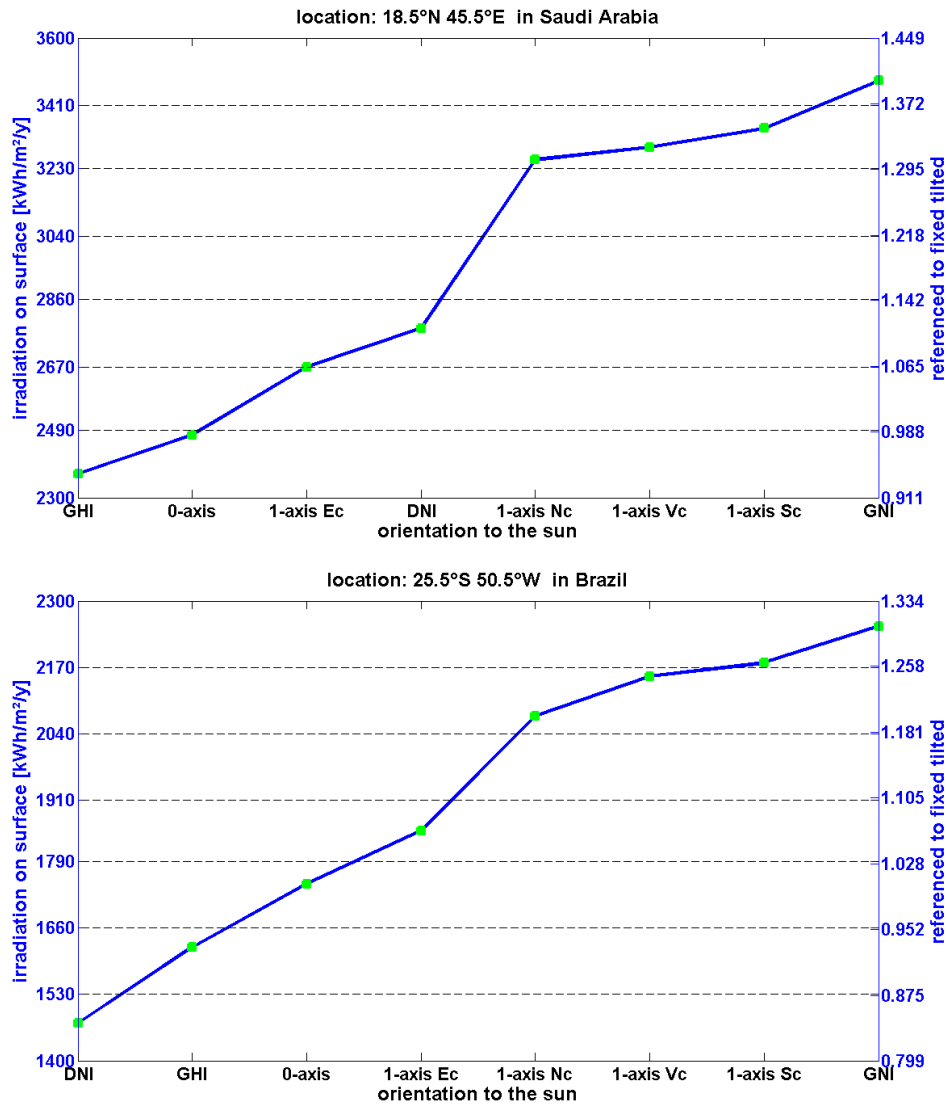


Figure 2.4-1: Absolute solar resource quality and respective relative performance in reference to fixed optimally tilted PV systems of representative coordinates in Northern (Saudi Arabia) and Southern (Brazil) hemisphere. Diffuse fraction of GHI is 20% and 40% for coordinates in Saudi Arabia and Brazil, respectively. Impact on tracking systems is depicted. Abbreviations stand for: global horizontal irradiation (GHI), fixed optimally tilted (0-axis), 1-axis horizontal east-west continuous tracking (1-axis Ec), 2-axes concentrating direct normal irradiation (DNI), 1-axis horizontal north-south continuous tracking (1-axis Nc), 1-axis vertical optimally tilted continuous tracking (1-axis Vc), 1-axis optimally tilted north-south continuous tracking (1-axis Sc) and 2-axes non-concentrating continuous tracking (GNI).

Similarly to the comparison of population weighted mean irradiation in Germany and Egypt, tracking PV systems are most advantageous for low absolute and relative diffuse GHI fraction. 1-axis tracking systems well adapted to respective sites increase irradiation on module surface by 30% and more, whereas additional irradiation yielded by 2-axes non-concentrating (GNI) systems is rather low. 2-axes concentrating (DNI) systems might be competitive in regions of high GHI but low diffuse GHI fraction and high power conversion efficiency of HCPV systems. In case of good economics 1-axis horizontal north-south continuous tracking PV systems might be the most competitive PV system besides fixed optimally tilted PV systems.

Chapter 3

Photovoltaic Economics

Sustainable power technologies need to fulfil the major criteria of competitive economics. The **fundamental trends** of photovoltaic economics, like growth rates, learning rates, research and development investments, regional PV markets, PV technology diffusion, energetic sustainability and specific emissions are discussed in respect to this major requirement (sub-chapter 3.1). Depending on geographic and technological conditions some **photovoltaic system concepts** for PV power plants are best adapted in maximizing economics (sub-chapter 3.2). On **end-users' level grid-parity** concept is a well known metric for evaluating **on-grid** photovoltaic competitiveness (sub-chapter 3.3), whereas **fuel-parity** concept is more appropriate for assessing **off-grid** photovoltaic benefits (sub-chapter 3.4). Economic considerations for energy system embedded large-scale photovoltaic power plants are discussed in chapters 6 and 7. Fundamental consequences of key aspects of photovoltaic economics are discussed at the end of each section in this chapter.

3.1 Fundamental Trends

Several fundamental trends drive the progress, development and diffusion of PV systems. The historic PV market growth patterns (section 3.1.1) and the stable PV experience curve (section 3.1.2) might be the most decisive factors. However, they are enabled by substantial research and development investments (section 3.1.3) and early access to regional markets (section 3.1.4). Research and development is the basis for the diffusion of the various PV technologies (section 3.1.5), as well as the progress in energetic sustainability (section 3.1.6) and a very low level of harmful emissions (section 3.1.7). The interaction of all these fundamental drivers lays the basis for the tremendous progress in reaching economic targets and might establish PV as the least cost power technology in many regions in the world by the end of the 2010s.

3.1.1 Historic Market Growth

Initial scientific publications on PV related phenomena were presented in the 19th century.^{1,2} They have been understood the first time by the work of Albert Einstein³ for which he got the Nobel Prize. First solar cell patent applications were filed in 1920s by Walter Snelling and Walter Schottky.^{4,5} These ground breaking works paved the way for the later growth of PV. The historic PV market growth is founded by major diffusion phases (section 3.1.1.1) showing outstanding high long-term growth rates (section 3.1.1.2). The first estimate of global PV market potential (section 3.1.1.3) in this thesis gives several indications that the high growth rates might be sustainable for further one to two decades.

¹ Becquerel E., Recherches sur les effets de la radiation chimique de la lumière solaire au moyen des courants électriques, 1839

² Smith W., Effect of light on selenium during the passage of an electric current, 1873

³ Einstein A., Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt, 1905

⁴ Snelling W.O., Photo-electric apparatus, 1920

⁵ Schottky W., Photoelectric Generator, 1929

3.1.1.1 Historic Photovoltaic Diffusion Phases

In history of PV three major inventions led to sustainable markets for PV systems (Fig. 3.1-1). Real market diffusion of PV started immediately after the invention of the silicon (Si) solar cell in 1954 by Darryl Chapin, Calvin Fuller and Gerald Pearson, associates of Bell Labs.⁶ The initial area was powering satellites as least energy cost option for space applications^{7,8} and induced the first growth phase for early PV industry (Fig. 3.1-1). In early 1970s PV as a former space technology was adapted to terrestrial applications by Exxon associate and founder of Solar Power Corp. Elliot Berman, who started the second growth phase of PV for terrestrial off-grid solutions (Fig. 3.1-1), which show very strong economics for decentralized energy supply in developing countries for rural population^{9,10} (sub-chapter 3.4). Roof-top programmes and feed-in tariff (FiT) laws in Japan¹¹ and Germany¹² started the third high growth regime for PV applications in on-grid markets (Fig. 3.1-1), which is characterized in its economy by the grid-parity concept (sub-chapter 3.3). In late 2000s and early 2010s the fourth high growth regime is being started by utility-scale PV power plants now fast gaining ground due to their positive economic impact, best described by the fuel-parity concept (sub-chapter 3.4 and chapter 6). A good overview on general PV diffusion patterns is given by Andersson and Jacobsson.¹³

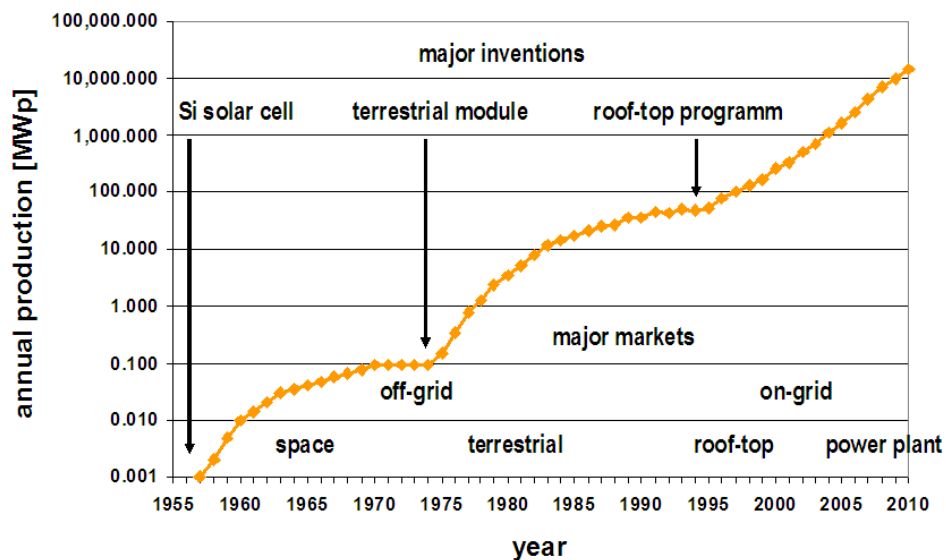


Figure 3.1-1: Historic PV production in dependence of major inventions and market segments. Annual growth rates increased from about 33% in space age and during off-grid diffusion to 45% for the last 15 years during

⁶ Chapin D.M. et al., A new Si p-n junction photocell for converting solar radiation into electrical power, 1954

⁷ Perlin J., From Space to Earth – The Story of Solar Electricity, 1999, p. 41-48

⁸ Loferski J.J., The First Forty Years: a Brief History of the Modern Photovoltaic Age, 1993

⁹ Breyer Ch. et al., Electrifying the Poor: Highly economic off-grid PV Systems in Ethiopia – A Basis for sustainable rural Development, 2009a

¹⁰ Breyer Ch. et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 2011c

¹¹ Ikki O. and Kaizuka I., PV in Japan – Yesterday, Today and Tomorrow, 2010, p. 359-366

¹² Fell H.-J., Will This Work? Is It Realistic? – Thoughts and Acts of a Political Practitioner with a Solar Vision, 2010, p. 297-303

¹³ Andersson B.A. and Jacobsson S., Monitoring and assessing technology choice: the case of solar cells, 2000

on-grid diffusion. Data are taken from IEA-PVPS ¹⁴, Swanson ¹⁵, Staffhorst ¹⁶, Nemet ¹⁷, Jäger-Waldau ^{18,19}, Sandén ²⁰, NREL ²¹ and Schindler ²².

The three diffusion phases are marked by three major inventions, Si solar cell, terrestrial PV module and roof-top programmes. Off-grid space applications dominated the first diffusion phase from 1957 – 1973 and showed average annual growth rates of about 33%. Terrestrial off-grid applications dominated the second diffusion phase from 1973 – 1995 and generated average annual growth rates of about 33%. Grid connected roof-top systems dominate the third diffusion phase and show average annual growth rates as high as 45%, whereas first utility-scale plants start the next diffusion phase right now. Off-grid PV markets have been growing at a constant high rate of about 15% - 20% in the years from mid 1990s to today but due to much higher growth rates of on-grid markets, the relative proportion of global off-grid installations declined to about 4% of total installed PV capacity.²³ Still, annual average growth rates for PV have been exceeding 30% for more than five decades and have been even increased by serving new markets. PV seems to tend to become the least cost option in every market segment, which has already happened for space applications and shown for off-grid solutions for rural energy supply in developing countries ²⁴. Analysing cost dynamics in on-grid roof-top markets reveal again the tendency of PV technology to become the least energy cost option (sub-chapter 3.3). Insights for utility-scale PV power plants (chapters 6 and 7) substantiate arguments for the least cost pathway, now on a par with wind power plants and hydro power plants (sub-chapters 4.2 and 7.1). Moreover, global electricity supply potential of both solar and wind power exceeds human demand by at least a factor of 20 (sub-chapter 7.3).^{25,26,27} Consequently, it is very likely that mid 21st century will be dominated by solar PV (chapters 3, 4, 6 and 7), wind power (sub-chapters 4.2, 4.3, 7.3 and 7.4) and supported by hydro power (sub-chapter 7.1), which might be complemented by solar thermal electricity generation (STEG) power plants (sub-chapters 4.1 and 7.2).^{28,29,30,31,32,33,34}

¹⁴ IEA-PVPS, Trends in PV Applications: Survey report of selected IEA countries between 1992 and 2008, 2009

¹⁵ Swanson R.M., A vision for crystalline silicon photovoltaics, 2006

¹⁶ Staffhorst M., The Way to Competitiveness of PV – An Experience Curve and Break-even Analysis, 2006

¹⁷ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

¹⁸ Jäger-Waldau A., PV Status Report 2004, 2004

¹⁹ Jäger-Waldau A., PV Status Report 2008, 2008

²⁰ Sandén B.A., The economic and institutional rationale of PV subsidies, 2005

²¹ NREL, PV Module Production Experience (or “Learning”) Curve, 2005

²² Schindler R., Towards Green Energy: Challenges and Options, 2010

²³ IEA-PVPS, Trends in PV Applications: Survey report of selected IEA countries between 1992 and 2009, 2010

²⁴ Breyer Ch. et al., Electrifying the Poor: Highly economic off-grid PV Systems in Ethiopia – A Basis for sustainable rural Development, 2009a

²⁵ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

²⁶ Schmid J. et al., Energiekonzept 2050: Eine Vision für ein nachhaltiges Energiekonzept auf Basis von Energieeffizienz und 100% erneuerbaren Energien, 2010

²⁷ Jacobson M.Z. and Delucchi M.A., Providing all global energy with wind, water, and solar power, 2011

²⁸ Pietzcker R. et al., The Role of Concentrating Solar Power and Photovoltaics for Climate Protection, 2009

²⁹ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

³⁰ Trieb F. et al., Global Potential of Concentrating Solar Power, 2009

³¹ Trieb F. et al., Financing concentrating solar power in the Middle East and North Africa – Subsidy or investment?, 2010

³² Kohn W., A world powered predominantly by solar and wind energy, 2010, p. 263-270

³³ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010, p. 47-63

³⁴ Jacobson M.Z. and Delucchi M.A., Providing all global energy with wind, water, and solar power, 2011

3.1.1.2 Photovoltaic Growth Rates

Growth rates of worldwide PV installations have been on a constant high level of 45% in the last 15 years (Fig. 3.1-1). Compared to industries of similar preconditions growth rates of worldwide PV installations are outstanding. Benchmarking industries are for example wind power, mobile phones and crude oil. In the end all these three industries offer commodity like products, due to respective standardization and modularity. In particular, wind power and mobile phones show this modular characteristic. Modularity and scalability might be one of the greatest advantages of PV, as solar cells can be used for both 10 Wp solar home systems and up to multi hundred MWp PV power plants. Furthermore a substituting effect can be expected for a demand of already existing and served needs, i.e. electricity and fixed line telecommunication.

All three industries, wind power, mobile phones and crude oil, need a capital intensive infrastructure for their products and serve existing needs and demand of customers. All this is also true for PV. Wind power and mobile phone industry generate their growth by increasing production volumes at stable or decreasing prices. Metric is set to be the sales volume due to the fact that scaling effects are used to reduce the costs and standardize the production which opens new markets. Global crude oil production seems to be on its top of historically Gaussian production profile (section 1.3.1), whereas a dramatic increase in price led to a significant growth rate in sales. For smoothening spikes of single years in this mid- to long-term consideration a five year average growth rate was taken into account (Fig. 3.1-2). Remarkably, a preliminary study revealed no single industry since industrial revolution achieving such high growth rates on global scale over more than one to two decades, like PV. The author of this thesis encourages other scientists on discussions on this topic due to its outstanding uniqueness.

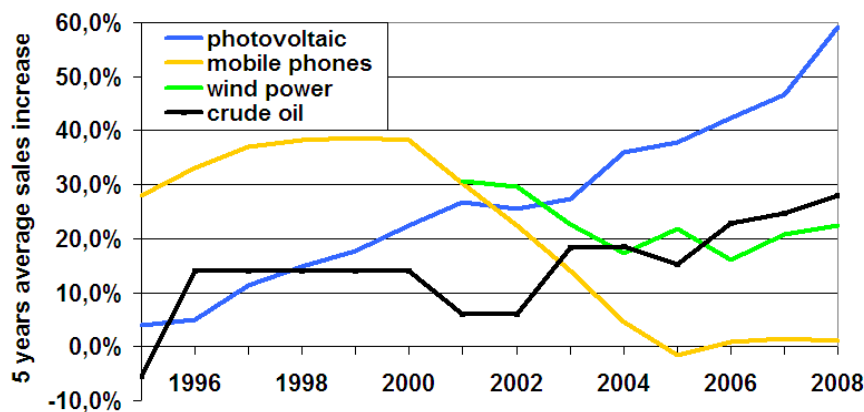


Figure 3.1-2: Growth rates of PV and comparable industries. Data are shown in a five years average for smoothening spikes of single years. Differences in growth rates to Figure 3.1-1, scaled in power units, are due to price effects. Data are taken from EPIA ³⁵, IEA-PVPS ³⁶, Photon Consulting ³⁷, GWEC ³⁸, Nokia ³⁹ and BP ⁴⁰.

For PV it will take a long time to reach fundamental growth limits (section 3.1.1.3) as the

³⁵ EPIA, Solar Generation V: Solar electricity for over one billion people and two million jobs by 2020, 2008

³⁶ IEA-PVPS, Trends in PV Applications: Survey report of selected IEA countries between 1992 and 2006, 2007

³⁷ Rogol M. et al., Solar Annual 2008: Four Peaks, 2008

³⁸ GWEC, Global Wind 2008 Report, 2009

³⁹ Nokia, Annual Reports 1994 - 2008, 2009

⁴⁰ BP, BP Statistical Review of World Energy, 2009

energy market is the largest market in the world at all, accounting for about 8,700 bn€ of annual sales ⁴¹. Moreover, there are tremendous needs to establish a sustainable energy industry as almost 90% of global energy market is structural not sustainable, either due to diminishing resources (crude oil, natural gas, uranium), climate change restrictions (coal, crude oil, natural gas) or severe lasting security problems (nuclear power) ^{42,43} (sub-chapters 1.2, 1.3 and 1.5). Need for a sustainable energy supply is greater than ever in history.

Structural characteristics of renewable energy technologies fit well to fundamental requirements of energy technologies in the 21st century: low greenhouse gas (GHG) emissions, high energy yield factors for a fast substitution of today's not sustainable technologies, i.e. short energy payback times (EPBT), and pathways to reach a sustainable low cost level. PV well fulfils these requirements: GHG emissions are between 12 – 42 gCO_{2eq}/kWh (section 3.1.7.1), energy yield factors are between 16 – 50 due to a EPBT of 0.8 to 2.5 years (section 3.1.6) and fast declining LCOE (sub-chapters 3.2 to 3.4 and chapters 6 and 7).

Remarkably, fundamental growth limits are still outstandingly far away for PV embedded in respective local and global electricity systems. For PV it will take a long time to reach these limits which are estimated to be at least between 1,500 and 12,000 GWp total installed capacity within the next four decades and depending on economically available storage solutions and global wealth convergence (section 3.1.1.3). There are several studies outlining technologically and economically feasible pathways for a PV share in local, nationwide, continental and even global electricity systems of 25% up to 100%. ^{44,45,46,47,48,49,50,51,52,53} The author of this thesis was involved in an estimate of overall energy supply potential of solar power ⁵⁴, which was calculated for solar thermal electricity power generation (STEG), but due to nearly identical overall land use efficiencies it can be transferred to PV and by applying the storage assumptions of Denholm and Margolis ⁵⁵ and Zweibel et al. ⁵⁶ it would be possible to entirely transfer the outcome to PV. By using only sites of very good solar resource conditions the power demand and total energy demand of 12 billion people consuming energy on the current European energetic wealth level could be fulfilled by a

⁴¹ Hartmann A. and Huhn W., (eds.), Wettbewerbsfaktor Energie: Neue Chancen für die deutsche Wirtschaft, 2009

⁴² Meyer B. et al., Staatliche Förderung der Atomenergie, 2009

⁴³ Barnaby F. and Kemp J., (eds.), Secure Energy? – Civil Nuclear Power, Security and Global Warming, 2007

⁴⁴ Zweibel K. et al., A solar grand plan, 2008

⁴⁵ Mason J. et al., Coupling PV and CAES Power Plants to Transform Intermittent PV Electricity into a Dispatchable Electricity Source, 2008

⁴⁶ Denholm P. and Margolis R.M., Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies, 2007

⁴⁷ Braun M. et al., Value of PV Energy in Germany - Benefit from the Substitution of Conventional Power Plants and Local Power Generation, 2008

⁴⁸ Quaschnig V., Bewertung von Methoden zur Bestimmung des PV-Anteils sowie von Ausbauszenarien und Einflüssen auf die Elektrizitätswirtschaft, 2011

⁴⁹ Mackensen R. et al., No limits for a full electricity supply by renewables, 2008

⁵⁰ Hoffmann C. et al., Design of transport and storage capacities for a future European power supply system with a high share of renewable energies, 2008

⁵¹ WWF, The Energy Report: 100% Renewable Energy by 2050, 2011

⁵² Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

⁵³ Jacobson M.Z. and Delucchi M.A., Providing all global energy with wind, water, and solar power, 2011

⁵⁴ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

⁵⁵ Denholm P. and Margolis R.M., Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies, 2007

⁵⁶ Zweibel K. et al., A solar grand plan, 2008

factor of 125 and 18, respectively, representing only 0.8% and 5.6% of available area.⁵⁷ The energy supply potential of PV is even higher, since regions of moderate solar resources become additionally accessible.

Growth rates of PV seem not to be limited for at least the next one to two decades. The assumption in this thesis of an average annual 30% growth rate of PV industry in the scenario period of 2010 to 2020 is considered to be conservative. Annual growth trend for the last 15 years has been 45% (Fig. 3.1-1). Probably, growth rates could be even higher or started earlier being higher if public research and development (R&D) support anticipated the true potential of PV (section 3.1.3). Statistics of public energy R&D budgets of the last three decades reveal a dramatic misallocation of scarce public financial resources in respect to requirements of energy technologies in the 21st century (section 3.1.3). Nevertheless, consensus of scientific researchers and financial analysts is a growth rate of about 30%.^{58,59,60,61,62,63,64,65} However, it has been very common to underestimate both near and long-term growth rates of PV⁶⁶, as it could be in this thesis.

3.1.1.3 Global Photovoltaic Market Potential Estimate

A rough estimate of global PV energy supply potential may emphasize the high probability of substantial further PV industry growth. In 2008 global electricity generation has been about 20,200 TWh⁶⁷ and global power plant capacity in operation has been about 4,600 GW in spring 2009, whereas annual new power plant capacity has been about 150 GW in late 2000s⁶⁸ (chapter 5). Studies confirmed a 10% PV electricity supply potential at very low or at least manageable additional electricity grid investments.⁶⁹ This has already been confirmed in practice, as one of the global leading distribution service operators concerning local PV grid integration, disclosed respective numbers.⁷⁰ Finalised investments on the low and medium voltage level in 2010 enabled this grid in South Germany to provide about 8% of local power demand by decentralised PV systems in terms of energy units. The cost are comparable to about 0.1 – 0.2 €/kWh per feed-in PV electricity over a 30 years lifetime or 0.02 – 0.03 €/Wp representing about 0.8% - 1.5% of PV Capex.⁷¹ Solar irradiation at optimally fixed-tilted module surface is about 1,700 and 1,850 kWh/m²/y for electricity generation and population weighted global average, respectively (sub-chapter 2.3). Hence, today's

⁵⁷ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

⁵⁸ EPIA, Global Market Outlook for Photovoltaics until 2014, 2010

⁵⁹ IEA, Technology Roadmap: Solar photovoltaic Energy, 2010

⁶⁰ Bumm P., Solar Power, 2010

⁶¹ O'Rourke S. et al., Solar Photovoltaic Industry 2010 global outlook Déjà vu?, 2010

⁶² Shah V. et al., Solar-Investor Guide 2010, 2010

⁶³ Krewitt W. et al. Globale Energieszenarien - Bedeutung der Erneuerbaren Energien und der Energieeffizienz, 2008

⁶⁴ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

⁶⁵ Mints P., First Markets and Applications for OPV, 2009

⁶⁶ Gredler C., Das Wachstumspotenzial der Photovoltaik und der Windkraft – divergierende Wahrnehmungen zentraler Akteure, 2008

⁶⁷ IEA, World Energy Outlook 2010, p. 620

⁶⁸ Platts, UDI World Electric Power Plants data base, 2009

⁶⁹ Braun M. et al., Value of PV Energy in Germany - Benefit from the Substitution of Conventional Power Plants and Local Power Generation, 2008

⁷⁰ Schwaegerl P. and Albrecht W., Solar impact on distribution grids – from the point of view of a southern German Distribution System Operator, 2011

⁷¹ Schwaegerl P. and Albrecht W., Solar impact on distribution grids – from the point of view of a southern German Distribution System Operator, 2011

technological total addressable global PV market volume is about 1,500 GWp, applying a global weighted PV performance ratio of 77% and electricity generation weighted global average irradiation. In the year 2000 average electricity needs had been 2.7 and 6.7 MWh_{el}/capita in the world and in Europe, respectively⁷². World population is assumed to grow from current 7.0 to 8.0 and 9.1 billion people in 2025 and 2050, respectively.⁷³ Therefore, global annual electricity generation might grow up to 60,000 TWh_{el}, assuming wealth convergence in the world and constant electricity efficiency improvements, which are likely to be compensated by increasing demand due to modal energy shifts, like electric vehicles. Increase in world population, and convergence of global wealth might allow for addressing a global total PV market volume of about 4,200 GWp by applying global population weighted irradiation at fixed optimally tilted module surface. Last but not least, sophisticated storage solutions might significantly increase global PV penetration level from 10% to 30%, or even more.^{74,75} A technical and economic feasible availability of storage solutions could multiply today's and mid century's PV market potential to about 4,500 and 12,000 GWp total global installed capacity. This order of magnitude is confirmed by the WWF Energy Report resulting in about 10,300 GWp installed PV capacity by 2050.⁷⁶ However, the IEA expects an increase in total installed PV capacity of about 210, 870, 2,020 and 3,160 GWp for the years 2020, 2030, 2040 and 2050, respectively.⁷⁷ This is a substantial confirmation of enormous PV market potential, since IEA has always underestimated PV diffusion to a very large extent in last decades.⁷⁸

Fundamental growth barriers are not existent, as energy pay back times and specific emissions for PV technologies are already low and still declining (sections 3.1.6 and 3.1.7), no rare materials are needed (at least for today's available back contact silicon solar cell technology), fundamental economics are excellent (sub-chapters 3.3 and 3.4 and chapters 6 and 7) and overall technological complexity for end-users is rather low⁷⁹. This early estimate of fundamental PV market potential is complemented by a significantly more precise economic PV market potential estimate for the year 2020 based on key results of this thesis and summarized in sub-chapter 6.6.

3.1.2 Experience Curve Concept

Solar PV is very modular and can be used in all power ranges from pocket calculators to power plants with several hundreds of megawatt. It is a semiconductor technology, which is highly influenced by surface and area related technologies and can work without any moving parts. This is a unique characteristic among all energy technologies and might be the fundamental reason for outstanding high and long-term cost reduction, which has been stable for the last four decades (Fig. 3.1-3) documented on a very good data basis, whereas strong

⁷² Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

⁷³ UN, World Population Prospects: The 2008 Revision Highlights, 2009

⁷⁴ Hoffmann C. et al., Design of transport and storage capacities for a future European power supply system with a high share of renewable energies, 2008

⁷⁵ Denholm P. and Margolis R.M., Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies, 2007

⁷⁶ WWF, The Energy Report: 100% Renewable Energy by 2050, 2011

⁷⁷ IEA, Technology Roadmap: Solar photovoltaic Energy, 2010

⁷⁸ Gredler C., Das Wachstumspotenzial der Photovoltaik und der Windkraft – divergierende Wahrnehmungen zentraler Akteure, 2008

⁷⁹ Breyer Ch. et al., Electrifying the Poor: Highly economic off-grid PV Systems in Ethiopia – A Basis for sustainable rural Development, 2009a

indication is given that this trend is stable for even nearly six decades^{80,81}. Furthermore, specific cost per power of PV can be steadily lowered as a consequence of continued increase in conversion efficiency of solar irradiation to electricity.⁸² One of the key levers of cost reduction is the power conversion efficiency of the solar cells. Its improvements give automatically savings all along the value chain from semiconductor ores to PV systems. An overview on the currently best solar cell and module efficiency records is given by Green et al.⁸³ and can be understood as near to mid-term upper limit for industrial solar cell production (Fig. 3.1-25), whereas the ultimate limit as a consequence of fundamental physics is far away⁸⁴ and gives room for many further discoveries, inventions and finally improved technological and economic performance of solar PV technology.

Analyses of technological change have identified patterns in the ways that technologies are invented, improved and diffuse into society. Studies have described the complex nature of the innovation process in which uncertainty is inherent, knowledge flows across sectors are important, and lags can be long. Perhaps because of characteristics such as these, theoretical work on innovation provides only a limited set of methods with which to predict changes in technology. The learning or experience curve model offers an exception.⁸⁵

Generally, industrial cost reduction follows the empirical law of learning curves, first found in the aviation industry in the 1930s⁸⁶ and shipbuilding industry in the 1950s⁸⁷ and later transferred to many other industries⁸⁸. The learning curve originates from observations that workers in manufacturing plants become more efficient as they produce more units. In its original conception, the learning curve referred to the changes in the productivity of labour which were enabled by the experience of cumulative production within a manufacturing plant. The experience curve approach was further developed to provide a more general formulation of the concept, including not just labour but all manufacturing costs and aggregating entire industries rather than single plants.⁸⁹ A good overview on experience curves in general and PV in particular is given by Nemet⁹⁰ and Swanson⁹¹.

The experience curve approach is an empirical law of cost reduction in industries⁹². It was observed that per each doubling of cumulated output the specific cost decrease by a nearly stable percentage (Eqs. 3.1-1). This stable cost reduction is defined as learning or experience rate. For use in calculations, the progress ratio is introduced, which is defined as unity minus learning rate.

$$c_x = c_0 \cdot \left(\frac{P_x}{P_0} \right)^{\frac{\log \text{progress ratio}}{\log 2}} \quad (\text{Eq. 3.1-1a})$$

⁸⁰ Kersten F. et al., PV-Learning Curves: Past and Future Drivers of Cost Reduction, 2011

⁸¹ Cherry W., Military considerations for a photovoltaic solar energy converter, 1955

⁸² Kazmerski L., NREL compilation of best research solar cell efficiencies, 2010

⁸³ Green M.A. et al., Solar cell efficiency tables (version 37), 2011

⁸⁴ Marti A. and Araujo G.L., Limiting efficiencies for photovoltaic energy conversion in multigap systems, 1996

⁸⁵ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

⁸⁶ Wright T.P., Factors Affecting the Cost of Airplanes, 1936

⁸⁷ Rapping L., Learning and World War II Production Functions, 1965

⁸⁸ BCG, Perspectives on experience, 1972

⁸⁹ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

⁹⁰ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

⁹¹ Swanson R.M., A vision for crystalline silicon photovoltaics, 2006

⁹² BCG, Perspectives on experience, 1972

$$P_x = \sum_{t=0}^T P_t \quad (\text{Eq. 3.1-1b})$$

$$P_t = P_{t-1} \cdot (1 + GR_t) \quad \text{for } t \geq 1 \quad (\text{Eq. 3.1-1c})$$

$$P_x = P_0 \cdot \prod_{t=0}^T (1 + GR_t) \quad (\text{Eq. 3.1-1d})$$

$$c_x(T, GR, LR) = c_0 \cdot (1 + GR)^{T \cdot \frac{\log(1-LR)}{\log 2}} \quad (\text{Eq. 3.1-1e})$$

$$T(c_x, GR, LR) = \frac{\log 2}{\log(1-LR) \cdot \log(1+GR)} \cdot \log\left(\frac{c_x}{c_0}\right) \quad (\text{Eq. 3.1-1f})$$

Equation 3.1-1: Empirical law of experience curves. Abbreviations stand for: cost at historically cumulated output level of P_x (c_x), cost at initial output level P_0 (c_0), historically cumulated output level (P_x), initial output level (P_0), unity minus learning rate (LR) defined as (*progress ratio*), annual production of a specific year (P_t), and growth rate of a specific year (GR_t). Equations 3.1-1b and 3.1-1d are equivalent. In this thesis the variables *Capex* and c_x are identical and describe the specific investment cost in a PV system in cost/Wp. Combination of Equations 3.1-1a and 3.1-1d effectively transforms the cost function from production volume dependence to time dependence, which is often more convenient for scenario analyses and derived for constant GR in Equation 3.1-1e. For analysing time periods (T) in dependence of c_x , constant GR and LR Equation 3.1-1f can be derived by Equations 3.1-1a and 3.1-1d.

Driving force for cost reduction is the growth rate and the learning rate. Both parameters are very high for PV, i.e. growth rates above 30% (Fig. 3.1-1 and 3.1-2) and learning rates at a constant level of 20% or slightly above (Fig. 3.1-3) for each doubling of historic cumulated installed capacity, confirmed by various authors and based on several datasets.^{93,94,95,96,97,98,99,100,101,102,103,104,105,106} All other energy technologies show either lower long-term growth rates or lower learning rates^{107,108,109} and typically both driving forces are lower. Historically, no energy technology showed such a high learning rate over such a long period of time.^{110,111} The high learning rate of PV is likely to be triggered by its core nature, i.e. aforementioned high modularity and its continuous production processes for most value chain steps, as industries characterized best by modular technologies or continuous processes show

⁹³ Swanson R.M., A vision for crystalline silicon photovoltaics, 2006

⁹⁴ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, p. 201-219

⁹⁵ Staffhorst M., The Way to Competitiveness of PV – An Experience Curve and Break-even Analysis, 2006

⁹⁶ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

⁹⁷ Nemet G.F., Interim monitoring of cost dynamics for publicly supported energy technologies, 2009

⁹⁸ Neij L., Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology, 1997

⁹⁹ Grübler A. et al., Dynamics of energy technologies and global change, 1999

¹⁰⁰ Zwaan v.d. B. and Rabl A., The learning potential of photovoltaics: implications for energy policy, 2004

¹⁰¹ Zwaan v.d. B. and Rabl A., Prospects for PV: a learning curve analysis, 2003

¹⁰² Christiansson L., Diffusion and Learning Curves of Renewable Energy Technologies, 1995

¹⁰³ McDonald A. and Schrattenholzer L., Learning rates for energy technologies, 2001

¹⁰⁴ Watanabe C. et al., Industrial dynamism and the creation of a “virtuous cycle” between R&D market growth and price reduction: The case of photovoltaic power generation (PV) development in Japan, 2000

¹⁰⁵ Schaeffer G.J. et al., Learning from the Sun, 2004

¹⁰⁶ Sark v.W.G.J.H.M. et al., Accuracy of Progress Ratios Determined From Experience Curves: The Case of Crystalline Silicon Photovoltaic Module Technology Development, 2008

¹⁰⁷ Nemet G.F., Interim monitoring of cost dynamics for publicly supported energy technologies, 2009

¹⁰⁸ McDonald A. and Schrattenholzer L., Learning rates for energy technologies, 2001

¹⁰⁹ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008, p. 201-219

¹¹⁰ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008

¹¹¹ Nemet G.F., Interim monitoring of cost dynamics for publicly supported energy technologies, 2009

learning rates of typically 20%.¹¹² Renewable energy technologies typically exhibit learning rates of about 10%, e.g. wind power and solar thermal power plants (STEGs).^{113,114,115} Even long-term negative learning rates are reported for nuclear power plants, i.e. every new power plant generation is more expensive per kW than the previous one.^{116,117}

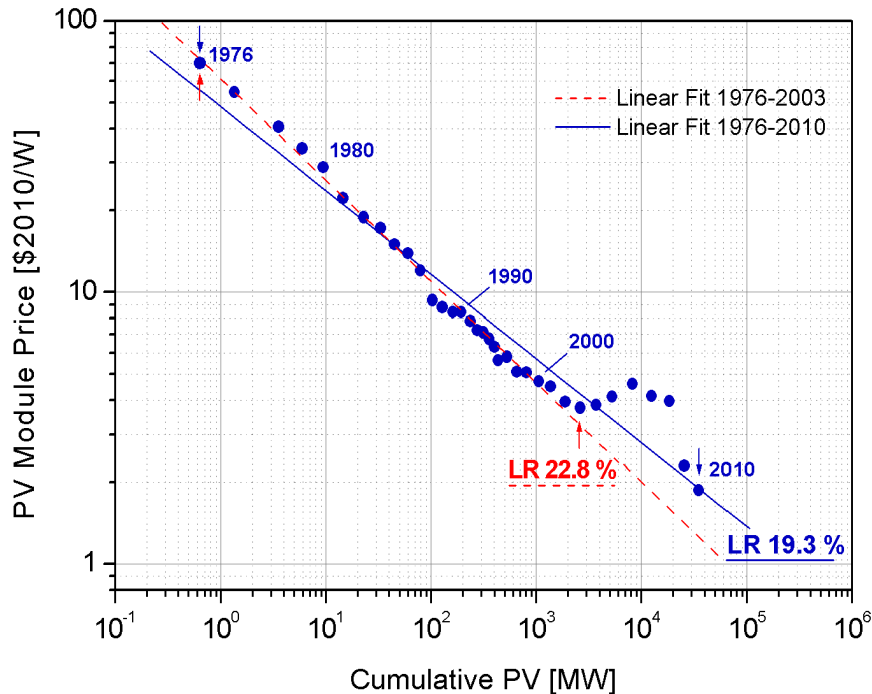


Figure 3.1-3: Learning curve for PV modules for the mid 1970s - 2010. Long-term cost trend of reducing PV module cost by 20% per doubling of historic cumulative average production and installations has been stable for the entire period. Best approximation for the cost is the price curve as information. Oscillations around this trend are mainly caused by varying PV industry market dynamics and therefore profit margins, documented by applying different learning rates of 22.8% and 19.3% for the periods 1976 – 2003 and 1976 – 2010, respectively. Data are taken from IEA-PVPS¹¹⁸, Swanson¹¹⁹, Staffhorst¹²⁰, Nemet¹²¹, Jäger-Waldau^{122,123}, Sandén¹²⁴, NREL¹²⁵ and Schindler¹²⁶.

PV learning curve characteristics are documented very well for the value chain steps from metallurgical Si or other semiconductor ores to PV modules. Key drivers for PV module cost

¹¹² Neij L., Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology, 1997

¹¹³ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008

¹¹⁴ Pitz-Paal R. et al., Ecostar – European Concentrated Solar Thermal Road-Mapping, 2004

¹¹⁵ Viebahn P. et al., The potential role of concentrated solar power (CSP) in Africa and Europe – A dynamic assessment of technology development cost development and life cycle inventories until 2050, 2010

¹¹⁶ Grubler A., The cost of the French nuclear scale-up: A case of negative learning by doing, 2010

¹¹⁷ Nemet G.F., Interim monitoring of cost dynamics for publicly supported energy technologies, 2009

¹¹⁸ IEA-PVPS, Trends in PV Applications: Survey report of selected IEA countries between 1992 and 2008, 2009

¹¹⁹ Swanson R.M., A vision for crystalline silicon photovoltaics, 2006

¹²⁰ Staffhorst M., The Way to Competitiveness of PV – An Experience Curve and Break-even Analysis, 2006

¹²¹ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

¹²² Jäger-Waldau A., PV Status Report 2004, 2004

¹²³ Jäger-Waldau A., PV Status Report 2008, 2008

¹²⁴ Sandén B.A., The economic and institutional rationale of PV subsidies, 2005

¹²⁵ NREL, PV Module Production Experience (or “Learning”) Curve, 2005

¹²⁶ Schindler R., Towards Green Energy: Challenges and Options, 2010

reduction in the years 1980 - 2001 had been increase of plant size (43%), module efficiency increase (30%), reduction of Si cost (12%) and increase of wafer size, reduction of Si use, increase of production yield, increase of mc-Si share and other factors (15%).¹²⁷ A few works also describe inverters, systems and the most relevant metric cost per generated energy.^{128,129,130,131,132,133,134} They generally confirm for entire PV systems a learning rate of 20% and an even higher learning rate for cost per energy, induced by increasing overall system efficiency and system availability. Even higher learning rates have been recorded for similar technologies: as a long-term trend for DRAM memory chips and flat panel displays learning rates of 40% and 35%, respectively.¹³⁵ Comparison to solar PV is quite interesting due to the fact that both technologies are semiconductor based, identical to PV, but DRAMs getting cheaper by increasing integration density of transistors while displays getting cheaper by increasing production area. The first cost reduction strategy is not possible for PV, except high concentrating PV (HCPV), whereas generating scaling effects by increasing area might also be a valuable pathway for further cost reductions in PV and have already been applied in last decades.¹³⁶ Fundamental differences in cost structures of displays and PV systems should be better analysed due to a nearly twofold higher learning rate for displays than for PV.

In many industries it was observed that as a function of cumulative production the learning rates declined and showed a more flattening characteristic which is a consequence of ultimate floor cost of a fully optimized product.¹³⁷ Nevertheless, until now this has not been observed in PV industry. Authors not fully aware of current and future potentials of PV cost structure usually assume much too high PV floor cost, i.e. lowest future possible cost for PV technology, e.g. recently published PV system floor cost assumption of 2.1 €/Wp for the year 2100.¹³⁸ Even today reality has already reached lower levels and cost might decline drastically in the decades to come. Leading PV experts estimate the achievable long-term cost potential for PV module technology and respective industry below 0.30 USD/Wp¹³⁹, Pietzcker et al. expect PV system floor cost, i.e. long-term cost level, of 0.60 USD/Wp¹⁴⁰ and leading European PV decision makers expect a long-term price level of 0.50 €/Wp¹⁴¹. Currently, lowest manufacturing cost of PV modules are 0.74 USD/Wp and are achieved by cadmium telluride (CdTe) PV company First Solar¹⁴² and lowest cost for c-Si modules is about 0.81 €/Wp¹⁴³. Lowest possible today's PV power plant system costs are about 1.5 – 1.6 €/Wp, including all manufacturing, sales, general administration and research cost, excluding cost for debt, equity and value chain inefficiencies, which can be achieved for both

¹²⁷ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

¹²⁸ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, p. 201-219

¹²⁹ Staffhorst M., The Way to Competitiveness of PV – An Experience Curve and Break-even Analysis, 2006

¹³⁰ Meinhardt M. et al., PV-Systemtechnik – Motor der Kostenreduktion für die Photovoltaische Stromerzeugung, 2007

¹³¹ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

¹³² Schaeffer G.J. et al., Learning from the Sun, 2004

¹³³ Kersten F. et al., PV-Learning Curves: Past and Future Drivers of Cost Reduction, 2011

¹³⁴ Kersten F., Photovoltaik-Lernkurve auf Systemebene und Analyse zukünftiger Kostensenkungspotentiale, 2011

¹³⁵ Hoffmann W. et al., Differentiated Price Experience Curves as Evaluation Tool for Judging the further Development of Crystalline Silicon and Thin Film PV Solar Electricity Products, 2009

¹³⁶ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

¹³⁷ Yelle L.E., The learning curve: historical review and comprehensive survey, 1979

¹³⁸ Rout U.K. et al., Uncertainty in the learning rates of energy technologies: An experiment in a global multi-regional energy system model, 2009

¹³⁹ Curtright A.E. et al., Expert Assessments of Future Photovoltaic Technologies, 2008

¹⁴⁰ Pietzcker R. et al., The Role of Concentrating Solar Power and Photovoltaics for Climate Protection, 2009

¹⁴¹ EU PV Technology Platform, A Strategic Research Agenda for Photovoltaic Solar Energy Technology, 2007

¹⁴² First Solar, Q2 2010 Earnings Call, 2010

¹⁴³ Fath P., Fully-integrated c-Si module production towards 0.60 €/Wp, 2011

CdTe PV and crystalline silicon PV technology.¹⁴⁴

Following sections analyse public and corporate PV R&D investment which had enabled the fast diffusion of PV in the past and lay the basis for ongoing high and fast cost reduction.

3.1.3 Research and Development Investments

In this section it is presented a detailed analysis of research and development (R&D) investments in solar PV based on historic PV deployment (section 3.1.1) and cost basis (section 3.1.2) which was partly induced by public R&D investment (section 3.1.3.1). In the last decade companies earned financial resources via PV roof-top programmes and feed-in tariffs (FiT), and have been investing significant resources in corporate R&D (section 3.1.3.2). Technological progress introduced to markets is protected by patents, which can be used as long-term indicator for analysing R&D activities (section 3.1.3.3). Major results of this R&D analysis need to be assessed in relation to current public energy R&D investments, other sources of energy and R&D investments of other industries (section 3.1.3.4). Main scientific question is the best possible understanding of the stability of mid-term learning rates being very decisive for most of the cost projections in this thesis.

3.1.3.1 Public R&D Investments

Public energy R&D investments in OECD countries (section 3.1.3.1.1) substantially grew in late 1970s as a consequence of oil-price crises and declined in early 1980s due to low oil prices and market liberalizations. This up-turn and in particular down-turn in public energy R&D investments had been even more dramatic consequences for public renewable energy R&D investments (section 3.1.3.1.2). These major trends are documented best by respective speeches of US Presidents Jimmy Carter¹⁴⁵ and Ronald Reagan¹⁴⁶. Discussion on public PV R&D investments in EU and Germany can be found elsewhere¹⁴⁷.

3.1.3.1.1 Energy R&D Investments

In 1979 Carter started to establish a large US PV industry in response to energy insecurity induced by oil price crises and after the US peak-oil event in 1971 as an inexpensive strategy for sustainable national security.^{148,149} Carter's solar energy pathway was flanked by a massive public PV R&D programme reflected in the worldwide energy R&D investments (Fig. 3.1-4 to 3.1-6). Nevertheless, Reagan administration decided already a few years later to stop investments in renewable energy sources (RES) and started to divert substantial financial resources in US military in response to cold war competition and to have flexible and powerful military forces, also available for securing fossil energy supply. However, this reliance has led to such military interventions as the ones in the Persian gulf, mainly induced by significant dependence on imports of respective energy resources, and in total the military

¹⁴⁴ Breyer Ch., How favourable is PV?, 2010a

¹⁴⁵ Carter J., Solar Energy: Proposals for a National Solar Energy Strategy, 1979

¹⁴⁶ Reagan R., Program for Economic Recovery, 1981

¹⁴⁷ Breyer Ch. et al., R&D Investments in PV – A limiting Factor for a fast PV Diffusion?, 2010c

¹⁴⁸ Carter J., Solar Energy: Proposals for a National Solar Energy Strategy, 1979

¹⁴⁹ Clark W. (ed.), Dispersed, decentralized and renewable energy sources: Alternatives to national vulnerability and war, 1980

investments led to cumulated capital investments in military of about 6,800 bnUSD for the period 1976 – 2007.¹⁵⁰

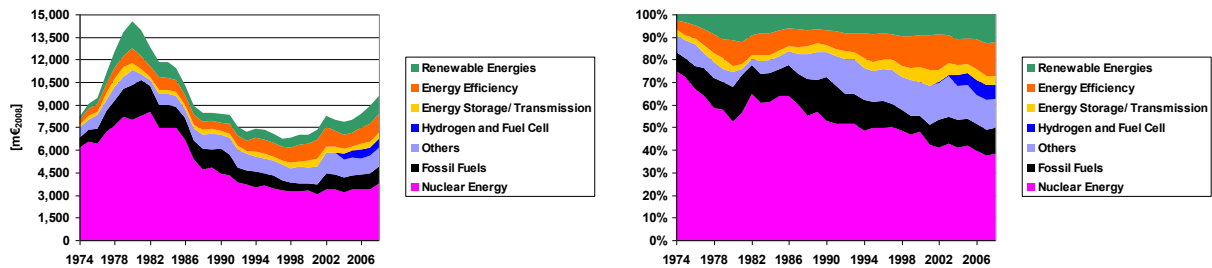
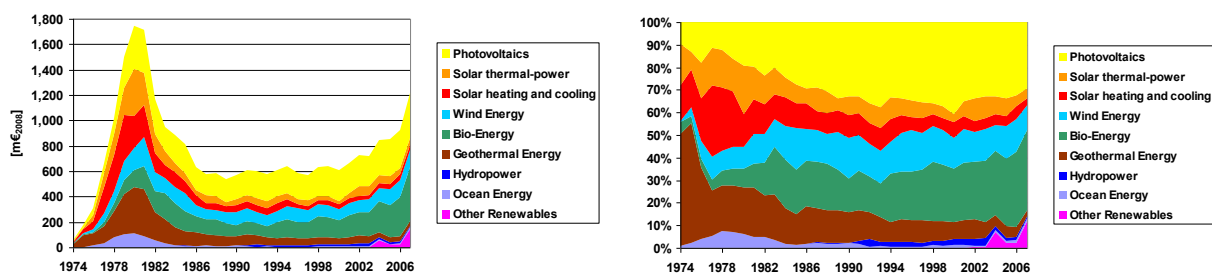


Figure 3.1-4: Public energy R&D investments in OECD for the years 1974 – 2008 in absolute (left) and relative (right) numbers. Substantial public R&D investments due to oil price crises in late 1970s were superseded by a constant decline in public energy R&D investments. Even until today, R&D expenses are below the early peak, despite of increasing demand for sustainable energy solutions. The fraction of nuclear energy in relation to RES does not reflect respective potentials. Data are taken from IEA.¹⁵¹

Today's public energy R&D investments are still below maximum investments of the early energy crises (Fig. 3.1-4), despite of pressing climate change issues, diminishing fossil and nuclear energy resources and enormous energy injustice in large parts of the world (sub-chapters 1.2 to 1.5). Energy technologies matching sustainability criteria are funded by significantly less than 50% of overall public energy R&D investments. Massive public investments are absorbed by nuclear energy, despite of multiple, yet unsolved drawbacks over decades and the small global supply share of nuclear energy of less than 6% in primary energy demand¹⁵². Global public energy R&D investments are expected to be only 10% - 15% higher than those of all OECD countries, as about 90% of all global R&D investments are funded by OECD member states¹⁵³.

3.1.3.1.2 Renewable Energy R&D Investments

Only a very low fraction of about 10% of overall energy R&D investments is spent for RES and as part of that for PV (Fig. 3.1.-4 and 3.1-5). A very steep increase in RES R&D in late 1970s due to Carter's policies was superseded by a dramatic decline in public RES R&D in early 1980s, which has never been reversed. Relative investments in major RES technologies show a significant misbalance, due to extremely low investments in STEG and low investments in wind power technology. Despite of low absolute public PV R&D investment, relative fraction of PV has been between 20% - 35% of public RES R&D investments.



¹⁵⁰ Stern R.J., United States cost of military force projection in the Persian Gulf 1976 – 2007, 2010

¹⁵¹ IEA, Energy Technology RD&D Budgets in OECD, 2009

¹⁵² IEA, World Energy Outlook 2010, p. 618

¹⁵³ UN, Statistical Yearbook 52nd issue, 2008

Figure 3.1-5: Public R&D investments of OECD in RES for the years 1974 – 2008 in absolute (top) and relative (bottom) numbers. In early 1980s a steep decline in public RES R&D investments by more than 50% has led to stagnating budgets until late 1990s and peak investments of early 1980s have never been reached again. Data are taken from IEA.¹⁵⁴

Annual public R&D investments in PV only have never exceeded 400 m€ in OECD countries and historic cumulated public R&D investments have been below 8 bn€ (Fig. 3.1-6). Only three countries, the US, Japan and Germany have funded more than 80% of all public PV R&D investments in OECD. For the years 1974 - 2008 cumulated R&D investments have been 2.7 bn€ (STEGs), 3.5 bn€ (wind power), 12.7 bn€ (all other RES), and 173.9 bn€ (nuclear energy). OECD nuclear energy R&D investments have been 24.3 and 6.7 times higher than for PV and all RES together, respectively.

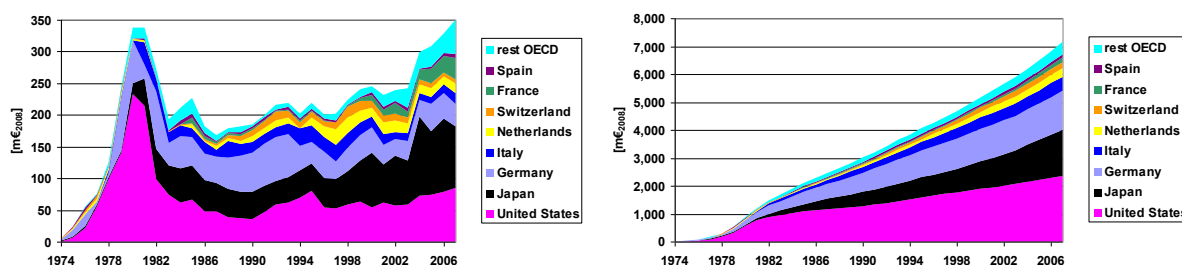


Figure 3.1-6: Annual (left) and historic cumulated (right) public R&D investments of OECD in PV for the years 1974 – 2008. In early 1980s a steep decline in public PV R&D investments by more than 40% has led to stagnating budgets until late 1990s. Peak investments of early 1980s have been reached again only since 2007. Cumulated public PV R&D investments in OECD are below 8 bn€ in the period 1974 – 2007, and have been funded to more than 80% by the US, Japan and Germany. Data are taken from IEA.¹⁵⁵

The International Energy Agency estimates 2009 solar energy R&D spendings of 20.3 m€ (China), 14.3 m€ (India), and 4.8 m€ (Russia).¹⁵⁶ These investments include solar PV, STEG and solar heating. Therefore, PV R&D investment of non-OECD countries can be estimated to be about 10% – 20% of OECD values, resulting in current global public PV R&D investments of about 500 m€ per annum.

Lack of data in IEA dataset for the years before mid 1970s cause some uncertainties about early market introduction cost of PV. In 1972 and 1973 US federal research on terrestrial PV applications was funded at less than 1 mUSD a year.¹⁵⁷ In the years 1950 – 1970 federal support for terrestrial PV was about 0.1 mUSD a year.¹⁵⁸ Even the US solar PV space R&D programme cost only 50 mUSD in the period 1958 – 1969.¹⁵⁹ These public investments are in 2009 currency value ¹⁶⁰ 346 mUSD (space R&D in 1958 – 1969), 15 mUSD (terrestrial PV in 1950 – 1970) and 10 mUSD (terrestrial PV in 1972/1973). Assuming that US PV R&D in these early days accounted for a third of global public PV R&D, one can estimate the global public cumulated PV R&D investments before mid 1970s to about 800 m€, which is fully commercially backed by PV as least cost energy supply in space.

¹⁵⁴ IEA, Energy Technology RD&D Budgets in OECD, 2009

¹⁵⁵ IEA, Energy Technology RD&D Budgets in OECD, 2009

¹⁵⁶ IEA, Global Gaps in Clean Energy Research Development and Demonstration, 2009

¹⁵⁷ Pegram W.M., The Photovoltaics Commercialization Program, 1991, pp. 321-363

¹⁵⁸ Pegram W.M., The Photovoltaics Commercialization Program, 1991, pp. 321-363

¹⁵⁹ Perlín J., From Space to Earth – The Story of Solar Electricity, 1999, p. 50

¹⁶⁰ OECD, Price indices (MEI), 2010

All significant investments before the mid 1970s can be estimated to about 800 m€, historic cumulated public PV R&D investments in OECD countries since 1974 have been 7.2 bn€ and OECD R&D investments represent about 90% of global R&D investment ¹⁶¹ and to a high probability 85% – 90% of global PV R&D investments. Thus, global historic cumulated public PV R&D investment is very likely to be about 9 bn€.

Solar and wind power have the potential to provide more than 50% of total energy supply in the world by 2050, which is possible without nuclear energy.¹⁶² Moreover, there are tremendous needs to establish a sustainable energy industry as almost 90% of global energy market is structural not sustainable, either due to diminishing resources (crude oil, natural gas, uranium), climate change restrictions (coal, crude oil, natural gas) or severe lasting security problems (nuclear power) (sub-chapters 1.2 and 1.3). Need for sustainable energy supply is greater than ever in history.

Thus, historic public energy R&D investments do not reflect a structural need for sustainable energy supply. This dramatic historic policy failure has to be rated as one of the most severe hurdles for surviving the interaction of climate change, diminishing fossil energy resources, energy insecurity and energy injustice our technological civilization is confronted with.

3.1.3.2 Corporate PV R&D Investments

Besides public PV R&D investments the corporate PV R&D investments have not yet been analysed in much detail. For best estimating these R&D investments the companies are separated in two groups, the public listed PV companies (section 3.1.3.2.1) and the companies without disclosed PV R&D financials (section 3.1.3.2.2). On basis of these analyses the current global corporate PV R&D investments can be estimated (section 3.1.3.2.3).

3.1.3.2.1 PV R&D Investments of Public Listed PV Focussed Companies

PV sceptics often claim that PV industry does not invest significant resources in R&D and new PV technologies, but would sell old PV technologies.^{163,164} This is partly due to a lack of significant global data for corporate PV R&D, e.g. documented by European Commission ¹⁶⁵ and International Energy Agency ¹⁶⁶. Therefore, several hundred annual reports of PV companies are analysed: for 45 public listed companies their R&D activities are summarized in Table 3.1-1 for the years 2003 – 2009, if available, and for further 62 companies with PV activities best possible estimates have been calculated and summarized in Table 3.1-2. These estimates are based on sales, general R&D investments, typical relative R&D investment for respective PV value chain companies, R&D headcount and PV patents.

¹⁶¹ UN, Statistical Yearbook 52nd issue, 2008

¹⁶² Schmid J. et al., Energiekonzept 2050: Eine Vision für ein nachhaltiges Energiekonzept auf Basis von Energieeffizienz und 100% erneuerbaren Energien, 2010

¹⁶³ Frondel M. et al., Economic impacts from the promotion of renewable energy technologies: The German experience, 2010

¹⁶⁴ DPG-AKE, Elektrizität: Schlüssel zu einem nachhaltigen und klimaverträglichen Energiesystem, 2010, pp. 95-103

¹⁶⁵ EC, R&D Investment in the Priority Technologies of the European Strategic Energy Technology Plan, 2009

¹⁶⁶ IEA, Technology Roadmap: Solar photovoltaic energy, 2010

Companies focussed on PV and listed at stock markets have increased their R&D budgets in recent years at a constant high growth rate of about 40% per year for the years 2003 – 2008 and more than 20% even in the financial crisis year of 2009. The companies of this group represent all value chain steps and all major technologies of PV industry. These companies represent about 600 m€ PV R&D investments in 2009 and sales of about 17 bn€, which might account for a value chain consolidated base for approximately 20% of global PV sales (Fig. 3.1-18). These companies have invested on average about 3.5% of their sales in 2009 in R&D, whereas the leading five and ten companies have invested an average of 6.5% and 4.6%, respectively. In general, PV equipment suppliers invest significantly more than average in R&D and tend to be at about 10%. 22 companies additionally gave numbers for their R&D staff (Table 3.1-1), accounting for a total R&D headcount (HC) of about 3,600 associates. Average total spending per employee including cost of research material, equipment and general overhead is therefore about 110 k€, whereas Chinese companies are significantly below average but not more than 50%. Furthermore, an analysis of patent activities of these companies (Table 3.1-1) reveals that on average one patent family is created per 1.3 m€ R&D investment, whereas some companies leading in their specific field of PV technology, like SunPower and von Ardenne are more productive and create a patent family every 0.6 – 0.8 m€ of R&D investment. However, different IP protection strategies of the companies might significantly influence the respective number of patent applications. Moreover, in reality corporate R&D programmes receive internal budgets and to protect the generated IP patent applications are filed, thus the number of patent families per invested R&D budget is a rather precise metric. A patent family includes all patent filings which are connected via their claimed priorities. A patent family is constituted by a patent application which is not claiming the priority date of any other patent application. All later applications which then claim the priority of this application under the Paris Convention for the Protection of Industrial Property¹⁶⁷ – either directly or indirectly – belong to this patent family in the definition of the authors. Follow up applications for a patent family are counted for the (earlier) priority year. The analysed companies need in average roughly 14 R&D employees per patent family, whereas leading companies like SMA Solar Technology (11 HC/patent) and SunPower (4 HC/patent) are significantly more productive than average.

Company	Value Chain Position	2009 R&D/sales	2009 [m€]	2008 [m€]	2007 [m€]	2006 [m€]	2005 [m€]	2004 [m€]	2003 [m€]
1 Solyndra ^{1,2}	US CIGS module	84.2%	58.7	90.2	58.4	15.1	0.7	0.0	0.0
2 SMA Solar Technology ^{1,2}	DE inverter	6.0%	56.3	34.7	19.7	15.6	12.3	n/a	n/a
3 First Solar ²	US CdTe module, system	3.8%	54.3	24.1	10.3	4.9	2.0	0.9	3.0
4 oerlikon Solar ²	CH Si-TF: equipment	13.9%	42.5	33.7	12.7	n/a	n/a	n/a	n/a
5 REC ²	NO c-Si: wafer, cell, module	3.3%	36.6	21.7	20.9	13.0	6.3	7.5	4.8
6 centrotherm PV ^{1,2}	DE c-Si, CIGS: equipment	5.6%	28.4	16.8	7.4	1.9	1.9	1.1	n/a
7 MEMC Electronic Mat.	US c-Si: Si, wafer, system	3.5%	28.0	29.3	26.7	27.2	28.0	28.3	26.1
8 Q-Cells ^{1,2}	DE c-Si: cell, module, system; CIGS/CdTe module	3.3%	26.5	33.1	21.9	8.1	3.5	1.1	0.5
9 SunPower ^{1,2}	US c-Si: cell, module, system	2.1%	21.9	15.4	9.2	7.4	5.5	10.1	7.8
10 Suntech Power ^{1,2}	CN c-Si: cell, module, system; Si-TF module	1.7%	20.1	11.0	10.2	6.4	2.8	0.3	0.1
11 Yingli Green Energy ^{1,2}	CN c-Si: Si, wafer, cell, module	2.5%	18.7	6.0	1.6	2.4	0.2	0.4	n/a
12 von Ardenne ^{*,2}	DE TF equipment	10.0%	16.7	16.7	19.6	n/a	n/a	n/a	n/a
13 Roth&Rau ¹	DE c-Si, CdTe: equipemnt	8.3%	16.5	4.9	2.5	2.7	n/a	n/a	n/a
14 Meyer Burger ¹	CH c-Si: equipment	5.3%	15.2	14.6	7.7	6.2	n/a	n/a	n/a
15 GT Solar ¹	US c-Si: equipment	4.4%	15.0	11.9	6.8	2.9	1.5	n/a	n/a
16 Schott Solar ^{*,2}	DE c-Si: cell, module, system, Si-TF module	4.0%	13.5	13.5	13.3	12.7	9.8	n/a	n/a
17 Evergreen Solar ^{1,2}	US ribbon-Si: wafer, cell, module	6.7%	12.6	15.8	14.0	14.0	9.7	3.7	3.0
18 Manz automation ²	DE c-Si-, TF: equipment	14.1%	12.1	10.3	3.6	2.3	1.4	n/a	n/a
19 SolarWorld ^{1,2}	DE c-Si: wafer, cell, module, system	1.2%	12.0	13.0	10.8	8.6	8.3	8.5	4.5
20 Wacker BU Polysilicon	DE c-Si: Si	1.0%	11.3	5.4	6.3	5.1	5.3	6.0	n/a

¹⁶⁷ WIPO, Paris Convention for the Protection of Industrial Property, 1883

21	DayStar Technologies²	US CIGS	-	10.2	12.7	7.1	7.6	3.0	1.2	0.2
22	ReneSola¹	CN c-Si: wafer	2.8%	10.1	7.0	0.7	0.0	0.0	0.0	0.0
23	PV Crystalox Solar	DE c-Si: Si, wafer	3.5%	8.4	6.2	4.4	4.1	4.2	3.8	n/a
24	Satcon Technology^{1,2}	CA inverter	16.0%	5.8	3.7	1.6	1.5	5.0	4.5	5.2
25	LDK Solar¹	CN c-Si: Si, wafer, cell, module, system	0.8%	5.8	5.5	2.2	0.2	0.1	0.0	0.0
26	E-Ton Solar	TW c-Si: cell	1.7%	4.8	9.5	2.6	0.8	n/a	n/a	n/a
27	Arise Technologies²	CA Si-TF module	22.4%	4.7	3.8	2.7	0.4	0.4	0.3	0.3
28	Motech	TW c-Si: cell, module	1.2%	4.7	5.7	4.1	1.1	n/a	n/a	n/a
29	JA Solar^{1,2}	CN c-Si: wafer, cell, module	1.2%	4.6	3.0	0.4	0.2	0.0	0.0	0.0
30	Solon^{1,2}	DE c-Si: module, system	1.1%	3.8	2.5	2.5	2.5	1.2	0.9	0.9
31	ECD Ovonic Solar²	US Si-TF module	1.8%	3.8	2.6	2.5	2.3	2.2	6.4	3.0
32	Trina Solar^{1,2}	CN c-Si: wafer, cell, module	0.6%	3.7	2.2	1.9	1.44	0.10	0.19	0.0
33	Solarfun^{1,2}	CN c-Si: wafer, cell, module	0.8%	3.3	2.1	2.6	0.7	0.1	0.0	0.0
34	China Sunergy²	CN c-Si: wafer, cell, module	1.5%	3.1	1.4	1.8	0.4	0.0	0.0	0.0
35	Dyesol²	AU DSSC material	192.5%	3.0	1.1	1.0	0.6	0.2	n/a	n/a
41	GCL-Poly Energy Hold.	CN c-Si: Si, wafer, cell, module, system	0.3%	2.7	3.1	n/a	n/a	n/a	n/a	n/a
36	PVA TePla	DE c-Si: equipment	1.8%	2.5	1.8	1.7	1.6	1.3	1.5	1.7
37	Canadian Solar^{1,2}	CN c-Si: cell, module	0.5%	2.2	1.3	0.7	0.3	0.0	0.0	0.0
38	Timminco	CA c-Si material	3.2%	2.2	0.2	0.8	0.7	0.5	0.4	0.0
39	Day4 Energy²	CA c-Si: cell, module	5.2%	2.1	1.3	1.3	0.9	0.8	0.3	n/a
40	Sunways^{1,2}	DE c-Si: cell, module	1.2%	2.1	3.0	2.7	2.9	2.3	1.5	1.0
42	Conergy^{1,2}	DE c-Si: wafer, cell, module, system, inverter	0.3%	1.7	1.2	14.2	10.6	12.8	5.1	1.2
43	Neo Solar Power	TW c-Si: cell, module	0.7%	1.5	1.8	0.5	0.5	n/a	n/a	n/a
44	Gintech	TW c-Si: cell, module	0.4%	1.4	1.1	0.7	0.5	n/a	n/a	n/a
45	5Nplus	CA CdTe material	1.7%	0.8	0.5	0.5	0.5	0.3	n/a	n/a

* 2009 estimated on 2008 basis

total	616.0	506.3	344.5	198.6	133.6	94.0	63.2
top25 total	557.2	457.2	299.5	169.8	111.4	77.3	55.1
total growth	21.7%	46.1%	57.2%	39.8%	15.0%	30.9%	
top25 growth	21.9%	52.7%	57.3%	44.5%	24.4%	19.8%	

Table 3.1-1: Corporate R&D investments of public listed PV companies for the years 2003 – 2009, sorted by R&D investments in 2009. Currency exchange rates are taken for end of respective year. Annual growth rates are corrected by available data of respective previous year. All data are taken from respective company reports. ^{1,2}Data for average R&D headcount (1) and patent families (2) of respective company is available for all years of R&D investment data. Abbreviations stand for: Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), crystalline silicon (c-Si), dye-sensitized solar cell (DSSC), silicon (Si) and thin-film (TF).

A rough correlation can be found between PV industry sales growth rates (Fig. 3.1-18) and growth rates of R&D investment of public listed PV companies (Table 3.1-1). Average growth rate in sales for the years 2004 – 2009 of about 50% resulted in an average growth rate of R&D investments of about 35% for these companies (Fig. 3.1-7).

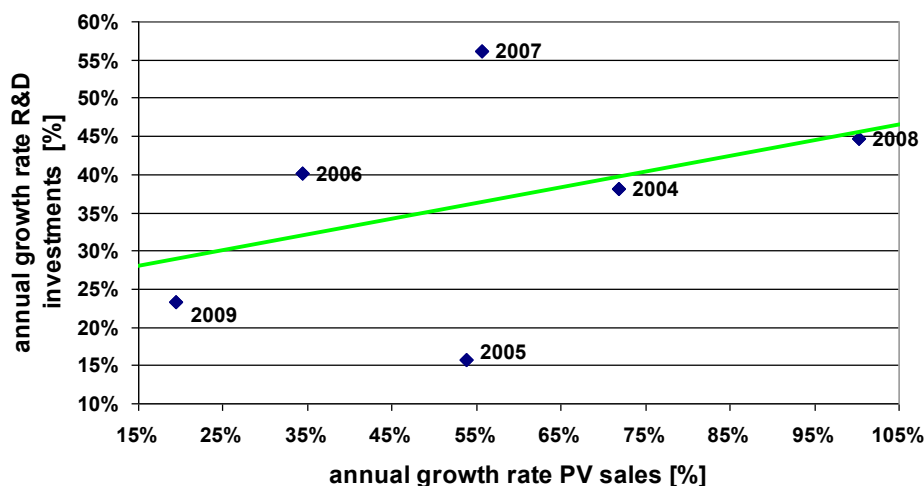


Figure 3.1-7: Correlation of PV industry sales growth rates and R&D investment growth rate for public listed PV companies for the years 2004 - 2009.

3.1.3.2.2 PV R&D Investment Estimates for Companies Without Disclosed PV R&D Financials

The PV R&D of a large group of 62 companies is estimated by available market insights (production and sales numbers), financial reports of their entire business (large conglomerates and diversified companies), their R&D staff (companies still in R&D mode) or their PV patent applications (all companies with at least five PV patents applied for in 2008 or significant PV activities). PV R&D investment of these companies is estimated to be about 1,500 m€ in 2009 (Table 3.1-2). Several leading PV companies with a long history in PV R&D are in this group, like Sharp, Samsung, Applied Materials, LG, DuPont, Jusung, Ulvac, Panasonic/Sanyo, Kyocera, Hemlock, General Electric, Bosch Solar Energy (former ersol), Mitsubishi Electric, Emcore, Fronius, Konarka Technologies, Soitec CPV (former Concentrix) and Solar Frontier (former Showa-Shell).

Company	Value Chain	R&D 2009e [m€]	PV fraction estimated by	PV sales	R&D staff	PV patents
1 Samsung	KR c-Si: cell, module	124.4				•
2 LG	KR c-Si: cell, module	124.4				•
3 AMAT	US c-Si, Si-TF: equipment	114.2	•	•		•
4 Sharp	JP c-Si: cell, module, Si-TF, HCPV, DSSC, inverter	100.0	•	•		•
5 Contrel Technology	TW Si-TF module	67.8				•
6 DuPont	US c-Si consumable	66.6		•		•
7 Sony	JP OPV module, misc	61.0				•
8 Fuji	JP OPV module, misc	53.2				•
9 Ulvac	JP c-Si, Si-TF, CIGS, CdTe: equipment	51.2				•
10 Sanyo	JP c-Si: wafer, cell, module, inverter; Si-TF module	44.1	•	•		•
11 Lumberg Connect	DE consumable	41.9				•
12 Jusung	KR c-Si, Si-TF: equipment	40.8				•
13 Mitsubishi Heavy Ind.	JP Si-TF module	37.8		•		•
14 Kyocera	JP c-Si: cell, module	36.2	•	•		•
15 Hon Hai Precision Ind.	TW DSSC module, consumable, system	31.6				•
16 General Electric	US next gen module, DSSC module, inverter, system	31.1				•
17 Hemlock	US c-Si material	28.6		•		
18 Fujikura	JP TF, DSSC: module	28.4				•
19 Canon	JP misc	27.6				•
20 Sumitomo	JP OPV material	27.6				•
21 Bosch Solar Energy	DE c-Si: wafer, cell, module, system; Si-TF module	26.3		•	•	•
22 Mitsubishi Electric	JP c-Si: cell, module, inverter	20.9	•	•		•
23 Tokuyama	JP c-Si material	19.3	•	•		
24 Dongjin Semichem	KR DSSC module	18.9				•
25 Guardian Industries	US TF, c-Si consumable	17.0				•
26 Emcore	US HCPV: cell, system	15.0	•			•
27 Solopower	US CIGS module	14.1				•
28 Fronius International	DE inverter	14.0		•		
29 Konarka Technologies	US OPV module	12.5			•	•
30 KACO New Energy	DE inverter	12.0		•		
31 Solar Frontier	JP CIGS module	10.4		•		•
32 Kaneka	JP Si-TF module	9.6		•		•
33 NEC	JP consumable	9.8				•
34 NPC	JP c-Si equipment	8.5		•		
35 Beijing Hikken Techn.	CN PVT	8.1				•
36 Soitec CPV	DE HCPV: module, system	8.0				•
37 Siemens	DE inverter	8.0		•		
38 Seiko Epson	JP unclear	7.9				•
39 BP Solar	UK c-Si system	7.7			•	•
40 Power-One	CA inverter	7.2	•	•		
41 OCI	KR c-Si material	6.9	•	•		

42	Sputnik Engineering	CH	inverter	6.7	•		
43	Solibro	DE	CIGS module	6.5		•	
44	Schneider Electric	FR	inverter	6.0	•		
45	Shinetsu Chemical	JP	c-Si: wafer, cell, consumable	5.9			•
46	Solamer	US	OPV module	5.7			•
47	Spectrolab	US	HCPV cell	5.7			•
48	Würth Solar	DE	CIGS module	5.6	•		
49	Sovello	DE	ribbon-Si: wafer, cell, module	5.0	•		•
50	Plextronics	US	OPV module	4.4			•
51	VHF Technologies	DE	Si-TF module	4.0			•
52	Heliatek	DE	OPV module	3.8			•
53	STR Holdings	US	c-Si consumable	3.1		•	
54	Komax	CH	c-Si equipment	2.9	•		
55	Solland	NL	c-Si module	2.8		•	
56	Photovoltech	BE	c-Si: cell	2.6		•	
57	Sunfilm	DE	Si-TF module	2.5			•
58	Isofoton	ES	c-Si: cell, module	2.5		•	
59	Photowatt	FR	c-Si: cell, module	1.8		•	
60	Orkla (Elkem Solar)	NO	c-Si material	1.4	•	•	
61	Ceradyne	US	c-Si consumable	1.3	•	•	
62	Phocos	DE	off-grid system	0.5		•	•
total				1481.0			

Table 3.1-2: Corporate PV R&D investments estimated for the year 2009. Key indicators for estimating respective PV R&D investments are production of PV products and related PV sales, typical relative R&D per sales investments of value chain competitors (PV sales), R&D investment of respective entire company (PV fraction), PV R&D staff and PV patents. Dots indicate available data for estimating PV R&D investments. Average R&D investment per patent family is estimated by average R&D investment per leading PV companies of 1.3 m€ and average R&D investment per patent in respective country of company headquarters. Every single criteria for estimating respective company PV R&D is not precise, but more than one fulfilled criteria might allow to estimate respective company PV R&D in the real order. Abbreviations stand for: Copper Indium Gallium Selenide (CIGS), crystalline silicon (c-Si), dye-sensitized solar cell (DSSC), high concentrating PV (HCPV), organic PV (OPV), silicon (Si) and thin-film (TF).

It can be assumed to cover by Table 3.1-2 about 60% of all PV companies of which precise data are available. Thus for a third group of PV companies where no resilient indicator could be found or even their existing, annual PV R&D investments are estimated to be about 1,000 m€. Among this third group are companies like IBM, Spectrawatt (Intel), 1366 Technologies, Abount Solar, Primestar Solar, Amonix, AQT, Avencis/ Saint Gobain, Azur Solar, G24i, Innovalight, Jonas & Redman, Miasolé, Nanosolar, SiC Processing, SolFocus, Yunicos, Steca, Deger, a+f and many more, in particular located in Asia. A recent study found venture capital and private equity investments of 5.5 bnUSD in solar companies in 2008.¹⁶⁸ Usually, investments in establishing new concepts, designs and manufacturing processes require significant financial resources. In all groups of documented and estimated corporate PV R&D investments, such companies are included, e.g. Solyndra (Table 3.1-1), Konarka Technologies, Solopower, Soitec CPV (former Concentrix), Plextronics, Solamer, Heliatek (Table 3.1-2) and 1366 Technologies, Abount Solar, Amonix, AQT, G24i, Innovalight, Miasolé, Nanosolar and SolFocus (general estimate).

3.1.3.2.3 Current Global Corporate PV R&D Investments

Bottom-up analysis of corporate PV R&D investments leads to a total expenditure estimate of 3,100 m€ in 2009 for the three discussed groups of companies. This estimate also corresponds to the numbers for public listed PV companies which invested about 600 m€ in

¹⁶⁸ UNEP, Global Trends in Sustainable Energy Investment, 2009

PV R&D and representing about 20% of global PV industry sales. This disproved the claim of low corporate PV R&D investments.

3.1.3.3 Global Historic PV Patent Applications

Technological innovations need tremendous resources for market introduction. Fundamental effects have to be explored, applications need to be found or adapted, first products and related production processes have to be designed and qualified, new products have to be explained to new customers and existing products need to be improved, best possible adapted to customer needs and reduced in overall product cost. Along this time and financial budget consuming process several technological innovations are typically generated. This know-how forms intellectual property (IP) for individual players and can be protected by patents. Such IP protection schemes have been established all around the world as a consequence of the industrial revolution and have been harmonized for several decades more or less on a global scale. Therefore, historic PV patents (sections 3.1.3.3.1 and 3.1.3.3.2) can be used as a very valuable dataset for an alternative way of analysing global PV technology diffusion (section 3.1.3.3.3 and 3.1.3.3.4) and corresponding corporate and public PV R&D activities (sections 3.1.3.3.5 and 3.1.3.3.6).

3.1.3.3.1 National PV and Inverter Patent Applications

For estimating PV R&D activities PV patent applications are evaluated for the years 1900 – 2008. The early time limit is applied for finding first innovations like first solar cells and solar products of Snelling¹⁶⁹, Schottky¹⁷⁰ and Ohl¹⁷¹, and the 2008 limit is due to the fact that patent applications are published 18 months after filing date. Significant PV patent activities started at end 1950s (always more than 20 patents per year since then) as a consequence of first PV diffusion phase in space applications (Fig. 3.1-8). Leading PV patent assignees at that time have been involved in the space business, e.g. Hoffmann Electronics.

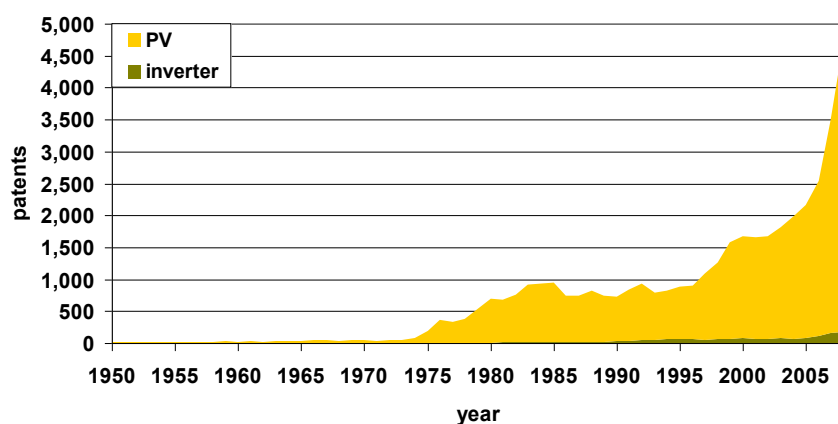


Figure 3.1-8: PV and inverter patent families filed in at least one country for the years 1950 – 2008. PV and inverter patent families are identified by keywords in patent application and their classification within at least one of the following classification systems: IPC (international patent classification), ECLA (Europe), DEKLA (Germany) or F-Index (Japan).

¹⁶⁹ Snelling W.O., Photo-electric apparatus, 1920

¹⁷⁰ Schottky W., Photoelectric Generator, 1929

¹⁷¹ Ohl, R.S., Light-sensitive electric device, 1941

Second PV diffusion phase can be also found in patent filings, since starting in 1975 at least 100 patent applications have been recorded for each year (Fig. 3.1-8). On-grid PV systems, which mark the third market diffusion phase, are documented by PV patents twice, firstly by a further significant PV patent application growth (always more than 1,000 patents per year since 1997) and secondly by begin of significant PV inverter patent activities (always more than 20 and 50 patents per year since 1990 and 1998, respectively).

PV patent filings and historic PV production show very similar dynamics (Fig. 3.1-1, 3.1-8 and 3.1-18). Correlation of PV industry sales growth rate and PV patent filing growth rate reveals a strong interaction between anticipated (large companies) and available (large companies and small medium enterprises) PV markets (Fig. 3.1-9).

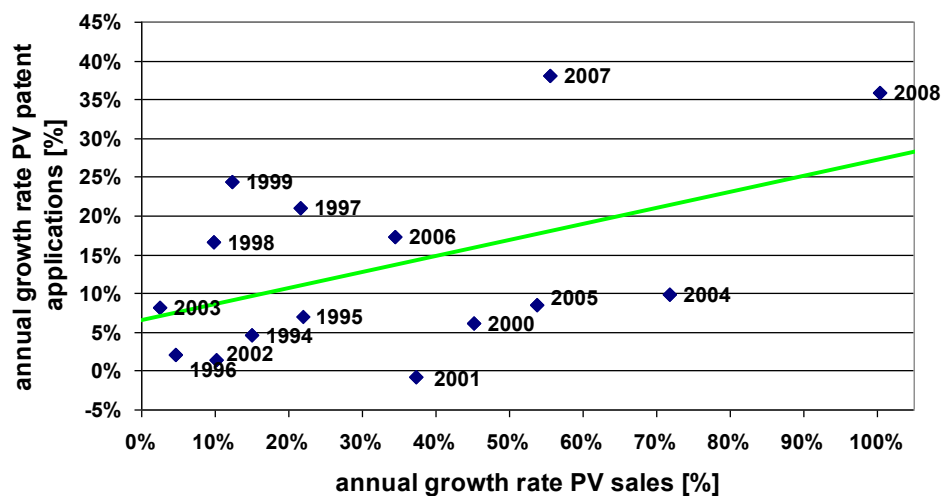


Figure 3.1-9: Correlation of PV industry sales growth rates and PV patent application growth rate for the years 1994 - 2009.

The third PV diffusion phase can be analysed for all years. In average a 50% growth rate in PV industry sales have been led to a 17% growth rate of PV and inverter patent applications. Nevertheless, there is a significant difference in patent application and R&D investment growth rate per PV industry sales growth rate of about a factor of two (Fig. 3.1-7 and 3.1-9). Two main reasons might drive this difference: size and age of companies and scaling effects. Firstly, most of the companies for whom precise PV R&D investment data is available have been established or transformed into a PV company within the last decade, hence their growth rate in R&D investments needs to be high to catch up with existing players. Moreover, most of them are pure or nearly pure PV companies whose core business is PV, consequently they are more focussed and motivated in driving a fast PV diffusion. Secondly, scaling effects seem to be very important in PV industry, since about 50% of ongoing cost reduction is generated via this approach.¹⁷² Consequently, identical technical solutions protected by patents are used for much more production volume as a function of time and market size.

¹⁷² Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

3.1.3.3.2 International PV and Inverter Patent Applications

Changes in global PV markets, global industrial production patterns and public PV R&D investments are reflected by origin of international PV patents. International PV patents are defined by patent families consisting of at least two national patent filings. Development of international PV and inverter patent families is depicted in Figure 3.1-10.

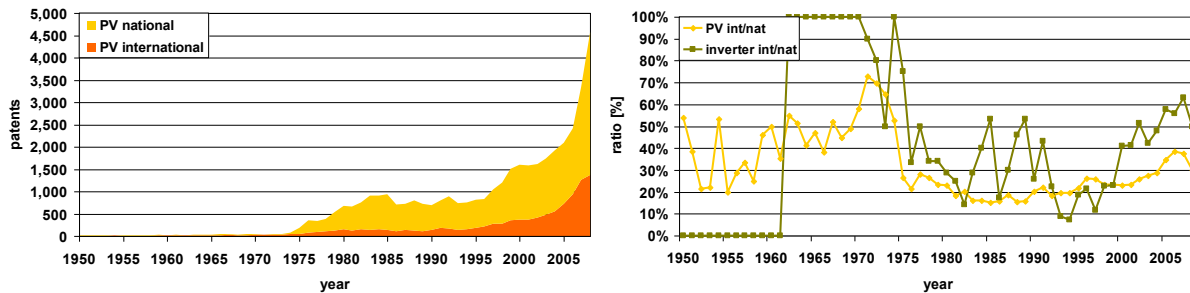


Figure 3.1-10: International PV patent families in absolute numbers (left) and relative (right) numbers for the years 1950 – 2008. Stagnating data points for the year 2008 result because of timelags between patent application disclosures and their availability within patent databases.

For the period 1950 – 2008 the PV patent assignees decided for 25.9% of their national patent families to protect their IP in more than one country. International patents are assumed to reflect relative business value, as most technical products are sold for international markets and IP rights are substantial intangible assets for technology driven corporations. More anticipated regional markets for PV products might be also reflected in international patent filings. Ratio of international to national PV patent filings are meaningful for the second and third PV diffusion phase, hence for mid 1970s to today. Dynamics for inverter patents are better regarded for years of mid 1990s, as on-grid PV systems started in these years their ongoing high growth phase. Ratio of international to national PV patent families has been increased from about 15% in mid 1980s to about 40% in late 2000s. Respective ratio for inverter patents increased from 10% to 60% for the period mid 1990s to late 2000s.

Relative significance of technologies can be estimated by comparing PV to peer technologies or to all technologies. Lee et al.¹⁷³ analysed patent trends for clean energy technologies and found for the last years nearly identical numbers of patents for PV and wind energy, whereas both PV and wind energy had more than twice and threefold the patents of carbon capture and STEG or biomass technologies. This relative patent numbers can be considered as industries' measure for the relative importance of respective energy technologies for the next decades. Constant high growth rate of PV R&D activities is also reflected by the ratio of international PV and inverter patent families to all international patent families (Fig. 3.1-11). Within one decade international PV patent families increased from 0.2% to 0.8% of all international patent families filed in the world. Players active in PV R&D seem to anticipate a much higher role of PV in global energy supply in the years to come. Ratio of PV industry sales to global gross domestic product (GDP) is only 0.12%.

¹⁷³ Lee B. et al., Who owns our low carbon future?, 2009

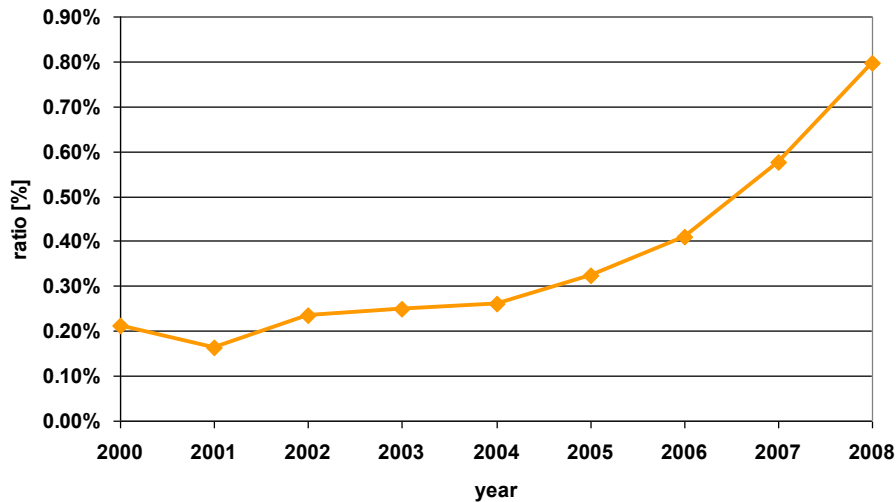


Figure 3.1-11: Ratio of PV and inverter to all international patent families filed in the world for the years 2000 - 2008.

3.1.3.3 Geographic Origin and Leading Assignees of International PV and Inverter Patent Applications

Constant public PV R&D investments (Fig. 3.1-6) and creation of respective PV markets (Fig. 3.1-19) is reflected by respective domestic PV players, which usually protect their generated IP in their origin counties, where R&D centers and headquarter functions are located (Fig. 3.1-12). In the first PV diffusion phase most PV patent families had been filed by players from the US, Germany, UK and France, whereas UK and France lost steadily ground in the second and third phase of PV diffusion. The only country entering the arena during the second PV diffusion phase at a large fraction had been Japan. In the last decade new players from South Korea, Taiwan and China have been gaining a growing share of international PV patent families. Companies from Korea and Taiwan have been very successful in semiconductor related technologies in the last two decades; hence they use their core know-how to enter technological comparable new growth markets, like PV. China intends to become a relevant player in all important industries, especially those of high growth rates, potentially high profit margins and enabling a sustainable domestic economic growth, which is the case for PV.

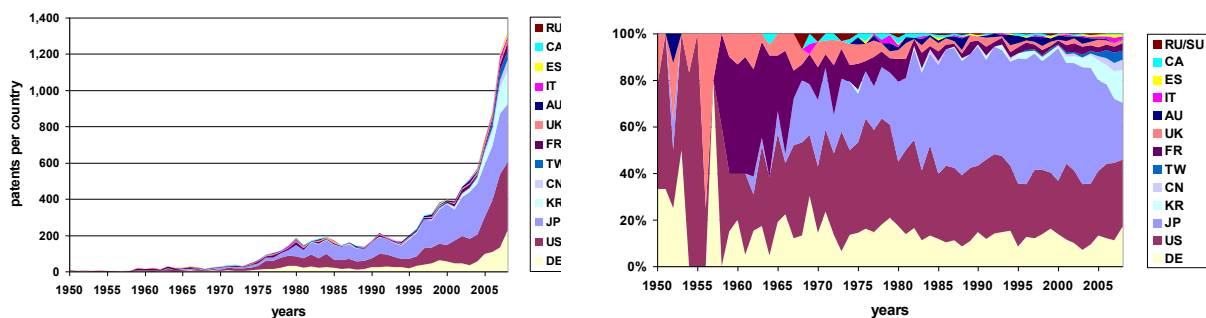


Figure 3.1-12: International PV patent families by countries of origin in absolute (top) and relative (bottom) numbers for the years 1950 – 2008.

An analysis of leading PV patent assignees for 2008 (Table 3.1-3) and the years 2000 – 2008 (Table 3.1-4) provides a more differentiated view on the aggregated numbers of Figure 3.1-12.

Company/ Institution					PV	Inverter	total	Company/ Institution					PV	Inverter	total
1	Samsung	KR	67	3	70	1	Samsung	KR	281	6	287				
2	LG	KR	67	0	67	2	Sanyo/ Panasonic/ Matsushita	JP	270	15	285				
3	Sharp	JP	59	1	60	3	Sharp	JP	267	10	277				
4	Sanyo/ Panasonic/ Matsushita	JP	48	5	53	4	Canon	JP	229	18	247				
5	Trina Solar*	CN	50	0	50	5	Fuji	JP	189	0	189				
6	Du Pont	US	41	0	41	6	LG	KR	172	0	172				
7	Applied Materials	US	40	0	40	7	Sony	JP	140	0	140				
8	von Ardenne*	DE	34	0	34	8	Applied Materials	US	96	0	96				
9	Sony	JP	31	0	31	9	Du Pont	US	89	0	89				
10	Beijing Hikeen Technology	CN	28	0	28	10	SunPower*	US	83	0	83				
11	Schott Solar*	DE	27	0	27	11	Semiconductor Energy Lab	US	78	0	78				
12	Fuji	JP	27	0	27	12	Industrial Technology Res. Inst.	TW	77	1	78				
13	Ulvac	JP	26	0	26	13	Kyocera	JP	77	0	77				
14	Industrial Technology Res.	TW	25	0	25	14	Seiko Epson	JP	67	2	69				
15	Contrel Technology	US	24	0	24	15	Konarka Technologies	US	67	0	67				
16	Emcore	US	24	0	24	16	Schott Solar	DE	67	0	67				
17	SMA Solar Technology*	DE	0	23	23	17	Sumitomo Chemical	JP	66	0	66				
18	Jusung	KR	22	0	22	18	SMA Solar Technology*	DE	0	65	65				
19	Q-Cells*	DE	21	0	21	19	General Electric	US	64	14	78				
20	Semiconductor Energy Lab	US	21	0	21	20	Fraunhofer Gesellschaft	DE	60	6	66				
21	Mitsubishi Electric	JP	19	0	19	21	Jusung	KR	55	0	55				
22	General Electric	US	11	8	19	22	Mitsubishi Electric	JP	54	11	65				
23	Fraunhofer Gesellschaft	DE	16	2	18	23	Korea Electronics Telecomm	KR	51	0	51				
24	Hon Hai Precision Industry	TW	17	0	17	24	Toshiba	JP	50	2	52				
25	Bosch Solar Energy	DE	15	2	17	25	Trina Solar	CN	52	0	52				
total top25					760	44	804	total top25					2701	150	2851

Table 3.1-3: Leading PV and inverter patent assignees in the year 2008. All PV and inverter patent families are taken into account. * Entire patent applications of respective company are included.

Table 3.1-4: Leading PV and inverter patent assignees for the years 2000 – 2008. All PV and inverter patent families are taken into account. * Entire patent applications of respective company are included.

PV seems to be a quite diversified technology, as the leading 25 companies account for only 15.5% and 12.7% of global national PV patent families in 2008 and for the years 2000 – 2008, respectively. Concentration for inverter patents is higher at values of 24.6% and 17.2% in 2008 and for the years 2000 – 2008, respectively. Outstanding technological position is documented for SMA Solar Technology as leading inverter manufacturer in the world, by accounting for 12.8% of global national inverter patent families filed in 2008. Respective relative number for the two leading PV patent filing companies Samsung and LG reaches only 1.5%.

Remarkably, several leading PV patent assignees have not yet started to sell PV products or they are in the preparation phase for PV market entry, e.g. Samsung, LG, Sony, Fuji, Contrel Technology, Emcore, General Electric, Hon Hai Precision Industry (Foxconn) and Konarka Technologies. This is also emphasized by international patent families by technology (Fig. 3.1-13). About 50% of technology specific patents are for c-Si, whereas respective market share is about 85%¹⁷⁴. However, emerging PV technologies like dye-sensitized and organic PV account for 20% – 30% of technology specific international patent families. Furthermore, several thin-film technologies are still in the market introduction phase, but account for

¹⁷⁴ Hering G., Survey on cell production 2010: Year of the tiger, 2011

25% – 40% of technology specific international patent families. This might explain for some PV companies their significant R&D investments but invisibility in PV production.

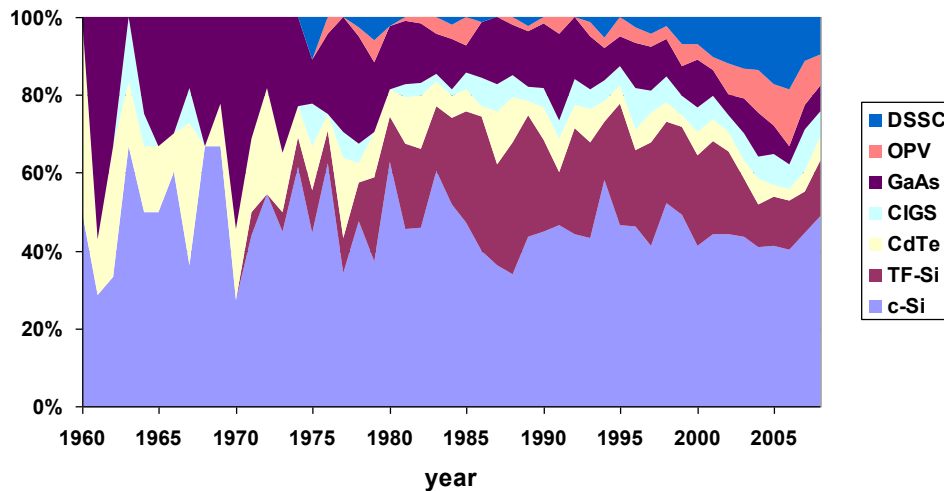


Figure 3.1-13: International PV patent families by technology for the years 1960 – 2008. Not depicted are patents for PV systems and for other PV technology applications. Abbreviations stand for: dye-sensitized solar cell (DSSC), organic PV (OPV), Gallium Arsenide (GaAs), Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe), thin-film silicon (TF-Si) and crystalline silicon (c-Si).

Moreover, several leading PV companies by market share¹⁷⁵ do not invest in a corresponding PV patent portfolio, e.g. First Solar, Suntech Power, Yingli, JA Solar, Gintech and centrotherm photovoltaics. For some companies a non publication strategy appears to be more advantageous, as valuable process IP is not as easy to protect as design IP, as it could be the case e.g. for First Solar.

3.1.3.3.4 Academic and Business Origin of International PV Patent Applications

Substantial contribution to global PV patent portfolio is provided by public research organizations like universities or research institutes (Fig. 3.1-14). Currently, about 10% of PV related international patent families are filed in by public research players. Assuming similar average expenditures per patent for public research organizations than for companies, one can estimate current PV R&D investments of public organizations of about 450 m€. Ratio of public to business international PV patent applications rose in last years, which might be a consequence of close cooperation of fast growing PV companies and public research institutions. This kind of cooperation may indicate an effective diffusion pattern of fundamental and applied research IP from public institutions to fast growing PV companies, which intend to develop new PV products and consequently lower PV industry cost structures.

¹⁷⁵ Hirshman W.P. and Schug A., Von wegen Krise: Solarzellenproduktion im Jahr 2009, 2010

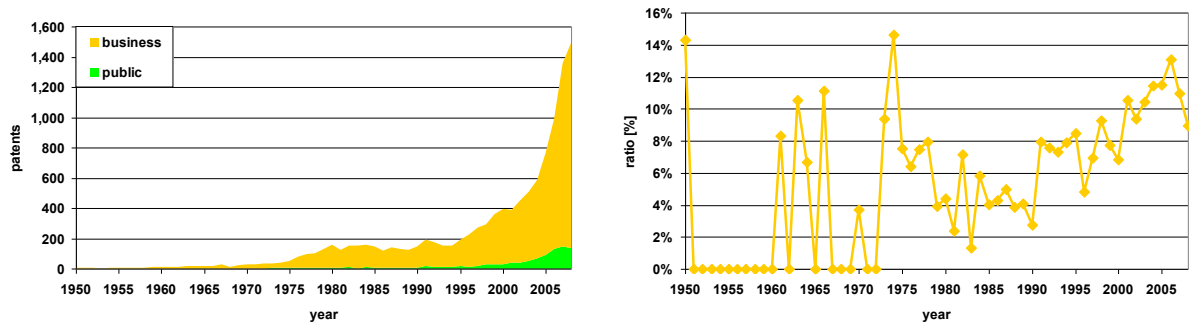


Figure 3.1-14: Public and business assignees of international patent families in absolute (left) and relative (right) numbers for the years 1950 – 2008. Public assignees are defined to be universities, research institutes and public organized and funded business like research institutes.

3.1.3.3.5 Global Annual and Historic Cumulated PV R&D Investments

PV patent databases provide an excellent dataset for estimating current but also historic and historic cumulated PV R&D investments. Fundamental dataset for this estimate are the historic international PV and inverter patent applications (Fig. 3.1-8 and 3.1-10). One can assume expenditures in the past by applying today's numbers, due to inflation corrected cost per patent in real currency value. Four approaches can be used for estimating best possible expenditures per PV patent filed.

Global R&D investment had been about 1,360 bn€ in 2007, which was financed to about 60% by enterprises.¹⁷⁶ Global international patent family applications can be found to be about 236,000 in 2007. Ratio of international to national patent families is found to be about 26%, i.e. about 910,000 patent families had been established in 2007. Taking global R&D investments and global national patent families into account, average expenditure per national patent family is estimated to be about 1.50 m€. Global R&D investment also include non technological R&D, hence real cost per invention need to be lower.

Another way for estimating average cost per PV patent is to weight **average cost of residential patent filings** by PV player of respective country (Fig. 3.1-12). Average generated residential patents per million USD are 2.48 (Japan), 0.72 (the US), 0.74 (Germany), 3.70 (South Korea), 0.37 (France), 0.50 (UK), 1.82 (China) and 0.19 (Australia).¹⁷⁷ These cost per residential patent are weighted by filed in cumulated international PV patents, which are 4,420 (Japan), 3,510 (the US), 1,500 (Germany), 590 (South Korea), 460 (France), 280 (UK), 170 (China) and 140 (Australia). Performing this approach leads to an average cost per national patent family of about 0.80 m€ by applying an average exchange rate of 1.30 USD/€.

Average patent expenditures of leading PV companies (Table 3.1-1) for their national patent families accounted to 1.3 m€ per filed patent family established, whereas experienced PV players have average cost per patent of about 0.6 – 0.8 m€. Nevertheless, statistical significance of that approach seems to be limited due to the fact that those companies do represent about 20% of global PV industry sales but filed only 3.5% and 2.4% of all PV patent families for the year 2008 and the period of the years 2003 – 2008.

¹⁷⁶ UN, Statistical Yearbook 52nd issue, 2008

¹⁷⁷ WIPO, World Intellectual Property Indicators 2009, 2009

Average R&D investments per international patent family can also be estimated by **PCT (Patent Cooperation Treaty) filings of international companies**¹⁷⁸ and their respective R&D investments¹⁷⁹, assuming that the most common follow-up application after the priority application is a PCT application. Results of this measure (Table 3.1-5) show average R&D investment per PCT of international technology leaders of about 3.24 m€. 11 in 20 of these technology leaders are also active in PV either in leading PV R&D (Tables 3.1-3 to 3.1-5) or selling products. In 2008 about 163,000 PCT and 250,000 international patent filings have been recorded, hence about 53% more international patent filings than PCT applications. Therefore, average expenditure per international patent family might be between 2.1 and 3.2 m€, which is depending on individual patent application strategy. Nevertheless, average cost per national patent family for leading PV companies is found to be approximately 1.3 m€ per national patent family.

Company			PCT filings 2008	R&D investment 2008 [m€]	investment per PCT 2008 [m€/PCT]
1	Huawei Tech.	CN	1,737	n/a	n/a
2	Panasonic ^{1,2}	JP	1,729	4,401	2.55
3	Philips	NL	1,551	1,613	1.04
4	Toyota	JP	1,364	7,610	5.58
5	Bosch ^{1,2}	DE	1,273	3,916	3.08
6	Siemens ²	DE	1,089	3,836	3.52
7	Nokia	FI	1,005	5,321	5.29
8	LG Electronics ^{1,2}	KR	992	1,304	1.31
9	Ericsson	SE	984	2,975	3.02
10	Fujitsu	JP	963	2,053	2.13
11	Qualcomm	US	907	1,641	1.81
12	NEC ¹	JP	825	2,795	3.39
13	Sharp ^{1,2}	JP	814	1,557	1.91
14	Mircosoft	US	805	6,482	8.05
15	Motorola	US	778	2,956	3.80
16	BASF ²	DE	721	1,372	1.90
17	IBM ^{1,2}	US	664	4,327	6.52
18	3M ²	US	663	612	0.92
19	Samsung ^{1,2}	KR	639	3,469	5.43
20	DuPont ^{1,2}	US	517	1,002	1.94
total			18,283	59,242	3.24

Table 3.1-5: International PCT applications, corporate R&D investments and R&D investments per PCT for the 20 leading PCT assignees.^{1,2} Several companies are also recorded as top PV patent assignees in Tables 3.1-3 and 3.1-4 (1) or they are active in PV business (2). Data are taken from WIPO¹⁸⁰ and EC¹⁸¹.

From a conservative point of view, the following cost estimation procedure seems to be most appropriate: average cost of national patent families of PV players is estimated to be 0.80 m€ and historic ratio of international to national PV and inverter patent families is 26%, hence in rough average an international PV related patent family might occur R&D investments of 3.1 m€. Average expenditures of international technology leaders for international patent families are most likely between 2.1 and 3.2 m€. For considerations in this publication the estimated average investment of 2.6 m€ per international patent family is used for not overestimating but also not underestimating PV R&D investments.

¹⁷⁸ WIPO, World Intellectual Property Indicators 2009, 2009

¹⁷⁹ EC, The 2009 EU Industrial R&D Investment Scoreboard, 2009

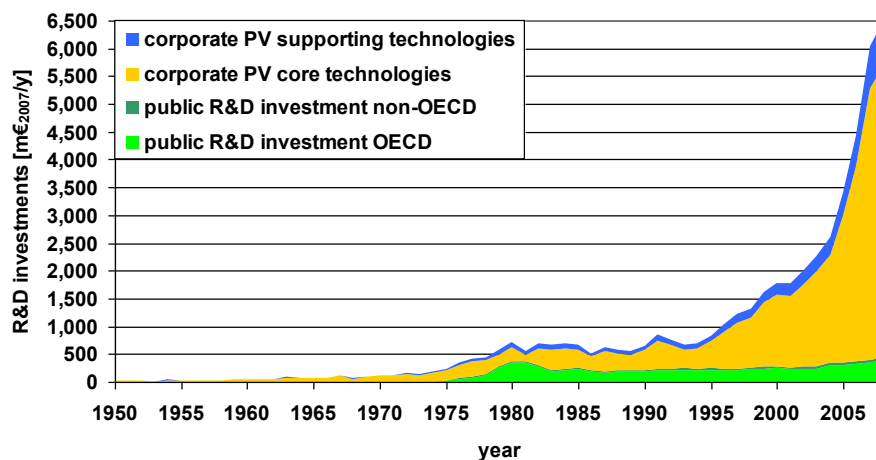
¹⁸⁰ WIPO, World Intellectual Property Indicators 2009, 2009

¹⁸¹ EC, The 2009 EU Industrial R&D Investment Scoreboard, 2009

Besides PV core technologies, like all kinds of solar cells, PV modules, inverters, system technologies and PV specific material, consumable and equipment innovations, there is a significant technological spill-over from neighbouring industries, e.g. glass, semiconductor material and manufacturing equipment of similar industries. These supporting technologies are estimated by Q-Cells' internal patent monitoring process, i.e. which patents are detected by a broad definition of technical fields in relation to PV and inverter patents of the definition used for this publication. About 95% more patents are detected by applying the broad definition versus the core definition used here. Nevertheless, the additional technical innovations can be used in several industries and PV industry might be of minor importance for respective assignees, hence relevance is estimated for PV industry by 15%, which in consequence lead to additional effective R&D investments of 14% by supporting technologies used in PV industry.

Difficulty in exact identification of PV patents lead to a further adjustment. A deviation of about 50% of detected PV patent families in the analysis to the entire patent family portfolio of leading PV companies (Table 3.1-1) is found, i.e. these companies applied for twofold the patents found by the search in PV patent databases. It is very likely that most of these patent applications are related to PV. However, by analysing some of these patent portfolios one can estimate that about 50% of those patent families belong to the group of supporting technologies, hence are included in the above estimates. The other 50% of estimated core PV patent applications are added to the detected PV core technologies.

Combining datasets of international PV and inverter patent families, assuming average R&D investment per international PV related patent family of 2.6 m€, including 50% not detected PV patent families, adding additional 14% of PV core technology R&D investments due to supporting technologies and datasets of public PV R&D investments one can compute best possible estimated annual and historic cumulated PV R&D investments (Fig. 3.1-15). Current annual PV R&D investments are estimated to be about 5.7 and 0.8 bn€ for PV core and supporting technologies, respectively. These R&D investments are funded to slightly less than 10% by public and to slightly more than 90% by corporate PV R&D investments (Fig. 3.1-16) whereas most of current generated resources of PV companies are supported by RES market introduction programmes, except space and most off-grid applications.



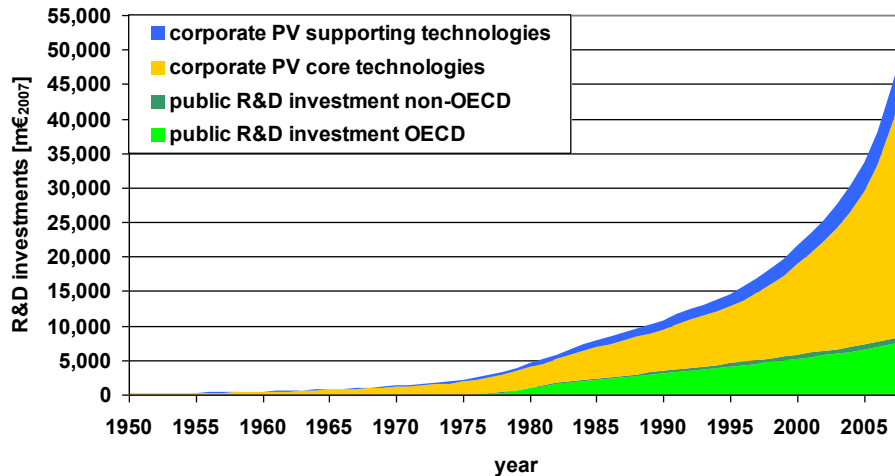


Figure 3.1-15: Total PV R&D investments estimated by international patent families per year (top) and historic cumulated (bottom) for the years 1950 – 2008. PV core technologies are all types of solar cells, modules, inverters, system technologies and manufacturing equipment. PV supporting technologies account for spill-over from other industries. Public R&D investments of OECD countries are taken from Figure 3.1-6, and non-OECD investments are estimated according to assumptions mentioned in section 3.1.3.1.2.

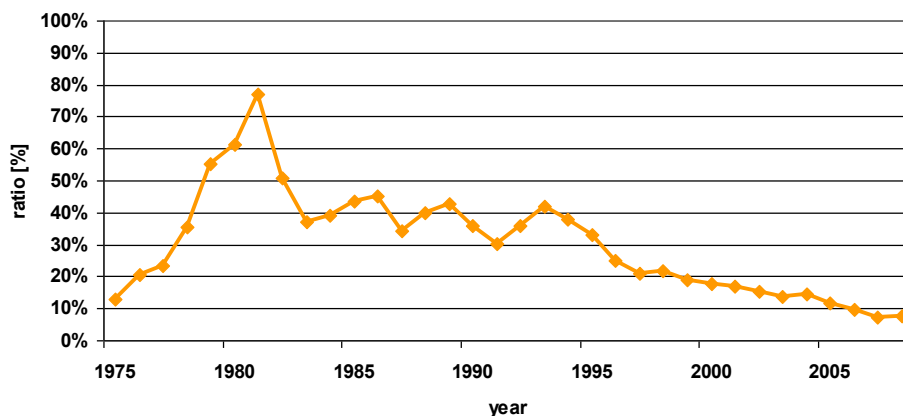


Figure 3.1-16: Ratio of public to total PV R&D investments for the years 1975 – 2008.

Global historic cumulated PV R&D investments can be estimated to be 44.2 bn€ for PV core and 6.3 bn€ for PV supporting technologies. Historic cumulated public PV R&D investments are in the order of about 9 bn€, hence corporate PV R&D investments can be estimated to be about 80% of total historic cumulated R&D investments of PV core technologies.

Bottom-up analysis of current annual corporate R&D investments leads to an estimate of about 3.1 bn€ (last section). Top-down analysis of current annual corporate R&D investments lead to an estimate of about 5.7 bn€. Difference of both approaches is about 2.6 bn€ or 50% of top-down approach. Two fundamental reasons for that difference are possible. Firstly, for bottom-up approach only 107 companies are taken into account and all others are estimated by a 60% coverage of companies providing at least one indication of R&D investments. If the real coverage had been 29%, one would estimate total corporate PV R&D investments to about 5.7 bn€. Secondly, for top-down approach one could assume average cost of international PV patent families of about 1.4 m€ and current annual corporate PV R&D investments would be about 3.1 bn€. Despite of these possible adjustments, the assumption

seems to be more convincing that the derived numbers do best possibly reflect in average the real data.

Summing up, total current annual PV R&D investments including supporting technologies might be between 3.6 and 7.0 bn€, of which current annual corporate PV R&D investments might be between 3.1 and 6.5 bn€.

3.1.3.3.6 Global PV R&D Workforce

Financial R&D investments do not show the full picture of resources engaged in PV R&D. A substantial R&D workforce seems to be active in order to steadily improve PV products, manufacturing processes and reduce cost. A global PV R&D headcount can be estimated by average total R&D expenditures per employed R&D associate, including wages, general overhead, research material and equipment. Global total R&D investments have been about 1,360 bn€ in 2007 and global R&D workforce had been about 10.9 million employees, hence global weighted average total cost per R&D employee is about 125 k€¹⁸². This estimate is quite close to the outcome for the 22 leading PV companies with documented R&D staff (Table 3.1-1) which spend about 110 k€ per R&D employee. European Commission¹⁸³ found for 31 investigated companies for 55% of them overall R&D investments per employee between 120 and 150 k€. Applying global average total R&D expenses of 115 k€ per R&D employee to total PV R&D investments estimated by international PV patent families a current global R&D headcount of about 69,000 researchers is very likely (Fig. 3.1-17). Global PV R&D workforce grew by a factor of five in the last decade and represent currently 0.6% of global R&D workforce.

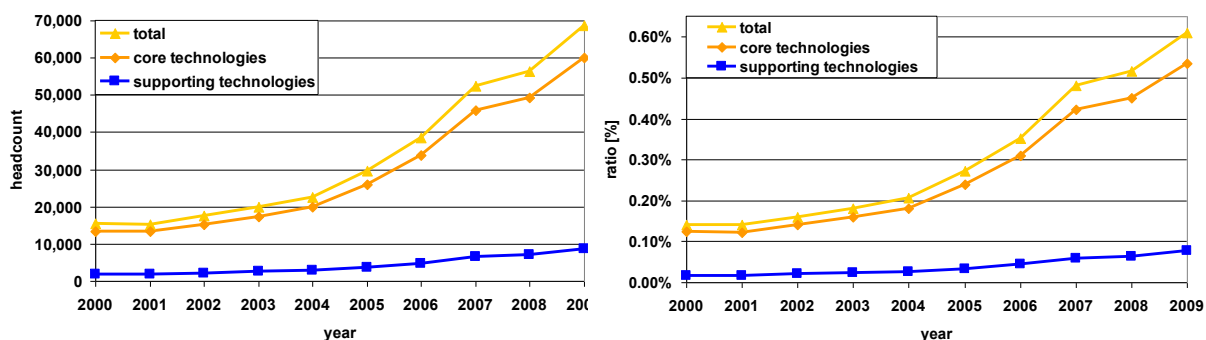


Figure 3.1-17: PV R&D headcount in global absolute numbers (left) and in ratio to total global R&D headcount (right) for the years 2000 – 2009.

An approach to estimate especially the R&D workforce in public institutions such as universities and research institutes, is to investigate scientific PV publications. Hence, the number of PV researchers is estimated by analysing the number of authors contributing to the big PV conferences in the year 2009. Around 3,728 authors contributed to the 24th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), September 2009 in Hamburg, in comparison to 3,068 authors at the 23th EU PVSEC. The 34th IEEE Photovoltaic Specialist Conference, June 2009 in Philadelphia saw 1,901 contributing authors, compared to 1,589 authors the year before. No aggregated data is available for the 19th Asia-Pacific Photovoltaic Science and Engineering Conference and Exhibition hold November 2009 in

¹⁸² UN, Statistical Yearbook 52nd issue, 2008

¹⁸³ EC, R&D Investment in the Priority Technologies of the European Strategic Energy Technology Plan, 2009

Jeju, South Korea. Therefore the data are used for the 18th PVSEC Asia-Pacific with roughly 591 contributing authors. There is a certain uncertainty in these numbers, because sometimes the same authors have been listed more than once in the data of the conference proceedings. Authors are counted with both the same surname and the same first initial only once. Therefore the presented numbers slightly underestimate the actual numbers of authors, because there might have been different authors with the same surname and the same first initial. Obviously, the group of participants at the different conferences are not distinct. For example 33 individuals are identified who contributed to all five mentioned conferences, and 683 individuals that contributed to at least three conferences. Therefore, the overlap between the different conferences is determined. Around 536 of the participants of the 24th EU PVSEC participated at the 34th IEEE Specialist Conference, which corresponds to around 14%. This means in return that around 28% of the participants of the IEEE conference attended the EU PVSEC as well. Hence there are a total of 5,093 individual authors contributing at least one of these two conferences. About 165 authors contributed both to the 24th EU PVSEC and the 18th PVSEC Asia-Pacific, and 122 authors to both 8th PVSEC Asia-Pacific and 34th IEEE Specialist Conference. By considering the 68 authors that contributed to all this three conferences the total number can be calculated to around 5,465 researchers contributing to the big three PV conferences in the year 2009.

The large majority of authors publishing at the leading international PV conferences in 2009 worked for public institutions. From counts at Fraunhofer-ISE, Freiburg (Germany), it is estimated that between 70% - 90% of the active researchers (counting employed researchers, technicians, PhD and Master students, but not students doing part time work during there studies) at dedicated research institutions participated at least at one publication. This leads to an estimate for the total number of researchers in public institutions between 6,000 and 8,000. Not surprisingly, the ratio between the number of researches at public institution to the number of researches employed in companies of very roughly 1:9 is reflected as well in the ratio of public R&D investment to corporate investment of about 500 m€ public money to 3,100 – 6,500 m€ corporate investment.

Similar to other technology driven industries, PV companies invest significant resources in R&D for generating new and more cost effective PV products. Both bottom-up and top-down approaches for estimating current annual corporate PV R&D investment provided comparable results of 3 – 6 bn€. Global historic cumulated PV R&D investments are estimated to be about 44 – 50 bn€. Current global PV R&D headcount is estimated to 69,000 researchers and about 5,500 of them publish their results at international PV conferences.

3.1.3.4 Discussion of Major Results of PV R&D Investment Analysis

Results presented in last sections clearly document an enormous growth of PV in production, sales, R&D investments, patent applications and R&D headcount. R&D related indicators are the key drivers for constant high learning rate of 20%, which is a fundamental driving force for ongoing cost reduction and enables steadily new markets which have been generating a high growth rate of about 45% which is the second fundamental driving force for a fast cost reduction. In the following some comparisons are drawn for the major results of PV R&D investments analysis and the PV market potential in relation to relevant industries (section 3.1.3.4.1), general sustainability requirements (section 3.1.3.4.2) and in particular in contrast to nuclear energy (section 3.1.3.4.3) but also to the willingness to invest for major public technological projects in the last decades (section 3.1.3.4.4).

3.1.3.4.1 PV R&D and Market Potential in Relation to Relevant Comparable Industries

Current public and corporate PV R&D investments are estimated to be about 400 – 500 m€ and 3,100 – 6,000 m€, respectively. Current total PV R&D investments comprising PV core and supporting technologies are about 6.5 bn€ representing slightly more than 12.7% of global PV industry sales of 51 bn€. About 90% of current global PV R&D investments are directly financed by companies, whereas nearly the entire market is supported by public PV market introduction programmes, hence indirectly publicly funded. Nevertheless, several large companies with significant PV R&D activities have not yet sold PV products and consequently had to finance R&D on their own. Total corporate PV R&D investments are moderate compared to leading technology driven companies, which invest significant amounts of resources in R&D, numbers for 2008 of the European Commission¹⁸⁴ are for some companies: Microsoft (6.5 bn€), Volkswagen (5.9 bn€), Nokia (5.3 bn€), Panasonic (4.4 bn€), Intel (4.1 bn€), Siemens (3.8 bn€), Samsung (3.5 bn€) and Google (2.0 bn€).

In 2008 R&D investments of semiconductor companies had been about 31 bn€ which had been 12.9% of semiconductor industry sales of 241 bn€.¹⁸⁵ Growth rate in semiconductor industry sales is limited due to high learning rates¹⁸⁶ and tough competition. Semiconductor industry sales might be compared to PV industry sales in late 2010s to mid 2020s. Assuming ongoing high PV growth rates of 30% – 45% PV industry could annually produce 100 GWp and 200 GWp in late 2010s and mid 2020s, respectively. Corresponding global average system sales prices at that time would be about 1.5 and 1.0 €/Wp for 100 and 200 GWp, hence annual sales volumes for PV systems of about 150 and 200 bn€ can be expected, respectively. Additional sales will be for new manufacturing plants and operation of total installed PV capacity. Sales volumes of PV might cross those of semiconductor industry in the 2020s. Current annual global energy sales are 5,400 bn€ (fossil fuels), 2,300 bn€ (energy supply infrastructure), 1,000 bn€ (power plants) and 8,700 bn€ (energy in total).¹⁸⁷ First market induced growth limits are not expected within next two decades. Consequently, further high growth in PV industry sales and corporate PV R&D investments is very likely.

3.1.3.4.2 Sustainability Requirements and Public Renewable Energy R&D Investments

Current public renewable energy sources R&D investment is substantially too low for a fast and successful tackling of climate change, diminishing fossil and nuclear energy resources, energy insecurity and energy injustice. Several leading institutions and scientists claim significant higher public R&D investments. International Energy Agency suggests a 2.5 – 5 times higher need for public solar energy R&D expenditures.¹⁸⁸ Lord Nicholas Stern recommended a doubling in public energy R&D including an immediate shift to clean energy technologies.¹⁸⁹ Nemet and Kammen give arguments for five to ten times higher public

¹⁸⁴ EC, The 2009 EU Industrial R&D Investment Scoreboard, 2009

¹⁸⁵ EC, The 2009 EU Industrial R&D Investment Scoreboard, 2009

¹⁸⁶ Hoffmann W. et al., Differentiated Price Experience Curves as Evaluation Tool for Judging the further Development of Crystalline Silicon and Thin Film PV Solar Electricity Products, 2009

¹⁸⁷ Hartmann A. and Huhn W., (eds.), Wettbewerbsfaktor Energie: Neue Chancen für die deutsche Wirtschaft, 2009

¹⁸⁸ IEA, Global Gaps in Clean Energy Research Development and Demonstration, 2009

¹⁸⁹ Stern N. (ed.), Stern Review on the economics of climate change, 2006

energy R&D investments.¹⁹⁰ United Nations Framework Convention on Climate Change and European Commission claim two and three times higher public energy R&D investments for achieving respective climate change mitigation targets.^{191,192} Schock et al. value energy R&D by estimating the cost of the insurance needed against four types of energy related risks (oil price shocks, power supply disruptions, local air pollution and climate change) and concluded that energy R&D needs to be increased by a factor of four.¹⁹³ All these results are also true for public PV R&D investments.

Besides current need for accelerating R&D, insights can be extracted by comparing data on energy R&D investments in the last decades. Historic cumulated public and corporate PV R&D investments are estimated to be about 9 bn€ and 35 – 41 bn€, respectively. In this decade these investments enable today's powerful global PV industry to address fast growing new commercial PV markets which will be an obvious economic consequence of grid-parity and fuel-parity events all around the world (sub-chapters 3.3 and 3.4 and chapters 6 and 7).

3.1.3.4.3 R&D Investment and Sustainability Impact – The Example of PV and Nuclear Energy

Historic energy R&D investments in OECD countries had been about 650 bn€ for the period mid 1970s – 2008, whereas nuclear energy absorbed more than 50% (Fig. 3.1-4). Public solar PV and RES R&D investments in OECD accounted for 7.2 and 28.3 bn€ for that period representing 1.1% and 4.4% of cumulated energy R&D investments, respectively. It is possible to estimate global historic cumulated nuclear R&D investments by combining nuclear R&D dataset for US and OECD for the years 1974 – 2008 and US nuclear subsidies for 1947 – 1999¹⁹⁴ and assuming similar R&D to overall subsidy ratio for other OECD countries and an OECD to global nuclear R&D ratio of 70%, a consequence of large nuclear R&D programmes in non-OECD countries like former Soviet Union, Russia, China, India, Pakistan, Brazil, South Africa, Libya and Iran. Adjustment of datasets to 2008 € currency value is applied.¹⁹⁵ Results for OECD nuclear R&D investment are 196 bn€ (1947 – 1973), 178 bn€ (1974 – 2008) and 374 bn€ (1947 – 2008). Therefore, global historic cumulated nuclear R&D investment can be estimated to about 534 bn€. Ratio of global historic cumulated public R&D investment for PV and nuclear is 9 to 534 bn€, i.e. PV R&D has been cost 1.7% of nuclear R&D. This result agrees with the results of the Goldberg report which conclude that total US energy subsidies had been 0.8% (wind power), 2.9% (PV/ STEG) and 96.3% (nuclear power).¹⁹⁶ Nuclear R&D investments in OECD have been 143.7 and 88.4 bn€ for the years 1979 – 2008 and 1986 – 2008, respectively. Severe nuclear accidents happened in 1979 in Harrisburg and 1986 in Chernobyl. Despite of these warning signs massive nuclear R&D investments in OECD and non-OECD countries have been continued. However, several international leading financial institutions have already documented that new nuclear power plants can only be financed by massive public grants and subsidies.^{197,198} Already in late

¹⁹⁰ Nemet G.F. and Kammen D.M., US energy research and development: Declining investment, increasing need, and the feasibility of expansion, 2007

¹⁹¹ UNFCCC, Investment and financial flows to address climate change, 2007, pp. 86-92

¹⁹² EC, R&D Investment in the Priority Technologies of the European Strategic Energy Technology Plan, 2009

¹⁹³ Schock R.N. et al., How Much is Energy Research & Development Worth as Insurance?, 1999

¹⁹⁴ Goldberg M. (ed.), Federal Energy Subsidies: Not all Technologies are created equal, 2000

¹⁹⁵ OECD, Price indices (MEI), 2010

¹⁹⁶ Goldberg M. (ed.), Federal Energy Subsidies: Not all Technologies are created equal, 2000

¹⁹⁷ Roy M. et al., Loan Guarantees for Advanced Nuclear Energy Facilities - Bankers' Comments on DoE Notice of Proposed Rulemaking, 2007

¹⁹⁸ Moody's, Nuclear plant construction poses risks to credit metrics ratings, 2008

1970s imbalance of nuclear and solar energy R&D investments in reference to technological, economic and even democratic criteria was fully understood.¹⁹⁹

True cost of nuclear electricity is in the order of 14 – 21 €/kWh^{200,201} still excluding substantial public subsidies for lack of full private insurance for nuclear accidents of any kind, which would be in the order of 0.14 to 67 €/kWh²⁰². This needs to be compared to today's cost of about 24 €/kWh for PV power plants in Germany in 2010 (sub-chapter 3.3) and 11 €/kWh for financially and technically optimised PV power plants in Middle East countries in 2010.²⁰³ Blackburn and Cunningham called this economic fact the historic crossover of PV and nuclear energy.²⁰⁴ Notably, PV needed less than 2% of nuclear R&D investment to reach that historic milestone.

Nuclear energy which absorbed more as 50% of tight public energy R&D investments in OECD for the period 1974 – 2008 and much more in the period 1947 - 2008 does not fulfil at least one sustainability criteria²⁰⁵. Besides true cost of nuclear electricity in the order of at least 14 – 21 €/kWh^{206,207}, further subsidies are needed especially for costly decommissioning^{208,209}, uranium resources are very limited (section 1.3.4)²¹⁰, environmental and health risks associated with mining^{211,212}, nuclear power plant learning rate is negative²¹³ and general risk for global security is structural high, due to nuclear proliferation, nuclear terrorism, very high technological complexity, unsolved nuclear waste disposal and nuclear melt-down risk, like in Chernobyl and Fukushima. It needs to be emphasised that solar PV fulfils and nuclear energy violates all relevant sustainability criteria. Even specific GHG emissions are higher for nuclear energy by a factor of three to four and relative difference is growing²¹⁴ (section 3.1.7.1).

3.1.3.4.4 Willingness to Invest for Major Public Technological Projects: A 20th Century Experience

In historic context significant amounts of financial resources had been regularly available for military and cold war competition but not for sustainable and peaceful renewable energies. Spending on such programmes had been about 30 bnUSD (Manhattan Project in the years 1940 – 1945), 220 bnUSD (Apollo Program in the years 1963 – 1972), 531 bnUSD (Reagan

¹⁹⁹ Hammond A.L. and Metz W.D., Solar Energy Research: Making Solar After the Nuclear Model?, 1977

²⁰⁰ Severance C.A., Business Risks and Costs of New Nuclear Power, 2009

²⁰¹ Blackburn J.O. and Cunningham S., Solar and Nuclear Costs: The Historic Crossover - Solar Energy is Now the Better Buy, 2010

²⁰² Günter B. et al., Berechnung einer risikoadäquaten Versicherungsprämie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren, 2011

²⁰³ Breyer Ch. et al., Value of Solar PV Electricity in MENA Region, 2010d

²⁰⁴ Blackburn J.O. and Cunningham S., Solar and Nuclear Costs: The Historic Crossover - Solar Energy is Now the Better Buy, 2010

²⁰⁵ Bundtland G.H. (ed.), Our common future, 1987

²⁰⁶ Severance C.A., Business Risks and Costs of New Nuclear Power, 2009

²⁰⁷ Blackburn J.O. and Cunningham S., Solar and Nuclear Costs: The Historic Crossover - Solar Energy is Now the Better Buy, 2010

²⁰⁸ Meyer B. et al., Staatliche Förderung der Atomenergie, 2009

²⁰⁹ NAO, The Nuclear Decommissioning Authority: Taking forward decommissioning, 2008

²¹⁰ Barnaby F. and Kemp J., (eds.), Secure Energy? – Civil Nuclear Power, Security and Global Warming, 2007

²¹¹ Meyer C., Der gelbe Fluch, 2010

²¹² Auth S. et al., Uranium - is it a country? Eine Spurensuche nach der Herkunft von Atomstrom, 2008

²¹³ Grubler A., The cost of the French nuclear scale-up: A case of negative learning by doing, 2010

²¹⁴ Sovacool B.K., Valuing the greenhouse gas emissions from nuclear power: A critical survey, 2008

defence in the years 1981 – 1989), 7,962 bnUSD (US nuclear weapon program in the years 1940 - 1996) and 223 bnUSD (War on Terror in the years 2002 – 2004) in 2009 USD.^{215,216} Project Independence as a consequence of oil price crises was funded with 60 bnUSD.²¹⁷ Today's visionary solar energy based large scale infrastructure projects in the US^{218,219} and EU-MENA region²²⁰ would cost subsidies of about 420 bnUSD for about 70% solar powered electricity in the US ('A Grand Solar Plan') and investments of about 400 bn€ for a solar powered backbone in EU-MENA (DESERTEC) - only a small fraction of military and cold war programs of the 20th century, but at a very high socio-economic return.

Facts summarized in this section document a dramatic international policy failure of historic dimension, despite of very early high level recognition of global benefits of a solar energy pathway by US President Jimmy Carter²²¹.

3.1.4 Regional Markets

High growth rates of PV markets (Fig. 3.1-1) have led to substantial PV industry sales in the last decade (Fig. 3.1-18). Three major categories of PV industry sales are regarded: capital expenditures (Capex) for new PV systems, Capex for new manufacturing plants and operational expenses (Opex) for existing PV systems. Industry sales are dominated by Capex for systems and manufacturing plants. Due to a very small basis but constant high PV growth rates (Fig. 3.1-1) significant PV industry sales have been starting in mid 1990s as a consequence of roof-top programmes and FiT laws.

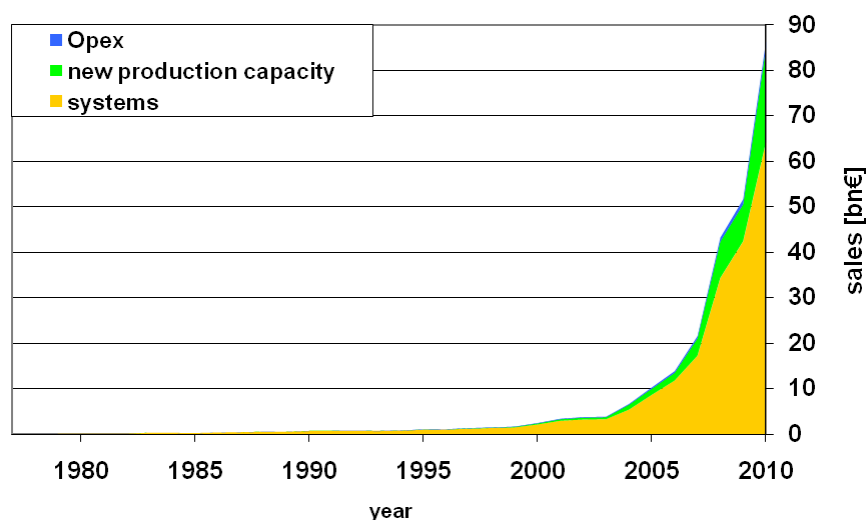


Figure 3.1-18: PV industry sales for the years 1979 – 2010. Sales are calculated by a global average PV system selling price (ASP) of 2.95 €/Wp (2010) and 4.3 €/Wp (2009), a global installation of 17.7 GWp (2010) and

²¹⁵ Nemet G.F. and Kammen D.M., US energy research and development: Declining investment, increasing need, and the feasibility of expansion, 2007

²¹⁶ Schwartz S.I. (ed.), Atomic Audit: The Costs and Consequences of US Nuclear Weapons since 1940, 1998

²¹⁷ Nemet G.F. and Kammen D.M., US energy research and development: Declining investment, increasing need, and the feasibility of expansion, 2007

²¹⁸ Zweibel K. et al., A solar grand plan, 2008

²¹⁹ Mason J. et al., Coupling PV and CAES Power Plants to Transform Intermittent PV Electricity into a Dispatchable Electricity Source, 2008

²²⁰ Knies G. (ed.), Clean Power from Deserts, 2009

²²¹ Carter J., Solar Energy: Proposals for a National Solar Energy Strategy, 1979

7.2 GWp (2009) and production of 27.2 GWp (2010) and 12.3 GWp (2009), respectively, ^{222,223,224,225} capital expenditures (Capex) for new capacities (ores to systems) of 1.4 bn€/GWp (2010) and 2 bn€/GWp (2009) ^{226,227} and operational expenses (Opex) for PV installed base of 1% of historic Capex. Numbers for previous years had been processed similarly.

High relative and absolute growth of PV industry sales is driven by high PV production growth rates, which are higher than sales growth rates as a consequence of decreasing average selling prices of PV products as result of the learning curve (Fig. 3.1-3). PV industry sales curve in Figure 3.1-18 does not indicate any decline in growth rates, as an inflexion point in a s-curve would represent such a slow down in market dynamics. No reduction in growth of annual installation or production can be found, but a drastic decline in average selling prices for PV systems in the years 2009 and 2010 as a consequence of fast cost reduction according to the learning curve but also due to a sharp reduction in profit margins in the PV industry caused by financial crises effects and the collapse of the Spanish markets in the end of 2008. Accessible data for all relevant on-grid PV markets (Fig. 3.1-19) identify the major countries which financed the industrial breakthrough of PV as a potential major source of energy for the 21st century. Germany, Japan and the US had been the major markets for nearly the entire period identical to public PV R&D investments (Fig. 3.1-6). In the last years new large on-grid markets for PV have become France, Italy, Czech Republic, Belgium and Spain, whereas the latter spiked in 2007 to 2008 and collapsed afterwards as a consequence of design failures of the market introduction programme.

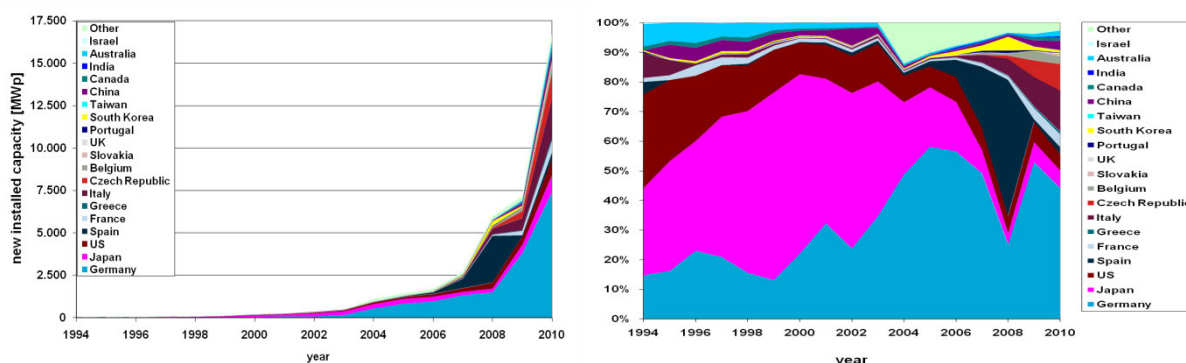


Figure 3.1-19: PV markets in absolute (left) and relative (right) numbers per country for the years 1993 – 2010. Data are taken from IEA-PVPS ²²⁸, EPIA ²²⁹ and Q-Cells Market Research.

PV markets depicted in Figure 3.1-19 highlight only the largest markets in the world, but it is known that in many other countries PV is used for a long time, in particular in developing and emerging countries. ^{230,231} Installations in these countries are usually grouped under the expression ‘Rest of World’. Publications by EPIA ^{232,233} and IEA ^{234,235,236,237} report a

²²² Bolman C. et al., Solar Annual 2010-2011: Cash In, 2011

²²³ Hering G., Survey on cell production 2010: Year of the tiger, 2011

²²⁴ EPIA, Global Market Outlook for Photovoltaics until 2014, 2010

²²⁵ Hirshman W.P. and Schug A., Von wegen Krise: Solarzellenproduktion im Jahr 2009, 2010

²²⁶ Fath P., Fully-integrated c-Si module production towards 0.60 €/Wp, 2011

²²⁷ Fath P. et al., centrotherm's grid parity factory, 2009

²²⁸ IEA-PVPS, Trends in PV Application: Survey report of selected IEA countries between 1992 and 2009, 2010

²²⁹ EPIA, Global Market Outlook for Photovoltaics until 2014, 2010

²³⁰ McNelis B., Promoting PV in Developing Countries, 2010

²³¹ Miller D., Selling Solar – The Diffusion of Renewable Energy in Emerging Markets, 2009

²³² EPIA, EPIA Annual Report 2009, 2010

²³³ EPIA, Global Market Outlook for Photovoltaics until 2015, 2011

cumulative installed PV power by end of 2010 of 39,953 MWp and 34,953 MWp, respectively. EPIA gives data for 36 countries in the world, whereas 2,075 MWp are claimed to be allocated in other than those directly named countries. IEA provides data for 22 countries with 2,439 MWp being estimated to be allocated in the rest of world.

For better understanding of global PV allocation public available data for PV installed base is collected, in particular provided by EPIA, IEA, GIZ and Photon. These data are complemented by interviews of experts from selected countries and Q-Cells' internal market research insights. Overview on all used sources and further details can be found elsewhere²³⁸. PV products, especially solar cells and solar modules are produced in only a few countries, but being sold to customers all over the world. These global trade relationships are documented by International Trade Centres (ITC). ITC data is accessible for about 190 countries for the years 2001 – 2010.²³⁹ The trade values are counted in USD, which enables the derivation of exported and imported PV capacity by applying average selling prices for respective years and groups of countries. Combining these two structurally different sources of PV related data enables the possibility to extract a comprehensive list of cumulative installed PV power capacities for all countries in the world. Consequently, non allocated PV power capacity is reduced to a minimum.

Market data for cumulative installed PV power are available for 102 countries by combining separated insights by EPIA (36 countries), Q-Cells' Market Research (35 countries), IEA (22 countries), Photon (20 countries), World Bank (8 countries), Infinergia Consulting (42 countries), Euroobserver (27 countries), EuPD Research (10 countries) and GIZ (4 countries).²⁴⁰ EPIA provides data for PV global installed base, but 2,075 MWp are allocated unnamed, being assumed to rest of world (RoW) countries. By combining all available data for the total of 102 countries it is possible to reduce RoW allocation by about 1,000 MWp in reference to EPIA. Analysis of ITC data for the years 2001 – 2010 enables an allocation of 120 MWp in 88 additional countries. Insights of local experts in several countries complement all other data. Resulting 1,075 MWp expected to be installed in RoW cannot be explained, however 487 MWp are assumed to be installed before 2001, i.e. it is not possible to generate PV market insight by ITC data applying this method. In this way, further 512 MWp of assumed PV installations of the years 2001 – 2010 cannot be allocated. This might be caused by shifted PV installations in respective following year, price deviations or simply incorrect prevailing market size assumptions.

PV installations are realised in at least 193 countries in the world, plotted in Figure 3.1-20. Besides well known large PV markets in industrialized countries (Fig. 3.1-19), several developing countries show a significant installed PV base, in particular Bangladesh (35 MWp), the Philippines (12 MWp), Nigeria (12 MWp), Indonesia (9 MWp), Kenya (9 MWp), Vietnam (7 MWp), Ethiopia (7 MWp), Sri Lanka (5 MWp), Senegal (5 MWp) and many more. In these countries typically PV installations are realized as solar home systems (section 3.4.1) of an average size of 50 Wp each, i.e. an installed base of 5 MWp represent coverage of basic energy needs for about 100,000 families.

²³⁴ IEA-PVPS, Trends in PV Application: Survey report of selected IEA countries between 1992 and 2009, 2010

²³⁵ IEA, World Energy Outlook 2009, 2009

²³⁶ IEA-PVPS, Trends in PV Application: Survey report of selected IEA countries between 1992 and 2008, 2009

²³⁷ IEA-PVPS, Trends in PV Application: Survey report of selected IEA countries between 1992 and 2010, 2011

²³⁸ Werner C. et al., Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, 2011

²³⁹ ITC, International Trade Centre Market Analysis Tool, Product Map, 2011

²⁴⁰ Werner C. et al., Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, 2011

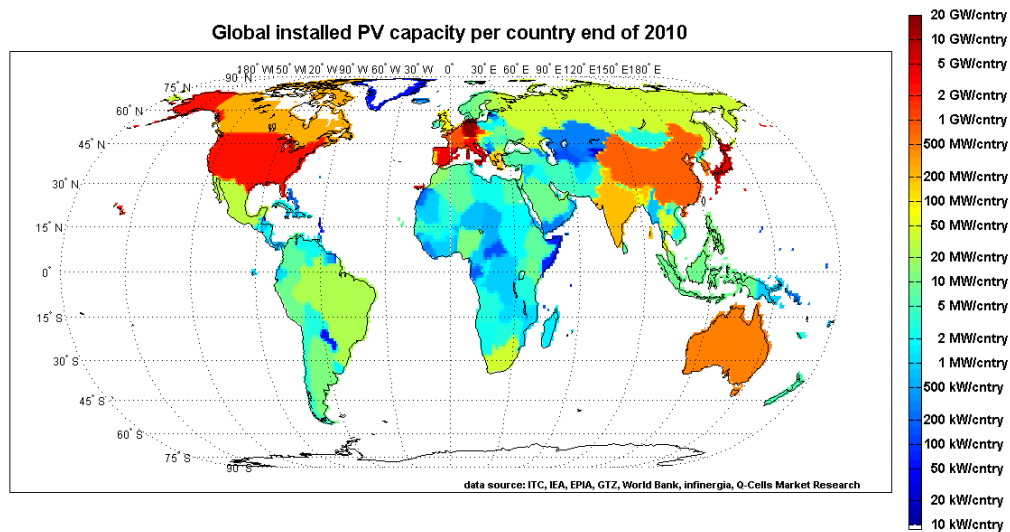


Figure 3.1-20: Global installed PV capacity per country by end of 2010. Data sources are described elsewhere²⁴¹. More details for all coloured countries can be found in the Appendix Table 2.

Figure 3.1-21 gives an overview on PV market growth in 2010. Some countries have reached huge growth rates in 2010. The Cape Verde PV market has grown more than 4500% due to having installed a 7.5 MWp PV power plant. But not only developing countries show high growth rates in 2010. Slovakian cumulative PV installations in 2010 are more than 1700% higher than by the end of 2009. Respective growth rates are reached in nearly all regions in the world. Several European PV markets have more than doubled in cumulative installed PV capacity (Czech Republic, Romania, Greece, Bulgaria, Italy, UK, France and Belgium). The dominant German market reached a growth rate of 78%, while other countries show growth rates not higher than 10% (e.g. Spain and Finland). Chinese PV installations have grown by about 180%. East Asian PV markets show growth rates typically in the order of about 40% - 50%, whereas South and South East Asian markets seem to explode with several countries reaching growth rates of more than 100% - 200% (the Philippines, Cambodia, Maldives, Vietnam, Myanmar, Mongolia, Laos, Nepal and Singapore). The Australian market has reached a growth rate of 190%. Most of the African markets grew very fast. Especially Cape Verde, Botswana, Djibouti, Zimbabwe, Togo, Swaziland, Uganda and the Comoros need to be distinguished. Growth rates in the Americas are quite different. While the markets of Uruguay (750%), Guyana (490%), Peru (420%), Costa Rica (380%), Barbados (250%), Guatemala (240%) and Canada (180%) have grown on a high scale, markets like Venezuela (2%), Mexico (8%) and Bolivia (14%) remained nearly static. The Brazilian market has grown by 38% and the PV installations in the United States grew by about 50%.

One can clearly see that every world region has the potential to become a great PV market. Enormous growth rates in specific regions of the world show that PV is on the way to become an important part of electricity supply. Notably, the majority of the 193 countries grew by more than 50% in the cumulative installed PV capacity in the year 2010, and 55 countries grew by even more than 100%. Some developing countries are on the road to solar electrification. Lower energy costs enabled by reduced dependence on energy imports, will contribute to lead these countries to sustainable development and stable growth.

²⁴¹ Werner C. et al., Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, 2011

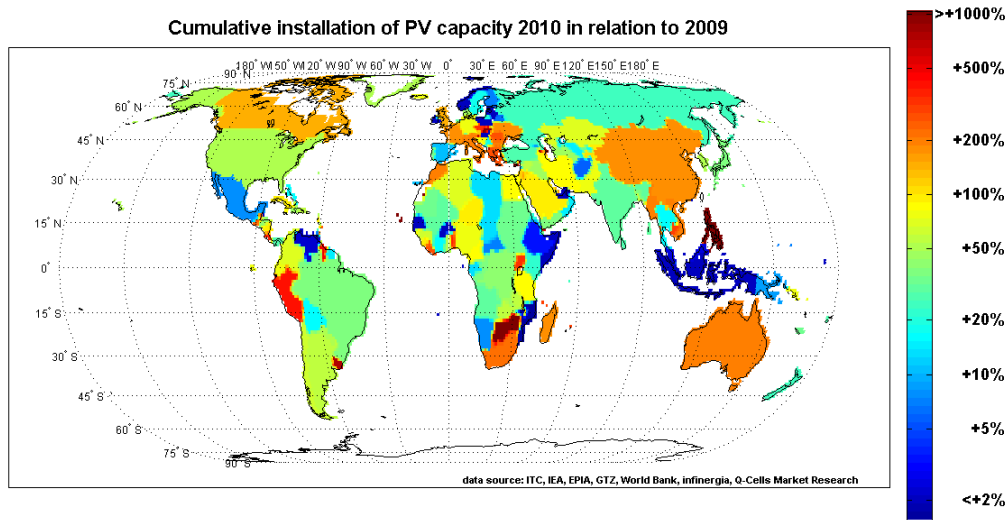


Figure 3.1-21: Growth rate of cumulative installed PV capacity in the year 2010. Displayed is the ratio of added PV capacity in 2010 to cumulative PV installations in 2009. Data sources are described elsewhere^{242,243}. More details for all coloured countries can be found in the Appendix Table 2.

People in several developing and emerging countries have recognised the potential of PV installations for decentralised energy supply to overcome low electrification rates (Fig. 3.1-21 to and 3.1-23). Furthermore, this is reflected by higher PV installations in developing countries than in comparably rich countries of a gross domestic product (GDP) per capita of 20,000 – 30,000 USD or even more. Very poor countries like Bangladesh, Ethiopia, Kenya or West African countries have more installed PV capacity per GDP than for example the US. This might be caused by two fundamental reasons. Firstly, most of the installations in the mentioned countries are off-grid PV solutions, which are highly profitable (section 3.4.1). Secondly, governments in several developing countries might have recognised the enormous potential of PV for sustainable development pathways in their rural areas and for overcoming energy injustice (sub-chapter 1.4).

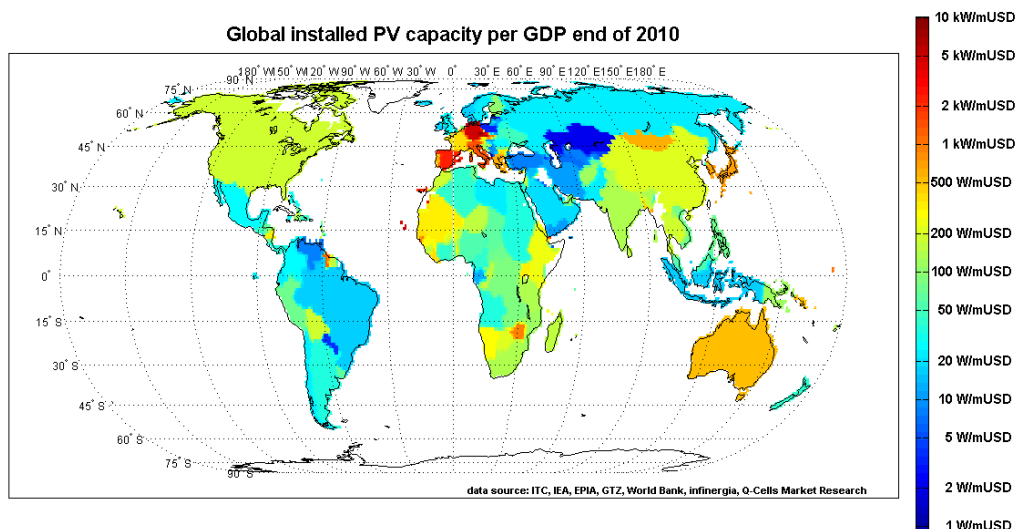


Figure 3.1-22: Global installed PV capacity per gross domestic product by end of 2010. Data are identical to Figure 3.1-20 plus GDP data taken from World Bank²⁴⁴. More details for all coloured countries can be found in the Appendix Table 2.

²⁴² Werner C. et al., Global Overview on cumulative installed Photovoltaic Power, 2011

²⁴³ Werner C. et al., Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, 2011

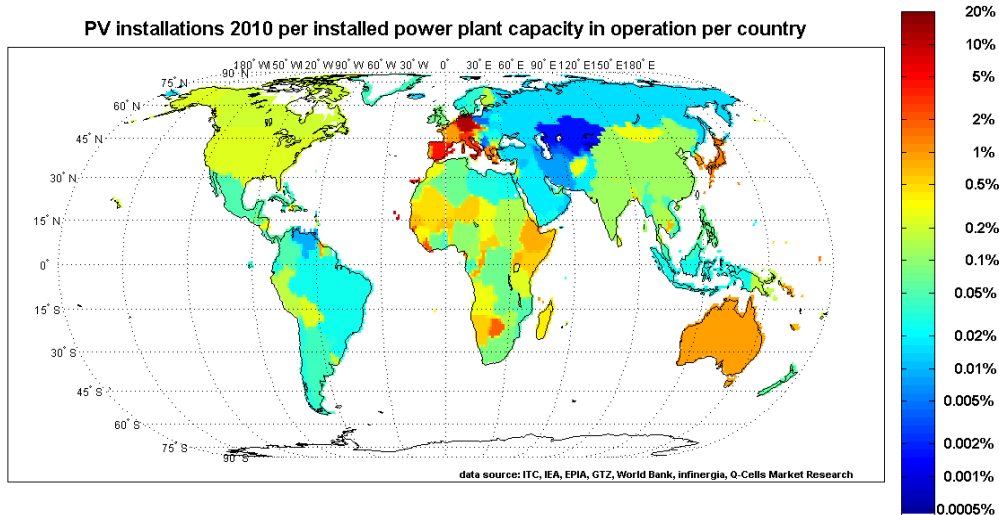


Figure 3.1-23: Ratio of global installed PV capacity to total power plant capacity per country by end of 2010. Data are identical to Figure 3.1-20 plus power plant data taken from UDI World Electric Power Plant database

Ratio of global installed PV capacity to total power plant capacity by end of 2010 clearly documents that all countries in the world show significant market potentials for PV systems. Without relevant grid constraints at least 10% of electricity generation can be supplied by PV systems (section 3.1.1.2). Population weighted annual irradiation on fixed optimally tilted modules is about 1,850 kWh/m²/y (section 2.3.1), equalling to about 1,500 full load hours of respective PV systems under the assumption of a performance ratio of 80%. Global average power plant full load hours are about 4,300 (sub-chapter 5.1). Summing up this key numbers, it would be possible to install at least 25% PV power plants of total power plant capacity. Including special hybrid PV power plant operation modes (chapters 6 and 7) and existing and arising electricity storage solutions (sub-chapter 7.4) this 25% threshold can be drastically increased towards 50%.

Development of PV markets is very heterogenous in the world and it was assumed that was mainly driven by market introduction programmes until the end of the 2000s. However, PV systems are already in operation in practically all countries in the world and show outstanding high growth rates for the majority of countries. This might be a good basis for an accelerated PV diffusion in the years to come.

3.1.5 Technology Diffusion

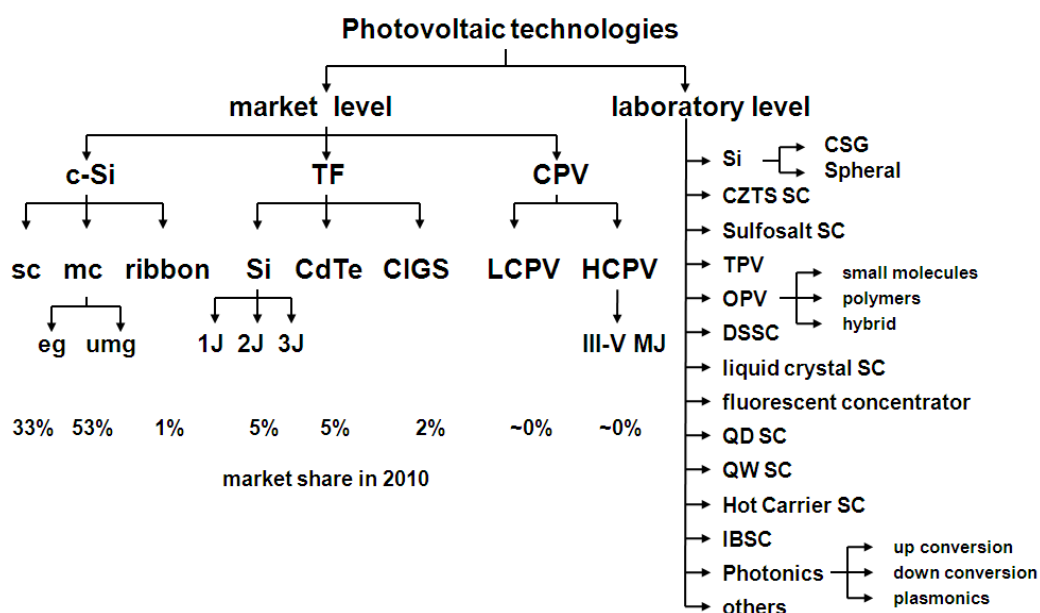
Photovoltaic is based on the separation of electrons from their atom cores by absorbing energy of photons. The electrons are lifted towards a higher energetic level in the semiconductor material of the solar cell. Such excited electrons are no longer energetically bounded to atom cores and thus are freely movable. The transport of these free charge carriers within the semiconductor is based on electric fields or diffusion processes. The excited electrons can be collected at metal contacts and the therein stored sun photon energy can be converted in an external current circuit from electric energy into the desired kind of final energy. During the conversion of the electric energy the equivalent amount of low energetic electrons flows back to the solar cell for balancing the total amount of charges. No

²⁴⁴ World Bank, Gross Domestic Production 2009, 2010

²⁴⁵ Platts, UDI World Electric Power Plants data base, 2009

other energy conversion mechanism can be operated in such an elegant way and without any mechanically moving elements.

Our knowledge on photovoltaic has been generated by an amazing number of outstanding scientists. The foundation of the field was laid by Edmond M. Becquerel (atomic theory), Albert Einstein (quantum mechanics) and William Shockley (information technology).^{246,247,248} The first solar cells have been invented by accident in the 1870s.²⁴⁹ In the 1930s, further progress in the field²⁵⁰ resulted in the proposal of transmitting solar energy by power lines from North Africa to Central Europe by a Siemens engineer.²⁵¹ In the early 21st century this vision might become reality.²⁵² The breakthrough for economic PV applications was the invention of silicon based solar cells in the Bell Labs in the 1940s and 1950s^{253,254} and a proper understanding of the physics behind²⁵⁵. Despite of small public PV R&D expenditures (section 3.1.3.1) a large variety of different solar cell types have been invented (Fig. 3.1-24) resulting in the recent record conversion efficiencies of 43.5%²⁵⁶ and 42.3%^{257,258} (Fig. 3.1-25). The most efficient modules on the market convert slightly more than 20% (non-concentrating) and 26% (concentrating) of incident radiant energy into electricity.^{259,260}



²⁴⁶ Becquerel E., Recherches sur les effets de la radiation chimique de la lumière solaire au moyen des courants électriques, 1839

²⁴⁷ Einstein A., Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt, 1905

²⁴⁸ Shockley W. and Queisser H.J., Detailed Balance Limit of Efficiency of p-n Junction Solar Cells, 1961

²⁴⁹ Smith W., Effect of light on selenium during the passage of an electric current, 1873

²⁵⁰ Schottky W., Photoelectric Generator, 1929

²⁵¹ Dominik H., Wunschträume beim Jahreswechsel, 1930

²⁵² Knies G. (ed.), Clean Power from Deserts, 2009

²⁵³ Ohl R.S., Light-sensitive electric device, 1941

²⁵⁴ Chapin D.M. et al., A new silicon p-n junction photocell for converting solar radiation into electrical power, 1954

²⁵⁵ Lehouec K., The Photo-Voltaic Effect, 1948

²⁵⁶ Solar Junction, Solar Junction Breaks World Record with 43.5% Efficient CPV Production Cell, 2011

²⁵⁷ Spire, Spire Semiconductor produces a world-record 42.3% efficient CPV cell, 2010

²⁵⁸ Wojtczuk S. et al., InGaP/GaAs/InGaAs concentrators using Bi-facial epigrowth, 2010

²⁵⁹ Kreutzman A. and Siemer J., Market survey on solar modules 2010: Smooth sailing, 2010

²⁶⁰ Gombert A. et al., Analysis of Long Term Operation Data of Flatcon CPV Systems, 2010

Figure 3.1-24: Overview on PV technologies already introduced to the market and still in the laboratory. Market shares are displayed for all PV technologies available to the market for the year 2010.²⁶¹ Abbreviations stand for: crystalline silicon (c-Si), mono-crystalline silicon (sc-Si), multi-crystalline silicon (mc-Si), electronic-grade silicon (eg-Si), upgraded metallurgical silicon (umg-Si), thin-film (TF), single junction (1J), tandem junction (2J), triple junction (3J), multi junction (MJ), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), low concentrating PV (LCPV), high concentrating PV (HCPV), crystalline silicon on glass (CSG), copper zinc tin sulfur (CZTS), solar cell (SC), thermo photovoltaic (TPV), organic PV (OPV), dye-sensitized solar cell (DSSC), quantum dot (QD), quantum well (QW) and intermediate bandgap solar cell (IBSC).

The broad variety of solar cells already invented (Fig. 3.1-24) is surely not the full list of all physical possible devices, in particular since only relative small public PV R&D expenditures have been invested so far (section 3.1.3.1). Wadia et al. have listed several other classes of semiconductors abundantly available for future solar cell types.²⁶² It is not the scope of this thesis to introduce all PV technologies, but a short overview and relevant literature references might be helpful.

Wafer-based silicon solar cells (Fig. 3.1-24) have been invented in 1940s and 1950s in the Bell Labs^{263,264} and achieved at this time efficiencies of about 6%. This has been fast increased to over 10% and used for multiple purposes, in particular for least cost energy supply in space applications. Crystalline silicon PV achieved continuous progress since these early years²⁶⁵ like for instance the introduction of multi-crystalline silicon²⁶⁶. It represents the major PV technology applied over the last six decades and is very likely to dominate the PV market for the years to come.^{267,268,269} The two major c-Si PV technologies are sc-Si and mc-Si solar cells both fabricated from electronic-grade silicon and achieving record efficiencies of 25.0% and 20.4%, respectively.^{270,271} Nevertheless, mc-Si solar cells manufactured from upgraded metallurgical silicon and string ribbon silicon solar cells are available on the market but achieve only a smaller market share.^{272,273,274} From all currently commercially sold PV technologies, only Si based PV systems can be fully built up from abundant materials.

Thin-film silicon solar cells (Fig. 3.1-24) were invented in the RCA Laboratories in 1976 by Carlson and Wronski and have been shown a fast progress.^{275,276,277} Highest stabilised efficiencies of Si-TF tandem and triple junction solar cells have been achieved in the range of

²⁶¹ Hering G., Survey on cell production 2010: Year of the tiger, 2011

²⁶² Wadia C. et al., Materials Availability Expands the Opportunity for Large-Scale PV Deployment, 2009

²⁶³ Ohl R.S., Light-sensitive electric device, 1941

²⁶⁴ Chapin D.M. et al., A new silicon p-n junction photocell for converting solar radiation into electrical power, 1954

²⁶⁵ Wagemann H.-G. and Eschrich H., Grundlagen der photovoltaischen Energiewandlung, 1994

²⁶⁶ Fischer H. and Pschunder W., Low-Cost Solar Cells Based on Large-Area Unconventional Silicon, 1977

²⁶⁷ Green M.S., Solar Cells: Operating Principles, Technology and System Applications, 1998

²⁶⁸ Goetzberger A. et al., Crystalline Silicon Solar Cells, 1998

²⁶⁹ Swanson R.M., A vision for crystalline silicon photovoltaics, 2006

²⁷⁰ Zhao J. et al., 24.5% Efficiency Silicon PERT Cells on MCZ Substrates and 24.7% Efficiency PERL Cells on FZ Substrates, 1999, [record efficiency was later corrected to 25.0%]

²⁷¹ Schultz O. et al., Multicrystalline Silicon Solar Cells Exceeding 20% Efficiency, 2004

²⁷² Petter K. et al., Latest Results on Production of Solar Cells Using umg-Si Feedstock, 2010

²⁷³ Kim D.S. et al., String Ribbon Silicon Solar Cells With 17.8% Efficiency, 2003

²⁷⁴ Rohatgi A. et al., Record-High-Efficiency Solar Cells on Multicrystalline Materials Through Understanding and Implementation of RTP-enhanced SiNx-induced Defect Hydrogenation, 2004

²⁷⁵ Carlson D.E. and Wronski C.R., Amorphous silicon solar cell, 1976

²⁷⁶ Vallat-Sauvain E., Advances in Microcrystalline Silicon Solar Cell Technologies, 2006

²⁷⁷ Zeman M., Advanced Amorphous Silicon Solar Cell Technology, 2006

11.7% - 12.5% by the companies United Solar, Oerlikon Solar and Kaneka.^{278,279,280} The latest record initial efficiency for Si-TF triple junction solar cells has been confirmed to 16.3% and has been achieved by United Solar.²⁸¹ Nevertheless, companies involved in the Si-TF business have become under significant pressure due to relative low Si-TF efficiencies, too high module manufacturing cost and high PV balance of system (BOS) cost resulting to the market retreat of Applied Materials as leading PV equipment manufacturer in 2010.²⁸² Future prospects remain unclear.

CdTe PV technology (Fig. 3.1-24) was invented by Bonnet and Rabenhorst in 1972 and has been developed in the last years to the fastest growing and least cost PV module technology.^{283,284,285} However, commercial module efficiency of 11.7% have already reached 70% of record efficiency of 16.5%.^{286,287} Most recently, the cell efficiency record has been increase to 17.3%, after more than 10 years of no new record.²⁸⁸ Moreover, the availability of extractable tellurium might limit the annual production to about 7 - 40 GW, whereas this limit could be extended by factors in case of enormously reducing the active layer thickness from current 3 μm to future 0.2 μm .^{289,290,291,292,293}

CIGS PV technology (Fig. 3.1-24) was invented in 1974 and is the thin-film PV technology which has shown the highest record efficiency of 20.3% among all TF technologies being introduced to the market.^{294,295,296} The best CIGS modules on the market show better efficiencies than the low efficient mc-Si modules.²⁹⁷ Fast progress of CIGS module efficiencies can be expected since several leading CIGS manufacturer announce new record efficiencies of modules produced under pilot line conditions but also in conventional production lines, like Q-Cells' subsidiary Solibro with 13.4% (full area, production line)²⁹⁸, MiaSolé with 13.8% (full area, production line)²⁹⁹ and Solar Frontier with 17.2% (aperture

²⁷⁸ Green M.A. et al., Solar cell efficiency tables (version 37), 2011

²⁷⁹ Bailat J. et al., Recent developments of high-efficiency micromorph tandem solar cells in Kai-M PECVD reactors, 2010

²⁸⁰ Yoshimi M. et al., High Efficiency Thin Film Silicon Hybrid Solar Cell Module on 1m²-Class Large Area Substrate, 2003

²⁸¹ United Solar, United Solar Reaches 16.3% Efficiency with Nano-Crystalline Technology, 2011

²⁸² Hering G., Applied Materials Restructuring – Sans SunFab, 2010

²⁸³ Bonnet D. and Rabenhorst H., New results on the development of a thin film p-CdTe/n-CdS heterojunction solar cell, 1972

²⁸⁴ Burgelman M., Cadmium Telluride Thin Film Solar Cells: Characterization, Fabrication and Modeling, 2006

²⁸⁵ First Solar, Q1 2011 Earnings Call, 2011

²⁸⁶ First Solar, Q1 2011 Earnings Call, 2011

²⁸⁷ Wu X. et al., 16.5%-Efficient CdS/CdTe polycrystalline thin-film solar cell, 2001, [record efficiency was later corrected to 16.7%]

²⁸⁸ First Solar, First Solar Sets World Record for CdTe Solar PV Efficiency, 2011

²⁸⁹ Green M.A., Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, 2006

²⁹⁰ Andersson B.A., Materials Availability for Large-scale Thin-film Photovoltaics, 2000

²⁹¹ Wadia C. et al., Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment, 2009

²⁹² O'Rourke S. et al., Solar Photovoltaics - Technology and economics: thin films and crystalline silicon, 2007

²⁹³ Zweibel K., The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics, 2010

²⁹⁴ Wagner S. et al., CuInSe₂/CdS heterojunction photovoltaic detectors, 1974

²⁹⁵ Jackson P. et al., New world record efficiency for Cu(In,Ga)Se₂ thin-film solar cells beyond 20%, 2011

²⁹⁶ Klenk R. and Lux-Steiner M.Ch., Chalcopyrite Based Solar Cells, 2006

²⁹⁷ Kreutzman A. and Siemer J., Market survey on solar modules 2010: Smooth sailing, 2010

²⁹⁸ Q-Cells, Q-Cells achieves with 13.4% new efficiency world record for CIGS thin film solar module out of mass production, 2011

²⁹⁹ MiaSolé, MiaSolé Sets World Record for Highest Efficiency of Commercial Scale TF Solar Modules, 2010

area, mini module, laboratory scale)³⁰⁰. Indium but also selen availability might become a limiting factor for a very large scale growth of CIGS PV technology, since the annual In and Se by-product extraction could be sufficient for about 20 - 70 GW and in case of In competition from LCD display industry need to be feared.^{301,302,303,304}

In 1975 a new chapter in the field of PV had been started, high concentrating PV based on GaAs cells.³⁰⁵ In the Spectrolab Laboratories the 40% efficiency threshold was crossed the first time in 2008³⁰⁶ staying in late 2010 at 42.3% achieved by Spire^{307,308} and in early 2011 at 43.5% reached by Solar Junction³⁰⁹. Commercially available HCPV modules (Fig. 3.1-24) reach a 26% efficiency level based on the FhG-ISE Flatcon technology³¹⁰ manufactured by Soitec CPV (the former Concentrix Solar)³¹¹. After many years of introducing HCPV to the market, the first large utility scale HCPV power plants start to gain market shares.³¹² Several LCPV approaches have been proposed and demonstrated but significant market shares have not yet been achieved. An excellent overview on concentrator PV is given by Luque and Andreev.³¹³

Plenty further solar cell concepts are still on the laboratory level and might be introduced to the market in the years to come. These concepts are not relevant for the PV systems discussed in this thesis but should be mentioned as a source of additional options for progress in the field of PV. In the following these solar cell concepts are briefly mentioned and referenced.

In the field of silicon solar cells, there are at least two further approaches both originally targeting a low silicon consumption. Crystalline silicon on glass (CSG) technology attempts to combine high efficiency of crystalline silicon solar cells and manufacturing advantages of TF PV technologies resulting in a record efficiency of 10.5%.^{314,315} Spherical Si solar cell technology was introduced in 1991 and has already reached module efficiencies of 17.5% at a superior angular efficiency and yield due to the spherical geometry.^{316,317,318,319}

The successful development of chalcopyrite-type semiconductors such as Cu(In,Ga)Se₂ has led to commercialization by an increasing number of companies. Despite or even as a direct consequence of its recent and near-future success, the scarcity and increasing prices of indium eventually could limit the production growth for this type of solar cells. Seeking

³⁰⁰ Solar Frontier, Solar Frontier Sets New Efficiency Record in Thin-Film CIS Technology, 2011

³⁰¹ Green M.A., Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, 2006

³⁰² Andersson B.A., Materials Availability for Large-scale Thin-film Photovoltaics, 2000

³⁰³ Wadia C. et al., Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment, 2009

³⁰⁴ O'Rourke S. et al., Solar Photovoltaics - Technology and economics: thin films and crystalline silicon, 2007

³⁰⁵ James L.W. and Moon R.L., GaAs concentrator solar cell, 1975

³⁰⁶ King R.R. et al., Raising the Efficiency Ceiling with Multijunction III-V Concentrator Photovoltaics, 2008

³⁰⁷ Spire, Spire Semiconductor produces a world-record 42.3% efficient CPV cell, 2010

³⁰⁸ Wojtczuk S. et al., InGaP/GaAs/InGaAs concentrators using Bi-facial epigrowth, 2010

³⁰⁹ Solar Junction, Solar Junction Breaks World Record with 43.5% Efficient CPV Production Cell, 2011

³¹⁰ Bett A.W. and Lerchenmüller H., The FLATCON System from Concentrix Solar, 2007

³¹¹ Gombert A. et al., Analysis of Long Term Operation Data of Flatcon CPV Systems, 2010

³¹² Soitec Solar, Soitec Announces Major U.S. CPV Solar Power Project, 2011

³¹³ Luque A.L. and Andreev V.M., Concentrator Photovoltaics, 2007

³¹⁴ Keevers M.J. et al., 10% Efficient CSG minimodules, 2007

³¹⁵ Beaucarne G. and Slaoui A., Thin Film Polycrystalline Silicon Solar Cells, 2006

³¹⁶ Levine J.D. et al., Basic Properties of the Spherical Solar Cell, 1991

³¹⁷ Liu Z. et al., A concentrator module of spherical Si solar cell, 2007

³¹⁸ Taira K. et al., New Type of Standard Measurements of Transparent Spherical Modules, 2005

³¹⁹ Gharghi M. et al., Modeling and Simulation of Spherical Solar Cells, 2005

alternatives not containing indium, the related kesterite-type thin-film semiconductor material $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) shows a very similar crystal structure with a direct band gap expected in the range of 1.4–1.5 eV, while containing solely abundant and nontoxic elements. Maximum efficiencies have been evolved to 9.7%.³²⁰

Many potential solar cell absorber materials can be found in the mineral class of sulfosalts.³²¹ Sulfosalt materials are similar to chalcopyrite minerals, e.g. CuInSe , but for most sulfosalts no abundance limitations are expected. However, the solar cell efficiencies still stay at about 1% being not relevant for commercial applications in the years to come.³²²

Thermo PV (TPV) is a specialised field focused on efficient power conversion of heat radiation (Fig. 3.1-24), i.e. utilization of the solar spectrum up to 2000 nm. The first TPV system was established in 1956 and ongoing research generated fundamental insights on the prospects and limitation of this discipline.³²³ The theoretical efficiency limit of TPV is assumed to be about 60%, but maximum efficiencies reached in the laboratory are about 18% for operation conditions of about 1,400 K. TPV is similar to thermoelectric energy conversion based on the Seebeck effect being able to convert about 10% of received heat to electricity.³²⁴ TPV needs further fundamental research.³²⁵

Organic PV (OPV) (Fig. 3.1-24) has been established in the 1970s and is based on the fundamental research on photoconductors like dyes and pigments in imaging applications and the discovery of semiconducting conjugated polymers.^{326,327} Basically, the photosynthesis of plants is in key sub-processes similar to the technological OPV approach and proved to be a very successful and sustainable way of energy harvesting.³²⁸ The energy efficiency of photosynthesis depends on exactly what point in the process is considered, but a representative value of the efficiency of energy conversion from photons to the chemical energy that can be recovered by metabolizing or burning sugars is about 20% - 25% for a wavelength of 680 nm³²⁹ and about 6% for the entire solar spectrum including various losses.³³⁰ The first organic solar cells had been single-layer heterojunction Schottky cells, but in 1978 the invention of organic donor-acceptor p-n junction cells based on copper phthalocyanine and perylene tetracarboxylic derivative enabled the first organic solar cell achieving 1% efficiency.^{331,332} Since these early days the introduction of C_{60} as excellent n-type acceptor semiconductor³³³ enabled to increase the efficiencies of both small molecule and polymer organic solar cell to current levels of about 8%³³⁴ and generated a steadily increasing momentum for the entire research field³³⁵ now even comprising liquid-crystal organic solar cells³³⁶. Related to pure organic photoactive materials, also hybrid solar cell

³²⁰ Todorov T.K. et al., High-Efficiency Solar Cell with Earth-Abundant Liquid-Processed Absorber, 2010

³²¹ Dittrich H. et al., Sulfosalts – A new class of compound semiconductors for photovoltaic applications, 2007

³²² Dittrich H. et al., First Thin Film Solar Cells Based on Sulfosalt Minerals, 1997

³²³ Nelson R.E., A brief history of thermophotovoltaic development, 2003

³²⁴ Schlegel T., GaSb-Photovoltaikzellen für die Thermophotovoltaik, 2005

³²⁵ Green M.A., Third Generation Photovoltaics: Advanced Solar Energy Conversion, 2003, pp. 111-123

³²⁶ Chamberlain G.A., Organic solar cells: A review, 1983

³²⁷ Shirakawa H. et al., Synthesis of Electrically Conducting Organic Polymers, 1977

³²⁸ Blankenship R.E., Natural Organic Photosynthetic Solar Energy Transduction, 2005

³²⁹ Blankenship R.E., Molecular Mechanisms of Photosynthesis, 2002, p. 35

³³⁰ Bolton J.R., Solar fuels, 1978

³³¹ Tang C.W. et al., Organic photovoltaic element, 1978

³³² Tang C.W., Two-layer organic photovoltaic cell, 1986

³³³ Sariciftci N.S. et al., Photoinduced Electron Transfer from a Conducting Polymer to Fullerene, 1992

³³⁴ Green M.A. et al., Solar cell efficiency tables (version 37), 2011

³³⁵ Sun S.-S. and Sariciftci N.S., (eds.), Organic Photovoltaics: Mechanisms, Materials and Devices, 2005

³³⁶ Kippelen B. et al., Liquid-Crystal Approaches to Organic Photovoltaics, 2005

devices based on organic and inorganic absorbers have been established and achieved recently 2% energy conversion efficiency.^{337,338,339,340} Most recently, record efficiencies have been improved to 2.8% for quantum dot and to 3.6% for quantum dot plus nanorod hybrid organic solar cells.³⁴¹ A special type of this group are the dye-sensitized organic solar cells reaching about 11% efficiency since mid 1990s but suffering stability issues hindering a broad market introduction.^{342,343} However, all the research progress in the broad field of OPV have not yet lead to a substantial market introduction of respective devices.

Fluorescent concentrators (Fig. 3.1-24) are a special type of light concentrating device. The underlying principle was first used in scintillation counters and then their application to concentrating solar radiation was proposed in the late 1970s.^{344,345} In a fluorescent collector, a luminescent material embedded in a transparent matrix absorbs sunlight and emits radiation with a different wavelength. Total internal reflection traps most of the emitted light and guides it to the edges of the collector. Solar cells optically coupled to the edges convert this light into electricity.³⁴⁶ Fluorescent concentrators are well suited for integrating photon management mechanisms like intensity concentration or photon up- and down-conversion. After 30 years of progress in the development of solar cells and luminescent materials and with new concepts, the potential of fluorescent concentrators is currently reinvestigated.^{347,348,349} The record efficiency of fluorescent concentrators in respect to the full optical absorption area is 6.9% using enhanced photon management.^{350,351}

The theoretic maximum solar energy conversion efficiency for a single junction solar cell is 31% and constitutes the Shockley-Queisser-Limit.^{352,353} For the special case of Si solar cells, the practical maximum efficiency is estimated to be about 28%.^{354,355,356} Most energy cannot be converted by a single junction due to two fundamental drawbacks: firstly, photons of higher energy than the bandgap can create only one electron-hole pair and transfer the exceeding energy to phonons and secondly, photons of an energy lower than the bandgap cannot generate electron-hole pairs at all. Several concepts address this limitations, e.g. multi junction solar cells^{357,358}, quantum dot solar cells^{359,360}, quantum well solar cells³⁶¹, multiple

³³⁷ Günes S. and Sariciftci N.S., Hybrid solar cells, 2008

³³⁸ Kamat P.V., Quantum Dot Solar Cells. Semiconductor Nanocrystals as Light Harvesters, 2008

³³⁹ Kumar S. and Scholes G.D., Colloidal nanocrystal solar cells, 2008

³⁴⁰ Zhou Y. et al., Improved efficiency of hybrid solar cells based on non-ligand-exchanged CdSe quantum dots and poly(3-hexylthiophene), 2010

³⁴¹ Jeltsch K.F. et al., Efficiency Enhanced Hybrid Solar Cells Using a Blend of QD and Nanorods, 2011

³⁴² O'Regan B. and Grätzel M., A low-cost high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films, 1991

³⁴³ Grätzel M., Nanocrystalline Injection Solar Cells, 2006

³⁴⁴ Goetzberger A. and Greubel W., Solar Energy Conversion with Fluorescent Collectors, 1977

³⁴⁵ Goldschmidt J.C., Novel Solar Cell Concepts, 2009

³⁴⁶ Goldschmidt J.C., Novel Solar Cell Concepts, 2009

³⁴⁷ Goldschmidt J.C., Novel Solar Cell Concepts, 2009

³⁴⁸ Rau U. et al., Efficiency limits of photovoltaic fluorescent collectors, 2005

³⁴⁹ Goldschmidt J.C. et al., Increasing the efficiency of fluorescent concentrator systems, 2009

³⁵⁰ Goldschmidt J.C., Novel Solar Cell Concepts, 2009

³⁵¹ Goldschmidt J.C. et al., Increasing the efficiency of fluorescent concentrator systems, 2009

³⁵² Martí A. and Araújo G.L., Limiting efficiencies for photovoltaic energy conversion in multigap systems, 1996

³⁵³ Shockley W. and Queisser H.J., Detailed Balance Limit of Efficiency of p-n Junction Solar Cells, 1961

³⁵⁴ Würfel P., Physik der Solarzellen, 2000, pp. 164-166

³⁵⁵ Swanson R.M., Approaching the 29% Limit Efficiency of Silicon Solar Cells, 2005

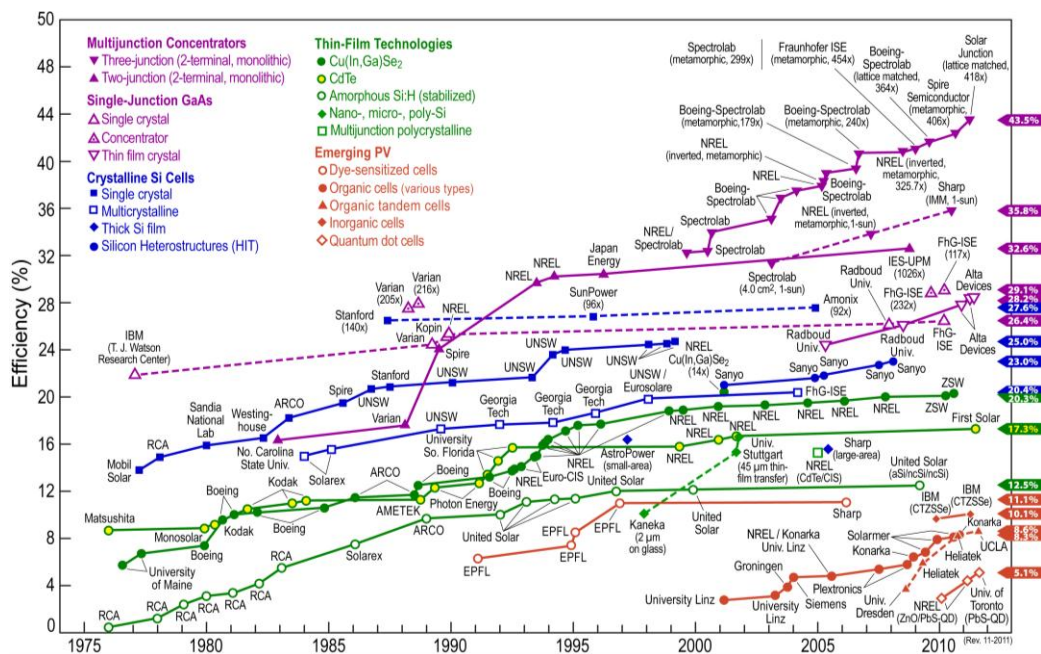
³⁵⁶ Ceuster De D. et al., Low cost, high volume production of >22% efficiency silicon solar cells, 2007

³⁵⁷ Martí A. and Araújo G.L., Limiting efficiencies for photovoltaic energy conversion in multigap systems, 1996

³⁵⁸ Wojtczuk S. et al., InGaP/GaAs/InGaAs concentrators using Bi-facial epigrowth, 2010

exciton generation³⁶², photon down-conversion³⁶³, photon up-conversion³⁶⁴, hot carrier solar cells³⁶⁵ and intermediate band solar cells^{366,367,368,369,370}. These concepts for improving the solar energy conversion efficiency of solar cells represent ongoing fundamental research, except multi junction solar cells, commercially applied in micromorph Si TF and high concentrating solar cell devices.

For being successful in the market PV technologies need to lead to low cost per generated energy. The two major drivers towards low cost electricity generation are manufacturing scaling and solar energy conversion efficiency.^{371,372} However, there is an inherent trade-off between manufacturing cost and efficiency, since higher energy conversion efficiencies often need more production steps, expensive manufacturing equipment or high cost materials. Nevertheless, solar energy conversion efficiency will stay a major driver of further progress and cost reduction for the various PV technologies. Confirmed world record solar cell and module efficiencies are regularly published for all major PV technologies by Green et al.³⁷³ The ongoing progress of record research efficiencies of these technologies is visualized in Figure 3.1-25.



³⁵⁹ Conibeer G. et al., Silicon Quantum Dot Based Solar Cells: Addressing the Issues of Doping, Voltage and Current Transport, 2010

³⁶⁰ Takeda Y. and Motohiro T., Realistic Limiting Conversion Efficiency Utilizing Multiple Exciton Generation, 2010

³⁶¹ Adams J.G.J. et al., Recent Progress in Quantum Well Solar Cells, 2010

³⁶² Takeda Y. and Motohiro T., Realistic Limiting Conversion Efficiency Utilizing Multiple Exciton Generation, 2010

³⁶³ Trupke T. et al., Improving solar cell efficiencies by down-conversion of high-energy photons, 2002

³⁶⁴ Trupke T. et al., Improving solar cell efficiencies by up-conversion of sub-band-gap light, 2002

³⁶⁵ Green M.A. et al., Recent Progress with Hot Carrier Solar Cells, 2010

³⁶⁶ Luque A. and Martí A., Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions at Intermediate Levels, 1997

³⁶⁷ Bosworth M. and San Segundo J.R., Intermediate-Band-Solarzellen: Brücke über die Lücke, 2011

³⁶⁸ López N. et al., Multiband Solar Cell, 2011

³⁶⁹ Green M.A., Third Generation Photovoltaics: Advanced Solar Energy Conversion, 2003

³⁷⁰ Luque A. et al., FULLSPECTRUM: a new PV wave making more efficient use of the solar spectrum, 2005

³⁷¹ Nemet G.F., Beyond the learning curve: factors influencing cost reductions in photovoltaics, 2006

³⁷² Kersten F. et al., PV-Learning Curves: Past and Future Drivers of Cost Reduction, 2011

³⁷³ Green M.A. et al., Solar cell efficiency tables (version 37), 2011

Figure 3.1-25: Progress of best solar cell research efficiencies of all major PV technologies for the years 1976 – 2011.³⁷⁴

The overview on record solar cell research efficiencies (Fig. 3.1-25) reveal, that several major PV technologies (Fig. 3.1-27) achieved no significant progress in record efficiencies within the last decade (sc-Si, mc-Si, CIGS, CdTe and Si-TF), whereas at least two emerging PV technologies have documented continued improvements (MJ HCPV and OPV). However, the aforementioned major PV technologies showed enormous progress on commercially available efficiencies, since plenty of research insights migrated towards industrial manufactured devices and significant further efficiency improvements can be realised (Fig. 3.1-26). The significant research progress of MJ HCPV and OPV devices has not yet led to substantial market shares (Fig. 3.1-27) but significant venture capital investments might accelerate this development.³⁷⁵

Despite of the impressive long-term increase in record solar cell efficiencies (Fig. 3.1-25) the best-in-breed multi-junction solar cell reaches 43.5% which is about the half of the theoretical limit. The maximum thermodynamic energy conversion limit for processes on earth receiving solar energy from the sun is calculated by Carnot to 95.0% and Landsberg and Tonge to 93.3%.³⁷⁶ These numbers have been adapted to conditions of photovoltaic to 85.4% by De Vos and Pauwels and 86.8% and 85.0% by Martí and Araújo for the case of multi junction PV systems for black body at 6000 K and AM1.5 DNI conditions.^{377,378} Without concentrating the solar radiation flux the maximum conversion efficiency of multi junction PV systems can reach 65.4%, whereas a best possible optimised single junction solar cell can theoretically convert 31.0% being very close to the calculated 30% by Shockley and Queisser in 1961.^{379,380}

Current commercially available PV module efficiencies still range considerably below their theoretical limits but also below the research records (Fig. 3.1-26). These PV technologies represent nearly the entire production for terrestrial PV applications (Fig. 3.1-27). Leading scientists and decision makers within the PV industry expect both a further increase in efficiencies of commercially available modules and substantial progress in research solar cell efficiencies.^{381,382}

³⁷⁴ Kazmerski L., NREL compilation of best research solar cell efficiencies, 2011

³⁷⁵ UNEP, Global Trends in Sustainable Energy Investment 2010, 2010

³⁷⁶ Landsberg P.T. and Tonge G., Thermodynamic energy conversion efficiencies, 1980

³⁷⁷ Vos de A. and Pauwels H., On the Thermodynamic Limit of Photovoltaic Energy Conversion, 1981

³⁷⁸ Martí A. and Araújo G.L., Limiting efficiencies for photovoltaic energy conversion in multigap systems, 1996

³⁷⁹ Martí A. and Araújo G.L., Limiting efficiencies for photovoltaic energy conversion in multigap systems, 1996

³⁸⁰ Shockley W. and Queisser H.J., Detailed Balance Limit of Efficiency of p-n Junction Solar Cells, 1961

³⁸¹ EU PV Technology Platform, A Strategic Research Agenda for Photovoltaic Solar Energy Technology, 2007

³⁸² IEA, Technology Roadmap: Solar photovoltaic energy, 2010

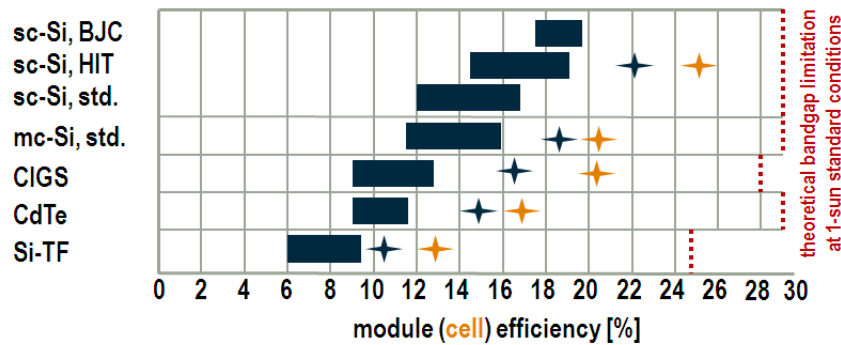


Figure 3.1-26: Large area module efficiency range of commercially sold products for all major PV technologies in the year 2010.^{383,384} The reference is displayed to best laboratory results for modules (blue star), solar cells (orange star) and theoretical limit of respective devices at one sun for standard test conditions. Abbreviations stand for: mono-crystalline silicon (sc-Si), back junction cell (BJC), heterojunction with intrinsic thin layer (HIT), standard (std.), multi-crystalline silicon (mc-Si), copper indium gallium selenide (CIGS), cadmium telluride (CdTe) and thin-film silicon (Si-TF).

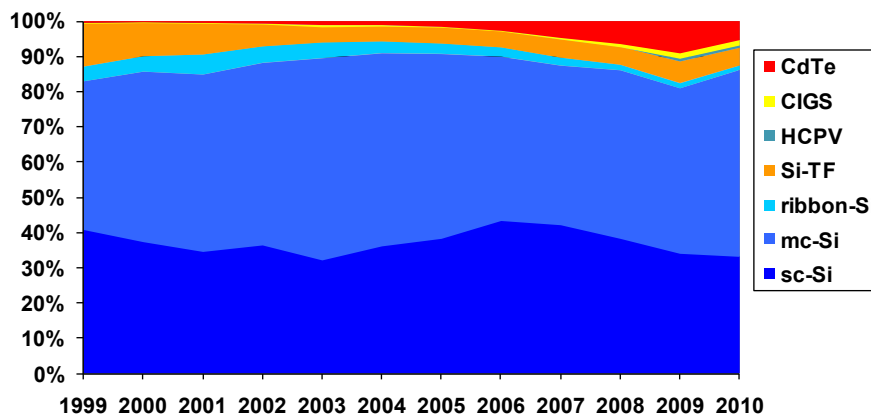


Figure 3.1-27: Market share of all major commercial PV technologies for the years 1999 – 2010.³⁸⁵ Abbreviations stand for: cadmium telluride (CdTe), copper indium gallium selenide (CIGS), high concentrating PV (HCPV), thin-film silicon (Si-TF), multi-crystalline silicon (mc-Si) and mono-crystalline silicon (sc-Si).

Despite of average annual growth rates of about 45% within the last 15 years (Fig. 3.1-1), the market shares of the major PV technologies were nearly stable in the last decade (Fig. 3.1-27). Largest gain in market share has been achieved by CdTe PV. The loss of market shares of wafer-based Si PV technology have been in total rather low, however ribbon-Si devices might have lost their competitiveness, mainly driven by wafer-related cost reductions of sc-Si and mc-Si solar cells and ribbon-Si solar cell efficiencies being lower than competing mc-Si ones. The largest loss of market share has been contributed for Si-TF modules, which is very likely due to the not competitive low module efficiencies. Nevertheless, the total change in market share is less than 10% for the years 1999 – 2010, which is remarkably low in a market of an average growth rate of 45%.

The device structure of 99% of all commercially available PV modules (Fig. 3.1-27) is quite similar (Fig. 3.1-28). The photoactive semiconductor materials are packed within a front glass and either back glass or back sheet foil and respective lamination foils. This PV module

³⁸³ Müller J., Crystalline Silicon PV Technology: Status and Outlook, 2011

³⁸⁴ Beneking A., Kratzen an der 20-Prozent-Marke, 2011

³⁸⁵ Hering G., Survey on cell production 2010: Year of the tiger, 2011

concept was introduced by Elliot Berman in the early 1970s.³⁸⁶ There are different solar cell connection techniques, in particular for thin-film and wafer-based PV technologies. However, the major difference might be the thickness of the photoactive material, since wafer-based Si solar cells are typically between 150 – 200 μm thick, whereas the respective layer thickness of TF modules are about 3 μm , which is a consequence of indirect and direct bandgaps of the semiconductors.

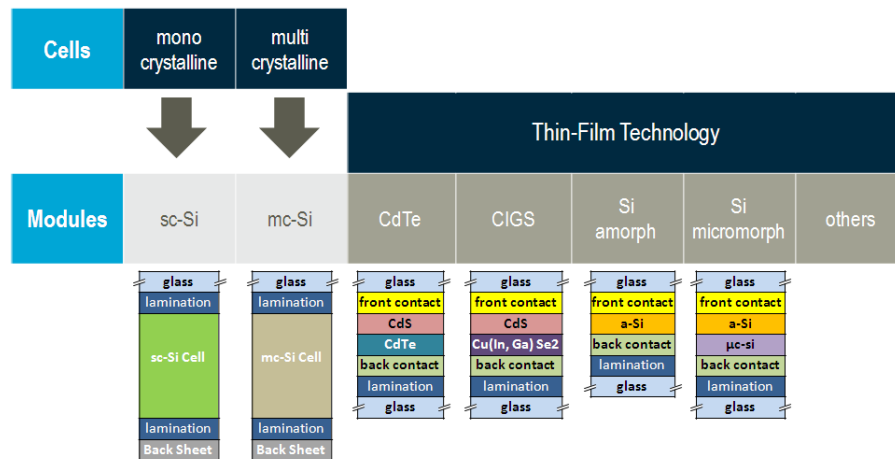
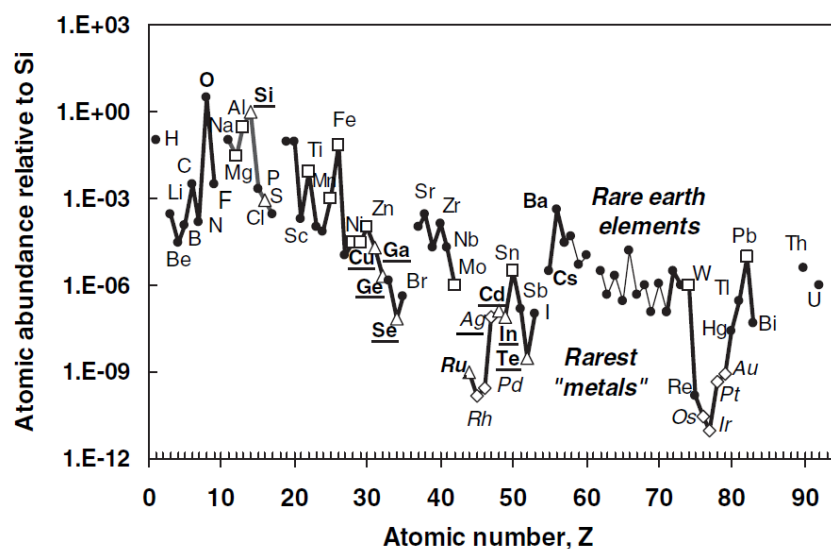


Figure 3.1-28: Overview on device structure of major PV technologies.³⁸⁷ The layer thicknesses are schematic, since c-Si cells are typically 150 – 200 μm thick, and photoactive thin-film technology layers are in the order of only a few μm .

The limit for PV systems for global power supply is estimated to be about 12,000 GWp in total installed capacity (section 3.1.1.3). Due to that high limit, the high average annual growth rate of about 45% (Fig. 3.1-1) for the period of mid 1990s to the year 2010 might be stable for the years to come and range between 30% and 45%. However, some of the fast growing TF PV technologies might be restricted in their growth rates to the fundamental availability for scarce resources, in particular for tellurium (Te), indium (In) and selenium (Se). The relative availability of elements is depicted in Figure 3.1-29.



³⁸⁶ Perlin J., From Space to Earth – The Story of Solar Electricity, 1999, pp. 49-56

³⁸⁷ Müller J., Crystalline Silicon PV Technology: Status and Outlook, 2011

Figure 3.1-29: Abundance of elements in earth's upper continental crust normalised to silicon.³⁸⁸ Elements of interest for PV are underlined, i.e. c-Si (Si, Ag), CdTe (Cd, Te), Si-TF (Si, Ge) and CIGS (Cu, In, Ga, Se).

The abundance of elements is normalised to Si, the photoactive material of c-Si and Si-TF PV devices. The only element on earth being more abundant than Si is oxygen (O). Quartz or sand represent a form of SiO₂, which is the raw material for glass, a core component of PV modules. The foils used for PV modules (Fig. 3.1-28) are based on hydrocarbon chemistry being also very abundant. However, there are several elements which could limit the growth rates of one or another PV technology. Wafer-based Si solar cells are constraint in silver (Ag), but only screen printed standard Si solar cells. This is no fundamental limitation for wafer-based Si solar cells, since Ag-free metallization can be realised by using copper (Cu) plating and is already on the market in case of back-contact solar cells manufactured by SunPower. But CdTe, CIGS and Si-TF PV technology might be limited in the availability of tellurium (Te), indium (In), selenium (Se) and Germanium (Ge).

Assuming that growth rates and cost reductions of the past decade could be maintained in the 2010s, the annual installation rate at the end of the 2010s might be in the order of about 150 – 250 GWp (section 6.6.2).

There are no mines for Te, In, Se and Ge, since the concentration of these materials even in ores containing them is very low, i.e. typical content is several hundred grams per tonne of good suited source ore. Te and Se is a by-product of Cu ores and can be found in concentrations of about 100 and 400 g/tonne Cu anode slime, which is the waste material after Cu refinery.³⁸⁹ Green estimates an annual available Te and Se stream due to Cu refinery of about 1,300 and 5,000 tonnes, respectively, but extraction efficiencies of 33% and 52% lead to available material of 430 and 2,600 tonnes, respectively.³⁹⁰ Even tenfold higher price would not allow to start Te and Se mining, since Te and Se content of one tonne Cu ore represents about 1.5% of the value. Green assumes a Te and Se consumption of CdTe and CIGS PV of about 0.1 g/W, i.e. 100 t/GW.³⁹¹ On basis of Te and Se prices of 170 USD/kg and 120 USD/kg (market prices in autumn 2005) the respective material cost are 0.017 USD/Wp and 0.012 USD/Wp, i.e. a tenfold higher price might be too high for a sustainable competitiveness of CdTe and CIGS PV technology. The numbers presented by Green result in an annual production potential of about 4.3 GW CdTe PV and 26 GW CIGS PV.

Andersson analysed the resource availability for PV production in a similar way.³⁹² Material requirements are estimated to about 65 t/GW (Te), 48 t/GW (Se), 5.3 t/GW (Ga), 29 t/GW (In) and 4.4 t/GW (Ge). Annual available material stream from by-products is estimated to about 290 t (Te), 2,200 t (Se), 54 t (Ga), 290 t (In) and 63 t (Ge). These numbers result in 4.5 GW CdTe (Te), 45 GW CIGS (Se), 10 GW CIGS (Ga), 10 GW CIGS (In) and 14 GW Si-TF (Ge). However, Andersson assumes that modified efficiencies and material requirements would enable an annual production of 20 GW CdTe (Te), 300 GW CIGS (Se), 400 GW CIGS (Ga), 70 GW CIGS (In) and 200 GW Si-TF (Ge).³⁹³

³⁸⁸ Green M.A., Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, 2006

³⁸⁹ Green M.A., Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, 2006

³⁹⁰ Green M.A., Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, 2006

³⁹¹ Green M.A., Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, 2006

³⁹² Andersson B.A., Materials Availability for Large-scale Thin-film Photovoltaics, 2000

³⁹³ Andersson B.A., Materials Availability for Large-scale Thin-film Photovoltaics, 2000

Wadia et al. discuss the material availability for various kinds of compounds applicable for PV devices.³⁹⁴ They estimate an annual maximum production of about 30 GW of CdTe and about 2,200 GW of CIGS PV. Zweibel analyses the Te availability for estimating the annual production potential of CdTe PV.³⁹⁵ The amount of annual available Te could be increased from about 500 to 1500 t, due to more efficient extraction and using further sources, i.e. waste material not only from copper mines but also from gold, zinc and lead mines. Zweibel assumes 100 t/GW Te requirement for 10% efficient modules of a 3 μm CdTe active layer. In the years to come, he expects that the technological potential of CdTe PV might enable to increase the efficiency of fabricated modules to 15%, being still below the already achieved CdTe solar cell efficiency record of 17.3% (Fig. 3.1-25 and 3.1-26), and the active layer thickness of 3 μm might be reduced to 0.2 μm . Such a technological evolution would reduce the Te requirement from 100 t/GW to about 4.4 t/GW.³⁹⁶ As a consequence, the increase of Te supply might increase the annual production potential from 5 GW to 15 GW, whereas the technological improvements might boost the annual production from about 110 GW (current Te supply) to about 340 GW (supply potential).

O'Rourke et al. from Deutsche Bank estimate that in 2008 a CIGS thickness of 3 μm , at a module efficiency of 11.7%, generate an In demand of 43 t/GW, which would be enough for an annual CIGS production of 2.3 GW for about 100 t available material.³⁹⁷ Their number for the year 2020 are 1 μm CIGS layer thickness, 15% module efficiency, 11.4 t/GW In requirement, 240 t available In supply and respective 21 GW annual production. The expectations for CdTe PV are performed in a similar way, i.e. active layer thickness of 3 μm in 2008 (0.9 μm in 2020), module efficiency of 9.6% (13.2% in 2020), resulting Te demand of 102 t/GW (22 t/GW in 2020), available annual Te supply of 60 t (280 t in 2020), hence resulting in an annual production potential of 0.6 GW (12.6 GW in 2020).³⁹⁸

The results of the different publications are summarized in Table 3.1-6.

reference	CdTe	CdTe	CIGS	CIGS
	current status	future potential	current status	future potential
	[GW/y]	[GW/y]	[GW/y]	[GW/y]
Green ³⁹⁹	4.3	-	26.0	-
Andersson ⁴⁰⁰	4.5	20.0	10.0	70
Wadia et al. ⁴⁰¹	-	30.0	-	2,200
Zweibel ⁴⁰²	4.4	340.0	-	-
O'Rourke et al. ⁴⁰³	0.6	12.6	2.3	21

Table 3.1-6: Estimates of annual production potential of CdTe and CIGS PV technology due to resource limitation. The estimates are for the current status of CdTe and CIGS PV technology, but include also the future potential of supply increase and progress in module efficiency and specific material requirement.

³⁹⁴ Wadia C. et al., Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment, 2009

³⁹⁵ Zweibel K., The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics, 2010

³⁹⁶ Zweibel K., The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics, 2010

³⁹⁷ O'Rourke S. et al., Solar Photovoltaics - Technology and economics: thin films and crystalline silicon, 2007

³⁹⁸ O'Rourke S. et al., Solar Photovoltaics - Technology and economics: thin films and crystalline silicon, 2007

³⁹⁹ Green M.A., Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, 2006

⁴⁰⁰ Andersson B.A., Materials Availability for Large-scale Thin-film Photovoltaics, 2000

⁴⁰¹ Wadia C. et al., Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment, 2009

⁴⁰² Zweibel K., The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics, 2010

⁴⁰³ O'Rourke S. et al., Solar Photovoltaics - Technology and economics: thin films and crystalline silicon, 2007

The results for annual production potentials of CdTe and CIGS PV heavily deviate among the referenced publications. Consensus is found for annual production potential of current status CdTe PV of about 4.5 GW, excluding obviously wrong data of O'Rourke et al. However, future potential expectations for CdTe PV deviates between about 13 GW and 30 GW on the one side and up to 340 GW on the other. Results for current status CIGS PV range between 2.3 GW and 26 GW, whereas the numbers for the future potential are 21 GW, 70 GW and 2,200 GW. All authors acknowledge material constraints for CdTe and CIGS PV but the consequences for annual current status and future production potential reveals an enormous range.

Summing up, only a few PV technologies have already reached the market, whereas several others are still before market entry. The efficiency potential of the entire PV technology is enormous, firstly for increasing the efficiencies of commercially available modules towards the already shown research records and secondly for increasing the research records towards the fundamental limits of physics. The PV technology has a substantial potential for shifting efficiency baselines. The working horse of PV industry is c-Si showing no substantial resource constraints. Thin-film technologies, like CdTe and CIGS, are material constraint, but it remains unclear whether the long-term annual production of these technologies might reach the limitation level.

3.1.6 Energetic Sustainability

The 21st century society is faced to escalating energy demand and various resource limitations and conflicts for energy fuels but also for raw materials and overstretched self-healing forces of regional and global ecosystems (chapter 1).^{404,405,406,407,408} Consequently, energy technologies need to fulfil a broad set of sustainability criteria for offering a valuable contribution to the energy demand in this century. Major criteria is the energy return on energy investment (section 3.1.6.2), which is driven by the energy payback time (section 3.1.6.1) and the lifetime of respective energy systems. Progress in the field of PV is summarized in the following. The solar breeder concept (section 3.1.6.3) is a very important tool for analysing sustainable energy supply potential in the decades to come, in particular for a fast growing energy demand.

3.1.6.1 Energy Payback Time

Key driver for evaluating energetic sustainability of PV systems is the energy payback time (EPBT), i.e. the time required for the solar PV system to generate the equivalent amount of energy consumed in the construction and decommissioning phases, as summarized by Equations 3.1-2.

$$EPBT = \frac{E_{in}}{E_{out}} \quad (\text{Eq. 3.1-2a})$$

⁴⁰⁴ Meadows D.H. et al., The limits to growth, 1972

⁴⁰⁵ Meadows D.H. et al., Limits to growth: the 30-year update, 2004

⁴⁰⁶ Welzer H., Klimakriege – Wofür im 21. Jahrhundert getötet wird, 2008

⁴⁰⁷ Wackernagel M. and Beyers B., Der Ecological Footprint: Die Welt neu vermessen, 2010

⁴⁰⁸ WBGU, Climate Chance as a Security Risk, 2007

$$E_{in} = E_{prod,sys} + E_{distr,sys} + E_{decom,sys} \quad (\text{Eq. 3.1-2b})$$

$$E_{out} = Irrad_{site} \cdot PerfR \cdot \frac{m^2}{kWp} \quad (\text{Eq. 3.1-2c})$$

Equation 3.1-2: Energy payback time of PV systems. Abbreviations stand for: energy payback time (*EPBT*), energy needed for production, distribution and decommissioning of the PV system (E_{in}), energy generated at a specific site per year (E_{out}), energy needed for production of the PV system ($E_{prod,sys}$), energy needed for distribution of the PV system ($E_{distr,sys}$), energy needed for decommissioning of the PV system ($E_{decom,sys}$), irradiation on module surface at a specific site ($Irrad_{site}$) and performance ratio of a specific PV system at a specific site ($PerfR$).

First life cycle assessment (LCA) study concerning EPBT of PV was calculated in mid 1970s by Hunt.⁴⁰⁹ Si solar cells used for space applications had also been used for first terrestrial PV modules at that time and showed an EPBT of less than 12 years at very sunny sites for solar cells being designed for a lifetime of at least 20 years. There are very little sources on LCA analysis from the 1970s, however Weingart also published estimates provided by a major PV manufacturer at that time resulting in an EPBT of about 15 years for conventional Si solar cells available for terrestrial applications at that time and further estimates for Si solar cells for space applications (40 years) plus ribbon-Si already in research in the late 1970s (2 years).⁴¹⁰ Notably, still today some PV sceptics claim that PV systems would not be capable of harvesting the energy invested in the system. This argument was wrong from the beginning. In mid 1980s, Aulich et al. reported EPBTs for manufactured sc-Si modules of that time of less than 8 years at very sunny sites.⁴¹¹ They also reported a reduction potential for c-Si technologies under research in mid 1980s to a level between 0.5 – 1.6 years at very sunny sites. In late 1980s and early 1990s, EPBT had been 3.0 years (sc-Si), 2.9 – 1.6 years (mc-Si) and 1.4 – 0.9 (a-Si) on module level and 3.6 years (sc-Si), 2.2 - 3.5 years (mc-Si) and 1.8 - 2.3 (a-Si) on system level for respective technologies in production at very sunny sites.^{412,413,414} Studies in 1990s have been based on comprehensive LCA data and reported EPBT of 3.2 – 10.3 years (mc-Si) and 2.8 – 4.5 years (a-Si) on PV system level at sunny sites.^{415,416,417,418}

Publications in the 2000s report EPBT of the major PV technologies of 1.7 – 2.55 years (sc-Si), 1.8 – 5.5 years (mc-Si), 1.05 years (mc-Si by fluidized bed reactor)⁴¹⁹, 1.1 years (mc-Si by umg-Si)⁴²⁰, 1.2 – 1.7 years (ribbon-Si), 1.3 – 2.3 years (Si-TF), 1.4 - 2.8 years (CIGS), 0.8 – 2.1 years (CdTe).^{421,422,423,424} EPBT of BOS components, i.e. everything excluding the

⁴⁰⁹ Hunt L.P., Total energy use in the production of Si solar cells from raw materials to finished product, 1976

⁴¹⁰ Weingart J.M., The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, 1978

⁴¹¹ Aulich H.A. et al., Energy pay-back time for c-Si PV modules using new technologies, 1985

⁴¹² Hagedorn G., Kumulierter Energieverbrauch und Erntefaktoren von Photovoltaik-Systemen, 1989

⁴¹³ Schaefer H. and Hagedorn G., Hidden energy and correlated environmental characteristics of PV power generation, 1992

⁴¹⁴ Palz W. and Zibetta H., Energy pay-back time of photovoltaic modules, 1991

⁴¹⁵ Alsema E.A. et al., Energy pay-back time of photovoltaic energy systems: present status and prospectus, 1998

⁴¹⁶ Alsema E.A., Energy Pay-back Time and CO2 Emissions of PV Systems, 2000

⁴¹⁷ Kato K. et al., EPBT and Life-cycle CO₂ Emissions of Residential PV Power System with Si PV, 1998

⁴¹⁸ Keoleian G.A. and Lewis G.McD., Application of Life-cycle Energy Analysis to PV Module Design, 1997

⁴¹⁹ Alsema E.A., Life-cycle assessment of crystalline silicon PV module production by REC, 2009

⁴²⁰ Wild-Scholten de M.J. et al., LCA comparison of the Elkem solar mg route and gas routes to solar Si, 2008

⁴²¹ Raugei M. et al., Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si, 2007

⁴²² Wild-Scholten de M. and Schottler M., Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, 2009

module, for PV power plants in very sunny sites is reported to be 0.21 years.⁴²⁵ Latest results for current most widely used PV technologies account for an EPBT of 0.8 – 1.7 years at sunny sites (Fig. 3.1-30).⁴²⁶ Expectations of EPBT in early to mid 2010s are under 1.0 year for all major PV technologies at sunny sites.^{427,428} Tracking systems further reduce c-Si EPBT by about 10% for 1-axis horizontal and 20% for 2-axes tracking.⁴²⁹ Off-grid PV systems including batteries may show significantly varying EPBT in dependence of battery recycling.⁴³⁰

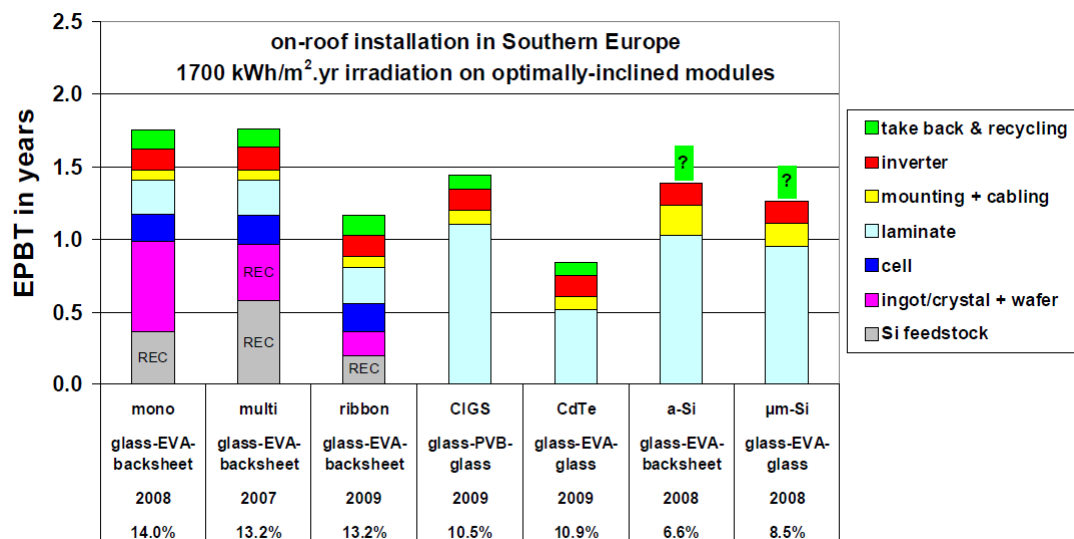


Figure 3.1-30: Energy payback time of currently used PV technologies at sunny sites.⁴³¹

Besides the mentioned currently used major PV technologies, new emerging PV technologies show promising EPBT as well. EPBT are reported for 0.7 – 2.1 years (DSSC), 2.0 – 4.0 years (OPV), 0.7 – 0.8 years (III-V TJ HCPV) and 1.3 years (sc-Si CPV) at sunny and very sunny sites.^{432,433,434}

Most numbers are given for sunny sites (1,700 kWh/m²/y irradiation on module surface). The results can be easily adjusted to moderates sites (1,000 – 1,200 kWh/m²/y irradiation on module surface) and to very sunny sites (2,200 – 2,400 kWh/m²/y irradiation on module surface) by subtracting and adding 30% - 40%, respectively.

⁴²³ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁴²⁴ Ito M. et al., Life-cycle analyses of very-large scale PV systems using six types of PV modules, 2010

⁴²⁵ Mason J.E. et al., Energy Payback and Life-cycle CO₂ Emissions of the BOS in an Optimized 3.5 MW PV Installation, 2006

⁴²⁶ Wild-Scholten de M. and Schottler M., Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, 2009

⁴²⁷ Alsema E.A. et al., Environmental impacts of PV electricity generation a critical comparison of energy supply options, 2006

⁴²⁸ Wild-Scholten de M. and Schottler M., Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, 2009

⁴²⁹ Perpinan O. et al., EPBT of Grid Connected PV Systems: Comparison Tracking and Fixed Systems, 2009

⁴³⁰ Jourde P., Battery energy pay-back time, 2000

⁴³¹ Wild-Scholten de M. and Schottler M., Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, 2009

⁴³² Garcia-Valverde R. et al., Life cycle analysis of organic photovoltaic technologies, 2010

⁴³³ Peharz G. and Dimroth F., Energy Payback Time of the High-concentration PV System FLATCON, 2005

⁴³⁴ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

By integrating available data sources on EPBT and cumulated installed PV capacity (Fig. 3.1-1 and 3.1-3) it is possible to transfer the concept of financial learning rates (section 3.1.2) to energetic learning rates in an analogous way.⁴³⁵ PV module technologies sold in the market show an energetic learning rate of about 17% for the years 1974 – 2010. Considering PV on-grid system installations, the energetic learning rate has been about 14% for the years 1974 – 2010. Based on these energetic learning rates and assumed annual growth rates of about 30% for the 2010s, the today's EPBT in average of all technologies and for moderate and excellent solar resources of about 1.0 – 2.0 years can be expected to reach about 0.3 – 1.0 years in the year 2020.⁴³⁶

3.1.6.2 Energy Return on Energy Investment

Energy payback time is an important metric, whereas the most relevant one in reference to energetic sustainability is the energy return on energy investment (EROI), sometimes also called yield factor. The EROI is based on the EPBT but expanded by the lifetime of the entire system (Eqs. 3.1-3).

$$EROI_{static} = \frac{N}{EPBT} \quad (\text{Eq. 3.1-3a})$$

$$EROI_{dynamic} = \frac{N}{EPBT} \cdot (1 - DR)^N \quad (\text{Eq. 3.1-3b})$$

Equation 3.1-3: Energy return on energy investment. Abbreviations stand for: energy return on energy investment (*EROI*), lifetime of entire system (*N*), energy payback time (*EPBT*) and annual system degradation rate (*DR*).

The higher the EROI the better fulfilled are the energetic sustainability requirements. EROI can be improved by the two key drivers system lifetime and EPBT. The first contributor, EPBT is summarized in the section before and resulted in values of 0.8 – 1.7 years for all major PV technologies produced in the late 2000s at sunny sites. By improving module efficiency and lowering energy needed for producing the modules, in particular the purifying of the semiconductor materials, a mid-term EPBT of 0.5 years in sunny regions should be feasible. The second contributor, the system lifetime, is for current systems about 30 years and expected to increase.^{437,438,439,440}

The warranty periods of 20 to 25 years on 80% - 85% of the labelled power of c-Si based modules refer to an average power drop of 0.5% per year from the module aging⁴⁴¹, i.e. 10% over 20 to 25 years plus an security tolerance interval of 5% - 10% to be on the sure side.⁴⁴² Real lifetime might be longer, as indicated by excellent performance of 26 year old modules recently measured at 92% of initial power output after continuous operations⁴⁴³, performance

⁴³⁵ Görig M., Solare Brüter – unter besonderer Berücksichtigung der Erntefaktoren von PV und Windkraft, 2011

⁴³⁶ Görig M., Solare Brüter – unter besonderer Berücksichtigung der Erntefaktoren von PV und Windkraft, 2011

⁴³⁷ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁴³⁸ Saleh Ibrahim I.M.S. et al., Performance of Thirty Years Stand Alone Photovoltaic System, 2009

⁴³⁹ Alsema E.A., Life-cycle assessment of crystalline silicon PV module production by REC, 2009

⁴⁴⁰ Ito M. et al., A comparative study on LCA of 20 different PV modules installed at Hokuto mega-solar plant, 2010

⁴⁴¹ Osterwald C.R. et al., Comparison of degradation rates of individual modules held at maximum power, 2006

⁴⁴² Grunow P. and Lehmann S., General assessment of the reliability of c-Si PV modules, 2009

⁴⁴³ Schott Solar, Power ohne Ende: Nach 26 Jahren noch über 90% Leistung, 2010

of 22 year old modules at 92% of initial power output⁴⁴⁴ and low degradation rates of about 0.1%/y for PV power plants over at least 6 years⁴⁴⁵. Power degradation seems to be stable over time more or less.⁴⁴⁶ Assuming a stable power degradation one can easily estimate the lifetime of modules, the most valuable and most energy intensive component of a grid connected PV system (Eqs. 3.1-4).

$$P_N = P_0 \cdot (1 - DR)^N \quad (\text{Eq. 3.1-4a})$$

$$N = \frac{\log(P_N / P_0)}{\log(1 - DR)} \quad (\text{Eq. 3.1-4b})$$

Equation 3.1-4: Lifetime of PV modules and respective power output. Abbreviations stand for: power output after N years (P_N), initial power output (P_0), annual PV module degradation rate (DR) and years in consideration (N).

Reported optimum long-term degradation rates are in the range of 0.3% - 0.5%/y.^{447,448,449,450} Even long-term annual degradation rates over 30 years of 0.5% - 1.1% for modules in a remote desert region in Libya have been reported.⁴⁵¹ By defining an end of lifetime at a power output of 70% of initial power one can obtain module lifetime of 70 up to 120 years by applying Equation 3.1-4b. An annual degradation rate of 0.7% would result in a lifetime of 50 years. Today's module concept has been introduced in the mid 1970s, thus a maximum lifetime of 35 years can be recorded and several PV systems of the late 1970s and early 1980s have been measured in the last decade showing annual degradation of 0.3% - 0.5%. Therefore an assumption of module lifetime of 50 years for high quality modules might be an appropriate mid-term estimate. Due to the fact that no moving parts are in operation, the only impact is the incident sunlight and a minimum of vapour in case of using high quality encapsulation. Benefit of PV module lifetime of 50 to 100 years might be very high, as standard financial amortization is within 10 to 20 years, i.e. the years after that period show very low operational cost and very high social benefit.⁴⁵²

Dynamic EROI for currently installed PV systems (Fig. 3.1-30) might be in the order of 16:1 – 33:1 for a conservative minimum system lifetime of 30 years and 24:1 – 51:1 for a realistic lifetime of 50 years, both calculated for an annual system degradation rate of 0.4% and sunny sites. Assuming optimised PV systems at 0.5 years EPBT and 50 years lifetime, one could expect a dynamic EROI of about 80:1 for an annual system degradation rate of 0.4% and sunny sites. Moreover, at very sunny sites it might be possible that PV systems built in the 2010s might exceed a dynamic EROI of 100:1, which would mark an outstanding high level in the history of energy technology.^{453,454}

Historic oil fields in the 1930s had EROIs in the order of 50:1 up to 100:1, whereas today's new conventional oil and gas field range 10:1 – 20:1, tar sand oil and shale oil range 2:1 - 5:1. Hard coal open field mining ranges 80:1 and nuclear power shows EROI of 5:1 – 15:1.

⁴⁴⁴ Lia de F. et al., Efficiency degradation of c-Si PV modules after 22-year continuous field exposure, 2003

⁴⁴⁵ Kiefer K. et al., A degradation analysis of PV power plants, 2010

⁴⁴⁶ Lia de F. et al., Efficiency degradation of c-Si PV modules after 22-year continuous field exposure, 2003

⁴⁴⁷ Osterwald C.R. et al., Comparison of degradation rates of individual modules held at maximum power, 2006

⁴⁴⁸ Grunow P. and Lehmann S., General assessment of the reliability of c-Si PV modules, 2009

⁴⁴⁹ Lia de F. et al., Efficiency degradation of c-Si PV modules after 22-year continuous field exposure, 2003

⁴⁵⁰ Saleh Ibrahim I.M.S. et al., Performance of Thirty Years Stand Alone Photovoltaic System, 2009

⁴⁵¹ Saleh Ibrahim I.M.S. et al., Performance of Thirty Years Stand Alone Photovoltaic System, 2009

⁴⁵² Zweibel K., Should PV be deployed sooner because of long operating life at low, predictable cost?, 2010

⁴⁵³ Murphy D.J. and Hall C.A.S., Year in review – EROI or energy return on (energy) invested, 2010

⁴⁵⁴ Heinberg R., Searching for a miracle: Net energy limits & the fate of industrial society, 2009

EROI of hydro power performs best at 100:1 and wind power achieves values of 20:1 – 50:1. Biomass energy EROIs are typically less than 10:1. The threshold EROI of 10:1 marks the sustainability limit, as hunter-gatherer societies operated on a ten-to-one net energy basis. They used the surplus energy for all of the social activities that made life sustainable and rewarding. Since hunter-gatherer societies are the simplest human groups in terms of technology and degree of social organization, 10:1 should probably be regarded as the minimum sustained average societal EROI required for maintaining human existence.^{455,456,457} It might be an outstanding historic mistake not to accept the fundamental barrier of a minimum EROI.^{458,459,460}

EROI is a measure for energetic sustainability of current and emerging energy technologies. The trend for conventional fossil fuels indicates their diminishing and degrading resource basis becoming a non sustainable energy option for mankind even from the perspective of EROI. PV shows fast improving EROI values from today's 16:1 – 51:1 and being in reach of a near-term level of up to 80:1 at sunny sites, whereas at very sunny sites the near-term potential might be beyond 100:1.

3.1.6.3 Solar Breeder Concept

In 1970s Slesser and Hounam introduced the revolutionary concept of solar breeders.⁴⁶¹ Having access to a renewable energy source, which is characterised by a dynamic EROI of >1:1 and no further raw material limitation enables a renewable power plant basis that can exponentially grow. The growing solar breeder system can steadily breed new energy capacity but also supply energy for consumption needs. The higher the EROI and the lower the construction time the faster can be the growth.⁴⁶² The first solar PV breeder had been built in 1982 by Solarex Corp. founded and led at that time by solar PV pioneer Joseph Lindmayer.⁴⁶³ Gusdorf expanded the mathematical description of the solar breeder concept and the relevance of EROI, as a key indicator how much energy is needed for self-preservation of the energy breeding system.⁴⁶⁴ In 1990s the solar breeder concept was coupled to the fundamental economic principles of Herman Daly⁴⁶⁵ for realising sustainable development.⁴⁶⁶ Recently, the solar breeder concept has received new momentum, as the “Silicon Solar Breeder Plan in Sahara”⁴⁶⁷ was co-initiated by the Sahara Solar Energy Research Center (SSERC) from Algeria and Kosuke Kurokawa, who is a pioneer in very large-scale PV power plants in desert regions.^{468,469}

The Solar Breeder Concept might have a catalytic impact on the further development of renewable energy technologies and in particular PV. A high dynamic EROI is the most

⁴⁵⁵ Murphy D.J. and Hall C.A.S., Year in review – EROI or energy return on (energy) invested, 2010

⁴⁵⁶ Gagnon L. et al., Life-cycle assessment of electricity generation options, 2002

⁴⁵⁷ Heinberg R., Searching for a miracle: Net energy limits & the fate of industrial society, 2009

⁴⁵⁸ Meadows D.H. et al., The limits to growth, 1972

⁴⁵⁹ Meadows D.H. et al., Limits to growth: the 30-year update, 2004

⁴⁶⁰ Bardi U., The mineral economy: a model for the shape of oil production curves, 2005

⁴⁶¹ Slesser M. and Hounam I., Solar energy breeders, 1976

⁴⁶² Grimmer D.P., Solar energy breeders, 1981

⁴⁶³ Smith J., The Solar Breeder: A Bold Step by Solarex, 1983

⁴⁶⁴ Gusdorf J., Energy paybacks and renewable breeders, 1992

⁴⁶⁵ Daly H.E., Steady-State Economics, 1991

⁴⁶⁶ Matsushashi R. and Ishitani H., Model analyses for sustainable energy supply under CO₂ restrictions, 1995

⁴⁶⁷ Koinuma H. and Kurokawa K., Silicon Solar Breeder Plan in Sahara, 2010

⁴⁶⁸ Kurokawa K. (ed.), Energy from the Desert: Feasibility of Very Large Scale PV Power Generation, 2003

⁴⁶⁹ Komoto K. et al., Energy from the Desert – Very Large Scale Photovoltaic Systems, 2009

relevant precondition for improved energetic sustainability and therefore excellent economic foundation. Energy technologies of an EROI of higher than 50:1, complemented by globally distributed energy resources and no constraints on raw material supply are very likely to be the core pillars of a sustainable energy supply in the 21st century. These requirements are fulfilled by hydro power and solar thermal electricity generation and to a very large extend by wind power and solar PV.

3.1.7 Specific Emissions

The limited and already overstretched absorption capacity of our plant (sub-chapters 1.2 and 1.5) focusses the emission stream of energy technologies. For a successful climate change mitigation the greenhouse gas emissions need to be radically reduced as soon as possible and in particular in the energy sector. The progress in reducing greenhouse gas emissions by applying PV technology is discussed in section 3.1.7.1.

Other social costs of energy supply are also not internalised in the energy prices, but have to be paid. Such costs are for instance: higher mortality and multiple illnesses due to heavy metal emissions of coal and oil power plants, military conflicts due to diminishing energy resources, reduced ecological value of destroyed ecosystems by use and exploitation of conventional energy and insecurity due to nuclear proliferation, nuclear terrorism and unclear nuclear waste disposal. Significant social cost are related to heavy metal emissions in the power sector, thus fast growing electricity technologies, like PV, need to offer excellent respective emission characteristics discussed in section 3.1.7.2.

3.1.7.1 Greenhouse Gas Emissions

Several factors are needed for a fully sustainable energy technology, like the energetic sustainability discussed for PV in section 3.1.6. Further major sustainability factors are availability of raw materials (section 3.1.5), economic performance (chapters 3, 4, 6 and 7), social benefit and harmless emissions. Renewable energies are characterized by two major advantages: no diminishing fuel and very low harmful emissions, in particular greenhouse gases dominated by CO₂. Therefore all greenhouse gases are normalised to CO₂ and the sum of all greenhouse gas emissions of an energy technology is rated in CO₂ equivalent (CO_{2eq}) emissions. In the following the CO_{2eq} emissions of various PV technologies are discussed and an outlook is given on the cost and benefit of PV for reducing CO₂ emissions.

First research on the CO_{2eq} emissions of PV systems has been published in the 1990s in the range of 100 – 250 gCO_{2eq}/kWh (sc-Si), 80 – 190 gCO_{2eq}/kWh (mc-Si) and 40 – 130 gCO_{2eq}/kWh (a-Si), respectively, for normalised irradiation values of 1,700 kWh/m²/y on inclined modules.^{470,471,472}

Data of research in the 1990s were based on manufacturing conditions of late 1980s to early 1990s and typical small scale non automatic production conditions. Latest publications in late 2000s concerning specific CO_{2eq} emissions over the entire PV system life cycle are in the

⁴⁷⁰ Schaefer H. and Hagedorn G., Hidden energy and correlated environmental characteristics of PV power generation, 1992

⁴⁷¹ Kato K. et al., EPBT and Life-cycle CO₂ Emissions of Residential PV Power System with Si PV, 1998

⁴⁷² Frankl P. et al., Simplified Life-cycle Analysis of PV Systems in Buildings: Present Situation and Future Trends, 1998

range of 29 - 37 gCO_{2eq}/kWh (sc-Si), 28 - 31 gCO_{2eq}/kWh (mc-Si) and 16 - 25 gCO_{2eq}/kWh (CdTe), respectively, all given for irradiation values of 1,700 kWh/m²/y on inclined modules.^{473,474,475,476} These numbers are dependent on input energy used for manufacturing and are valid for US and European manufacturers. In case of production in China typical mc-Si PV systems achieve about 64 gCO_{2eq}/kWh due to coal based Chinese power supply.⁴⁷⁷ A comparison of most relevant PV technologies is shown in Figure 3.1-31.

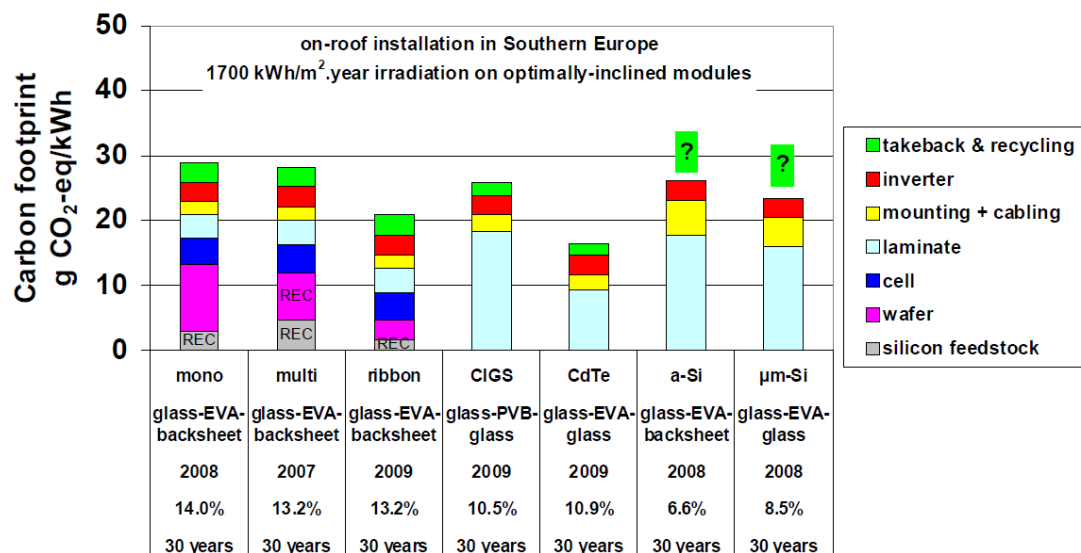


Figure 3.1-31: Specific CO_{2eq} greenhouse gas emissions of currently used PV technologies at sunny sites.⁴⁷⁸

The numbers are given for sunny sites (1,700 kWh/m²/y irradiation on module surface). The results can be easily adjusted to moderate sites (1,000 – 1,200 kWh/m²/y irradiation on module surface) and to very sunny sites (2,200 – 2,400 kWh/m²/y irradiation on module surface) by subtracting and adding 30% - 40%, respectively.

The scientific consensus for CO_{2eq} emissions of PV systems range between 10 – 15 gCO_{2eq}/kWh expected for the years in the 2010s.^{479,480,481} Moreover, the specific CO_{2eq} emissions can be further reduced by about 30% - 50% in case of renewable electricity used for all PV manufacturing processes.^{482,483} Current and future CO_{2eq} emissions of PV systems

⁴⁷³ Alsema E.A. and Wild-Scholten de M.J., Reduction of the Environmental Impacts in Crystalline Silicon Module Manufacturing, 2007

⁴⁷⁴ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁴⁷⁵ Wild-Scholten de M. and Schottler M., Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, 2009

⁴⁷⁶ Alsema E.A. et al., Environmental impacts of PV electricity generation a critical comparison of energy supply options, 2006

⁴⁷⁷ Wild-Scholten de M., Solar as an environmental product, 2011

⁴⁷⁸ Wild-Scholten de M. and Schottler M., Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, 2009

⁴⁷⁹ Alsema E.A. and Wild-Scholten de M.J., Reduction of the Environmental Impacts in Crystalline Silicon Module Manufacturing, 2007

⁴⁸⁰ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁴⁸¹ Alsema E.A. et al., Environmental impacts of PV electricity generation a critical comparison of energy supply options, 2006

⁴⁸² Alsema E.A. and Wild-Scholten de M.J., Reduction of the Environmental Impacts in Crystalline Silicon Module Manufacturing, 2007

⁴⁸³ Wild-Scholten de M.J. et al., LCA comparison of the Elkem solar metallurgical route and conventional gas routes to solar silicon, 2008

clearly document PV technology among the leading energy technologies for a climate change constraint world.

The CO₂ emissions of PV systems need to be discussed in comparison to the other renewable and conventional power technologies. An overview on the CO₂ emissions and the energy return on energy invested (EROI) is summarized in Table 3.1-7.

Power technology	CO _{2eq} emissions [g/kWh _{el}]	EROI	references
Hydro power	17 – 40	100:1	484,485
Wind power	7 – 24	20:1 – 50:1	486,487
Photovoltaic	12 – 42	16:1 – 51:1	488,489,490,491
Solar thermal power	22 – 33	50:1 – 70:1	492,493
Geothermal power	15 – 120	30:1 – 50:1	494,495,496
Biomass (Biogas for CO ₂)	120	0.8:1 – 10:1	497,498
Lignite coal power	1150 – 1210	not sustainable	499,500
Hard coal power	900 – 950	not sustainable	501,502
‘Clean’ coal with CCS	255 – 440	not sustainable	503
Natural gas power	400 – 760	not sustainable	504,505
Oil power	880	not sustainable	506,507
Nuclear power	66	not sustainable	508

⁴⁸⁴ Fritsche U. et al., Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung, 2007

⁴⁸⁵ Sovacool B.K. and Watts C., Going Completely Renewable: Is It Possible (Let Alone Desirable)?, 2009

⁴⁸⁶ Fritsche U. et al., Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung, 2007

⁴⁸⁷ Sovacool B.K. and Watts C., Going Completely Renewable: Is It Possible (Let Alone Desirable)?, 2009

⁴⁸⁸ Alsema E.A. and Wild-Scholten de M.J., Reduction of the Environmental Impacts in Crystalline Silicon Module Manufacturing, 2007

⁴⁸⁹ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁴⁹⁰ Wild-Scholten de M. and Schottler M., Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, 2009

⁴⁹¹ Alsema E.A. et al., Environmental impacts of PV electricity generation a critical comparison of energy supply options, 2006

⁴⁹² Viebahn P. et al., NEEDS: Final report on technical data, costs and life cycle inventories of solar thermal power plants, 2008

⁴⁹³ Ungeheuer U., Schott White Paper on Solar Thermal Power Plant Technology, 2006

⁴⁹⁴ Sovacool B.K. and Watts C., Going Completely Renewable: Is It Possible (Let Alone Desirable)?, 2009

⁴⁹⁵ Bertani R. and Thain I., Geothermal Power Generating Plant CO₂ Emission Survey, 2002

⁴⁹⁶ BMU, Renewable Energies: Innovations for the Future, 2006

⁴⁹⁷ BMU, Renewable Energy Sources in Figures – National and international development, 2009

⁴⁹⁸ Murphy D.J. and Hall C.A.S., Year in review – EROI or energy return on (energy) invested, 2010

⁴⁹⁹ Fritsche U. et al., Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung, 2007

⁵⁰⁰ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁵⁰¹ Fritsche U. et al., Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung, 2007

⁵⁰² Fthenakis V. and Alsema E., Photovoltaic Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004-early 2005 Status, 2006

⁵⁰³ Sovacool B.K. and Watts C., Going Completely Renewable: Is It Possible (Let Alone Desirable)?, 2009

⁵⁰⁴ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁵⁰⁵ Fthenakis V. and Alsema E., Photovoltaic Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004-early 2005 Status, 2006

⁵⁰⁶ Fritsche U. et al., Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung, 2007

⁵⁰⁷ Fthenakis V.M. and Kim H.C., Photovoltaics: Life-cycle analyses, 2011

⁵⁰⁸ Sovacool B.K., Valuing the greenhouse gas emissions from nuclear power: A critical survey, 2008

Table 3.1-7: Overview on specific greenhouse gas emissions and the energy return on energy invested (EROI) for the major power technologies.

The four major renewable power technologies, i.e. hydro power, wind power, solar PV and solar thermal power, show excellent specific CO_{2eq} emissions of about 10 – 40 gCO_{2eq}/kWh and outstanding EROI of about 20:1 up to 100:1 (section 3.1.6.2). The outcome for biomass and geothermal power is strongly dependent on the specific conditions. The CO₂ emissions of conventional power plants are far too high for climate change constraints, even the so-called ‘clean coal’, i.e. carbon capture and storage technology, might emit much more CO₂ than renewable sources. Nuclear power plants emit about three times more CO₂ than renewable power technologies. A positive EROI cannot be achieved for conventional power plants in a sustainable way, since limited resources have to be exploited. If this constraint had not taken into account the EROI would be in the range of 5:1 – 20:1 for nuclear power, oil power and natural gas power, however coal power would still be very competitive.⁵⁰⁹

Usually, solar PV sceptics claim that PV would be one of the most expensive options for reducing greenhouse gas (GHG) emissions.^{510,511,512,513} The specific CO_{2eq} emissions discussed in this section clearly document PV technology among those technologies emitting the lowest greenhouse gases. In the first regions in the world, PV power plants are already lower in levelized cost of electricity (LCOE) than nearby oil fired power plants and competitiveness to natural gas will be reached by mid 2010s and to coal by end of 2010s (chapter 6). After these fuel-parity events, reducing GHG emissions by combining fossil power plants and PV power plants generates economic GHG reduction benefits. This new fact might be surprising, in particular for conventional energy economists.

3.1.7.2 Heavy Metal Emissions

Besides GHG emissions (section 3.1.7.1), power generation causes various further harmful pollutants. The specific emissions for the European UCTE grid mix are: greenhouse gases (470 t/GWh), NO_x (0.8 t/GWh), SO_x (2.1 t/GWh), arsenic (17 g/GWh), cadmium (4 g/GWh), chromium (19 g/GWh), lead (54 g/GWh), mercury (11 g/GWh), nickel (247 g/GWh), thorium-230 (7 kBq/GWh), uranium-238 (35 kBq/GWh), and some more.⁵¹⁴ The specific emissions can be reduced by 89% to 98% by substituting the UTCE grid mix by the CdTe PV thin-film technology (section 3.1.5).⁵¹⁵ The heavy metal emissions are mainly caused by coal fired power plants, in particular by burning lignite coal, but also oil fired power plants. These heavy metal emissions are typically denominated as PM_{2.5} and PM₁₀, i.e. particles with an aerodynamic diameter less than 2.5 and 10 µm.

The harmful health impacts of the pollutants are classified in the mortality, i.e. a reduction in life expectancy due to acute and chronic mortality, and the morbidity which can be measured

⁵⁰⁹ Murphy D.J. and Hall C.A.S., Year in review – EROI or energy return on (energy) invested, 2010

⁵¹⁰ Frondel M. et al., Economic impacts from the promotion of renewable energy technologies: The German experience, 2010

⁵¹¹ Birnbaum L. et al., Kosten und Potenziale der Vermeidung von Treibhausgasemissionen in Deutschland, 2007

⁵¹² Naucélér T. and Enkvist P.-A., Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve, 2009

⁵¹³ DPG-AKE, Elektrizität: Schlüssel zu einem nachhaltigen und klimaverträglichen Energiesystem, 2010

⁵¹⁴ Fthenakis V.M. et al., Emissions from Photovoltaic Life Cycles, 2008

⁵¹⁵ Fthenakis V.M. et al., Emissions from Photovoltaic Life Cycles, 2008

for instance by respiratory hospital admissions, restricted activity days, cardiovascular hospital admissions, cases of bronchodilator usage, cases of chronic bronchitis, cases of chronic cough in children, cough in asthmatics or lower respiratory symptoms.⁵¹⁶ In China, cancer has become the major cause of death, led by lung cancer being closely related to the dirty air poisoned by the largest coal fired power plant fleet in the world.⁵¹⁷ For example the coal mining and processing areas of Shanxi Province are home to the world's highest birth defect rate of over 8.4%. Of the about 1 million affected babies born each year in China, some 20% - 30% may be treated, but 40% will have permanent disabilities. The rest die shortly after birth.⁵¹⁸ The situation in China is not an outstanding failure of coal based industrialization, but only an example.

Comparable disastrous health impacts of coal power supply have been recorded all around the world. Fisher et al. reported for the US between annually 8,000 to 34,000 premature deaths from inhaling fine particulate matter from coal combustion.⁵¹⁹ This translates to 4 to 18 deaths per TWh generated coal electricity and about 1,000 to 4,300 deaths per 1 GW coal power capacity over a 40 years lifetime. A study for the Ontario Ministry of Energy reported about 25 deaths per TWh coal electricity.⁵²⁰ Markandya and Wilkinson estimate even higher numbers for Europe, since they derive 25 to 33 deaths per TWh, about 225 to 300 serious illnesses per TWh and about 13,300 to 17,700 minor illnesses per TWh.⁵²¹ They conclude, that population health would substantially benefit from improved access to electricity and from modal switch away from fossil fuels towards renewable sources of electricity generation where possible. Krewitt et al. reported data for Germany, where an annual loss of 44,000 life years are caused by coal fired power plants, translating to about 180 life years per TWh.⁵²²

These enormous health costs are not included in the electricity generation cost and are typically accounted as external costs, but they have to be paid year by year in the respective public health systems and by lost quality of life. Several authors derived the health related social costs of coal electricity to 2.5 USDct/kWh⁵²³, 7.6 to 13.7 USDct/kWh⁵²⁴, 3.4 to 14.2 USDct/kWh⁵²⁵, about 9 USDct/kWh⁵²⁶ and 2 to 16 USDct/kWh⁵²⁷. The high health costs of coal electricity lead to beneficial health gains through decarbonising the electricity production.⁵²⁸ Ontario, as the first state in the world, decided no longer to publicly finance these enormous social subsidies related to coal power generation, since 70% of total coal power generation related cost are due to health damages, thus all coal fired power plants have to be phased-out by latest 2014.^{529,530}

⁵¹⁶ Krewitt W. et al., Environmental damage costs from fossil electricity generation in Germany and Europe, 1999

⁵¹⁷ Larsen J., Plan B Updates: Cancer Now Leading Cause of Death in China, 2011

⁵¹⁸ Larsen J., Plan B Updates: Cancer Now Leading Cause of Death in China, 2011

⁵¹⁹ Fisher J. et al., Benefits of Beyond BAU: Human Social and Environmental Damages Avoided through the Retirement of the US Coal Fleet, 2011

⁵²⁰ Boulton W. et al., Cost Benefit Analysis: Replacing Ontario's Coal-Fired Electricity Generation, 2005

⁵²¹ Markandya A. and Wilkinson P., Electricity generation and health, 2007

⁵²² Krewitt W. et al., Environmental damage costs from fossil electricity generation in Germany and Europe, 1999

⁵²³ Krewitt W. et al., Environmental damage costs from fossil electricity generation in Germany and Europe, 1999

⁵²⁴ Epstein P.R. et al., Full cost accounting for the life cycle of coal, 2011

⁵²⁵ Fisher J. et al., Benefits of Beyond BAU: Human Social and Environmental Damages Avoided through the Retirement of the US Coal Fleet, 2011

⁵²⁶ Boulton W. et al., Cost Benefit Analysis: Replacing Ontario's Coal-Fired Electricity Generation, 2005

⁵²⁷ Hirschberg S. and Bauer C., Clean Energy for China, 2006

⁵²⁸ Markandya A. et al., Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation, 2009

⁵²⁹ Boulton W. et al., Cost Benefit Analysis: Replacing Ontario's Coal-Fired Electricity Generation, 2005

Investments in PV capacities help to reduce the coal subsidies paid through the public health systems and to increase the quality of life through less premature deaths and illnesses, since the harmful heavy metal emissions are reduced by about 70% - 98% per generated electricity depending on applied PV technology, local irradiation and type of pollutant.⁵³¹

3.2 Systems Overview

Nearly all major drivers for long-term sustainability have been discussed so far: more or less homogeneous availability of solar resources (chapter 2), energetic sustainability (section 3.1.6), low specific emissions (section 3.1.7), broad technological potential (section 3.1.5), impressive PV R&D investment dynamic (section 3.1.3), fundamental experience curve concept (section 3.1.2), historic high and sustainable growth rates (section 3.1.1) and structural and pressing need for sustainable energy solutions (chapter 1). This sub-chapter is dedicated to the economics of PV systems, as last major piece of puzzle for understanding the enormous impact potential of PV. In the next sections the fundamental concept of leveled cost of electricity (section 3.2.1) is introduced and in combination with the experience curve concept used for cost projections in the decade of the 2010s (section 3.2.2) mainly focussed on PV power plants. All major PV systems are analysed on basis of their respective solar resources for finding least cost of PV systems (section 3.2.3). The least cost result of the beginning of the 2010s might not stay constant over the entire decade in all regions of the world, hence potential diffusion of least cost PV systems is investigated (section 3.2.4) as well.

3.2.1 Levelized Cost of Electricity of PV Systems

Most important indicator for competitiveness in the power industry is the cost per generated electricity used in units of €/MWh or €/kWh. Several further characteristics of respective power technologies are very relevant, e.g. power plant availability, fast ramp-up time, fuel resource availability, low emissions, low maintenance need, long lifetime, social acceptance and several more. Nevertheless, cost per energy is the most important.

Using the leveled cost of electricity (LCOE) method (Equations 3.2-1)⁵³² one can easily transform the cost/Wp numbers usually used in PV industry into the more decisive cost/kWh category of the power industry. All cost categories, i.e. investment and capital expenditures (Capex), operation and maintenance expenditures (Opex), have to be put on an annual basis. LCOE are obtained by dividing annual costs by annual electricity generation. LCOE enables a direct comparison of alternative energy technologies in terms of cost per energy, in this thesis €/MWh or €/kWh.

$$LCOE = \frac{Capex \cdot crf + Opex}{Y_{ref} \cdot PerfR} = \frac{Capex}{Y_{ref} \cdot PerfR} \cdot \left(\frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} + k \right) \quad (\text{Eq. 3.2-1a})$$

⁵³⁰ Duguid B. (ed.), Ontario's Long-Term Energy Plan, 2010

⁵³¹ Fthenakis V.M. et al., Emissions from Photovoltaic Life Cycles, 2008

⁵³² Short W. et al., A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, 1995

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (\text{Eq. 3.2-1b})$$

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \quad (\text{Eq. 3.2-1c})$$

$$Opex = k \cdot Capex \quad (\text{Eq. 3.2-1d})$$

$$k = k_{ins} + k_{O\&M} \quad (\text{Eq. 3.2-1e})$$

$$Y_f = Y_{ref} \cdot PerfR \quad (\text{Eq. 3.2-1f})$$

Equation 3.2-1: Levelized cost of electricity (LCOE) for PV systems. Abbreviations stand for: capital expenditures (*Capex*), annual operation and maintenance expenditures (*Opex*), annuity factor (*crf*), reference yield for specific PV system at specific site (Y_{ref}), performance ratio (*PerfR*), weighted average cost of capital (*WACC*), lifetime of PV system (N), annual insurance cost in percent of Capex (k_{ins}), equity (E), debt (D), return on equity (k_E), cost of debt (k_D), annual operational expenditures in percent of Capex ($k_{O\&M}$), annual cost of Opex in percent of Capex (k), and net electrical energy/ final yield (Y_f).

For most cost per energy calculations the Equations 3.2-1 are best adapted to the respective considerations. Annual rates can be treated explicitly in LCOE calculations, like cost of insurance, cost of capital for equity and debt and operational cost.

Non financial structural cost components are typically part of the system performance ratio (*PerfR*), which aggregates all energetic losses of a PV system defined at standard test conditions (STC)⁵³³ when converting from name-plate DC rating to AC output.⁵³⁴ One further annual rate can be excluded and separately incorporated in the LCOE formula. PV modules degrade over time by about 0.2% - 0.5% per year in reference to their power output of respective previous year (section 3.1.6.2).

LCOE method is based on the total life cycle cost (TLCC) approach.⁵³⁵ TLCC itself is based on annual cost per energy and annual electric yield which is used in electric energy per name-plate DC-rated kWp installation, i.e. kWh_{AC}/kWp_{DC}. It can also be interpreted as the number of hours the system has to be operated under STC conditions to deliver the same amount of energy. In the power industry this is named full load hours (FLh). Annual reference yield (Y_{ref}) depends not only on location, but also on tilt angle or yield improving tracking systems. It can be interpreted as the effective number of peak hours of STC definition during one year for that installation. Annual electric yield is multiplied by LCOE and discounted by weighted average cost of capital, year by year and summed up. Mathematical description is summarized in Equations 3.2-2.^{536,537}

$$TLCC = \sum_{n=1}^N \frac{Y_n \cdot LCOE}{(1 + WACC)^n} \quad (\text{Eq. 3.2-2a})$$

$$Y_n = Y_1 \cdot (1 - DR)^n \quad (\text{Eq. 3.2-2b})$$

$$Y_1 = Y_{ref} \cdot PerfR \quad (\text{Eq. 3.2-2c})$$

⁵³³ IEC, International Standard 60904-1 2nd edition 2006-09 - Part 1: Measurement of photovoltaic current-voltage characteristics, 2006

⁵³⁴ Kymakis E. et al., Performance analysis of a grid connected photovoltaic park on the island of Crete, 2009

⁵³⁵ Short W. et al., A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, 1995

⁵³⁶ Doll R., LCOE: an overview, 2009

⁵³⁷ Kymakis E. et al., Performance analysis of a grid connected photovoltaic park on the island of Crete, 2009

$$Y_{ref} = \frac{I_{T,y} [kWh_{AC} / m^2 / y]}{1 [kWp_{DC} / m^2]} \quad (\text{Eq. 3.2-2d})$$

$$TLCC = Capex + \sum_{n=1}^N \frac{Opex_n}{(1+WACC)^n} \cdot (1-tax) - \sum_{n=1}^N \frac{D_n}{(1+WACC)^n} \cdot tax - \frac{residual\ value}{(1+WACC)^N} \quad (\text{Eq. 3.2-2e})$$

Equation 3.2-2: Total life cycle cost (TLCC) for PV systems. Abbreviations stand for: system lifetime (N), annual electric system yield in year n (Y_n), levelized cost of electricity ($LCOE$), weighted average cost of capital ($WACC$), annual system degradation rate (DR), annual electric system reference yield (Y_{ref}), performance ratio ($PerfR$), annual solar irradiation on tilted module surface of respective PV system ($I_{T,y}$), capital expenditures ($Capex$), annual operation and maintenance expenditures ($Opex$), tax rate (tax) and depreciation in year n (D_n).

However, annual electric yield is reduced by annual system degradation rate (DR) expressed in Equation 3.2-2b, therefore DR can be separated in contrast to Equations 3.2-1. Combining Equation 3.2-2a and Equation 3.2-2e leads to $LCOE$ formula including PV system degradation rate by neglecting a tax rate and a residual set to a value of zero, respectively.⁵³⁸

$$LCOE = \frac{Capex + \sum_{n=1}^N \frac{Opex_n}{(1+WACC)^n}}{\sum_{n=1}^N \frac{Y_n}{(1+WACC)^n}} \quad (\text{Eq. 3.2-3a})$$

$$LCOE = \frac{Capex}{Y_{ref} \cdot PerfR} \cdot \left(\frac{(WACC + DR) \cdot (1+WACC)^N}{(1-DR) \cdot [(1+WACC)^N - (1-DR)^N]} \right) \times \left(1 + k \cdot \frac{(1+WACC)^N - 1}{WACC \cdot (1+WACC)^N} \right) \quad (\text{Eq. 3.2-3b})$$

$$k = k_{ins} + k_{O\&M} \quad (\text{Eq. 3.2-3c})$$

Equation 3.2-3: Levelized cost of electricity including annual PV system degradation rate. Abbreviations stand for: levelized cost of electricity ($LCOE$), capital expenditures ($Capex$), system lifetime (N), annual operation and maintenance expenditures ($Opex$), weighted average cost of capital ($WACC$), annual electric system yield in year n (Y_n), annual electric system reference yield (Y_{ref}), performance ratio ($PerfR$), annual system degradation rate (DR), annual cost of $Opex$ in percent of $Capex$ (k), annual insurance cost in percent of $Capex$ (k_{ins}) and annual operational expenditures in percent of $Capex$ ($k_{O\&M}$).

Schematic overview on the impact factors and its interdependencies of the $LCOE$ formula is depicted in Figure 3.2-1. Key driving forces of $LCOE$ are system cost driven by module cost and BOS (both largely influenced by solar cell efficiency), annual operational cost, $WACC$, system lifetime and annual energy yield driven by location, solar resource, system performance ratio and annual system degradation (both partly influenced by fundamental solar cell characteristics).

⁵³⁸ Doll R., *LCOE: an overview*, 2009

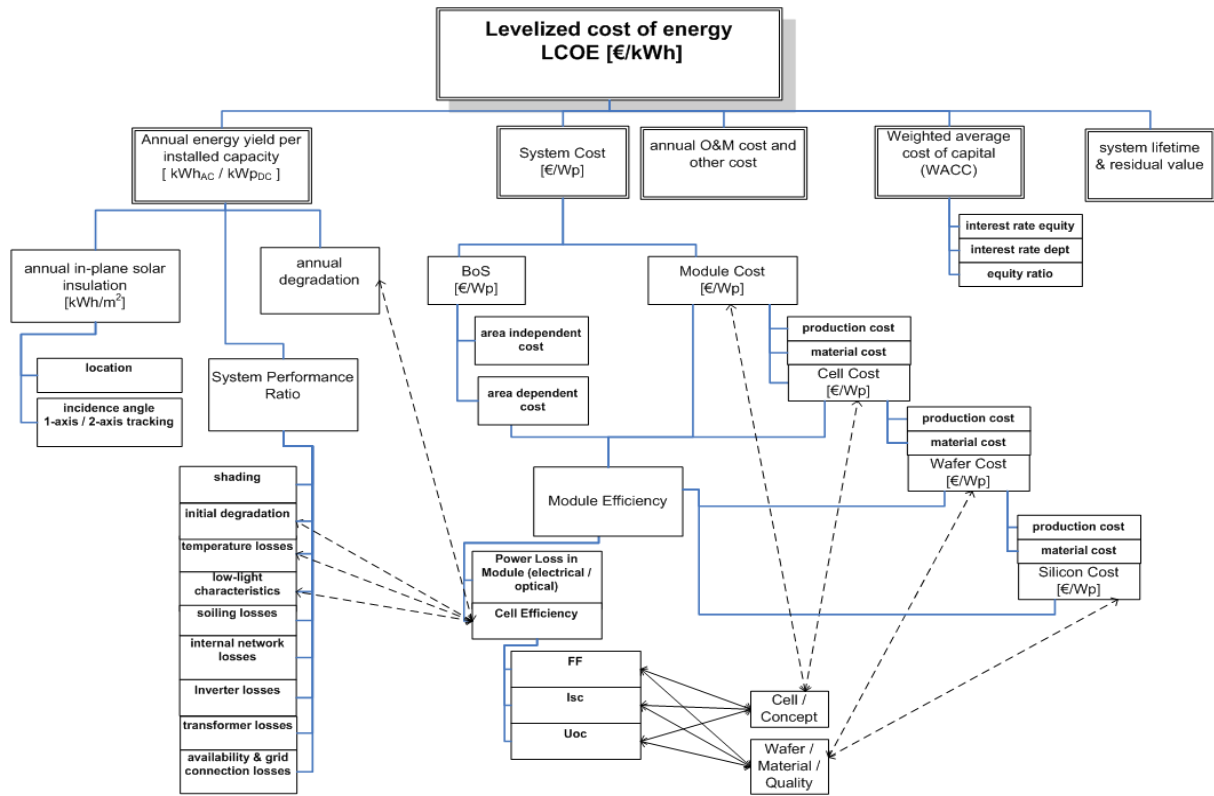


Figure 3.2-1: Schematic overview on the LCOE and its impact factors and interdependencies.⁵³⁹ Abbreviations stand for: operation and maintenance (*O&M*), balance of system (*BOS*) and parameters for electrical description of solar cell characteristics (*FF*, *I_{sc}*, *U_{oc}*).

For most considerations standard LCOE formula for PV systems (Eq. 3.2-1a) fulfils all requirements, however for exact treatment of annual degradation the LCOE formula including annual PV system degradation (Eq. 3.2-3b) might be more appropriate.

The input parameters for LCOE formula are mainly dependent on circumstances regarding geography, time, energy and financial markets. Reference yield is a function of local solar irradiance, which is given by latitude and average annual weather conditions of a specific site (chapter 2). Capital expenditures for PV systems are derived for future projections by the empirical experience curve for PV (Eqs. 3.1-1 and Fig. 3.1-3). A fast reduction of PV Capex is mainly dependent on the growth rate of global PV markets (Fig. 3.1-1) but also on time and the general energy markets.

For analysing the economic potential of PV, the critical input parameters are the learning rate (progress ratio) of PV (section 3.1.2), the growth rate of the global PV industry (section 3.1.1), both key drivers of the experience curve, and the fossil energy price trends (sub-chapters 1.1 and 1.3 and section 6.1.4). The interdependencies of these key driving forces are discussed in more detail in section 3.3.2.

The relative impact of the WACC needs to be highlighted in reference to portfolio theory, in particular for comparing fossil and renewable energy technologies. The economic portfolio theory is a research field of modern finance theory and was developed to investigate investment decisions on the capital markets.⁵⁴⁰ Objective of portfolio theory is the development of methods to find an optimized portfolio of investments. Main result of

⁵³⁹ Doll R., LCOE: an overview, 2009

⁵⁴⁰ Markowitz H., Portfolio Selection, 1952

portfolio theory is risk diversification, i.e. investors tend to differently optimised portfolios depending on their individual chance-risk profile. Portfolio theory was originally developed for capital markets but is adapted to the energy sector in the meantime.^{541,542} Fuel costs and resulting emission costs do not exist for nearly all renewable energy technologies, hence no respective price risk is given. Fossil fuel prices systematically fluctuate, thus portfolio theory have to regard risks which cannot be diversified in a fossil portfolio. Solar irradiation, wind, hydro power and geothermal heat flux are relative constant in the annual average and no comparable price risk can be observed. An increase of the proportion of renewable energies in an energy mix automatically reduces the risk of the energy mix. A further advantage is given besides this classical risk diversification effect. Every fossil-dominated energy portfolio which is improved by renewable energies shows lowered energy cost on each risk level whatever cost of renewable energies are taken into account.⁵⁴³ The new mixed portfolio of a higher proportion of renewable energies provides energy of lower cost on the same level of risk or the identical energy cost is achieved on a lowered level of risk. However, in this thesis this effect is not taken into account, since no proper data have been found for quantifying this effect. Nevertheless, the risk effect exists and in consequence the WACC for renewable energy technologies should be lower than that of fossil technologies. As a consequence the such derived relative LCOE have to be considered conservative.

3.2.2 Cost Projections of Systems

The input parameters for LCOE formula are mainly dependent on circumstances in geography, time, energy and financial markets (Eqs. 3.2-1 and Fig. 3.2-1). Net generated energy is a function of local solar irradiation, which is given by latitude and annual aggregated average monthly weather conditions of a specific site and performance of all components for local conditions, summarized in the performance ratio. Capital expenditures for PV systems are cost for PV modules, inverters, mounting structure, cabling, grid connection, civil works, project engineering, project development and cost for plant area. Except modules and inverters, all the other cost components are defined as balance of system (BOS) cost. Cost for inverters, project engineering, project development and grid connection are dependent on the power output of the PV plant. Cost for mounting structure, cabling and civil works are dependent on area of modules and distance of adjacent module rows, which reflects shading considerations. Module area needed for a specific power output is mainly determined by the module efficiency. Today's commercially available modules convert 6% to 19% of incident solar irradiance (Fig. 3.1-26).⁵⁴⁴ Commercial PV systems have to be designed for minimum LCOE, hence a trade-off between maximum irradiation and minimum overall cost and in particular BOS cost has to be optimised.

3.2.2.1 Ground Cover Ratio and Shading

Local solar irradiation is a very important factor for LCOE (Eqs. 3.2-1). PV systems need to minimize electricity generation cost, measured in cost/kWh by LCOE method. A large fraction of BOS cost is dependent on the ground cover ratio (GCR) of the PV system, i.e. ratio of entire module surface to site area, hence a higher GCR (Eqs. 3.2-4) reduces BOS cost

⁵⁴¹ Awerbuch S., Investing in photovoltaics: risk, accounting and the value of new technology, 2000

⁵⁴² Awerbuch S. and Berger M., Applying Portfolio Theory to EU Electricity Planning and Policymaking, 2003

⁵⁴³ Awerbuch S., Portfolio-based electricity generation planning: policy implications for renewables and energy security, 2006

⁵⁴⁴ Kreutzman A. and Siemer J., Market survey on solar modules 2010: Smooth sailing, 2010

and maybe LCOE, whereas annual irradiation on module surface might be decreased by shading effects as well (Fig. 3.2-2).

$$GCR = \frac{A_{PV \text{ array}}}{A_{occupied \text{ ground}}} = \frac{l \cdot b}{l_{NS} \cdot l_{EW}} \quad (\text{Eq. 3.2-4})$$

Equation 3.2-4: Ground cover ratio (GCR). GCR is dependent on specific ground requirements for a unit of module arrays, therefore shading in one or two directions significantly differs for respective systems at a specific site for identical shading loss over the year. One directional shading occurs for fixed optimally tilted and 1-axis horizontal tracking PV systems. Two directional shading is given for 1-axis vertical, 1-axis optimally tilted north-south and 2-axes tracking PV systems. Abbreviations stand for: dimensions of module array (l , b) and dimensions of ground requirements for module array (l_{NS} , l_{EW}).

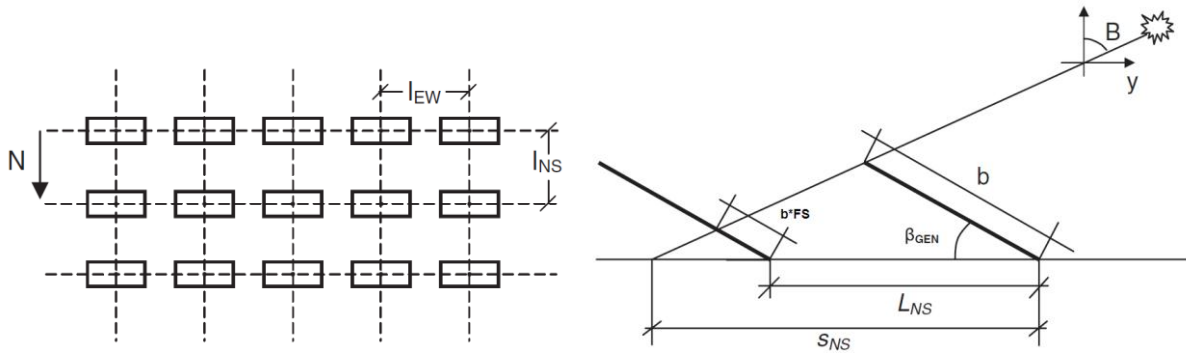


Figure 3.2-2: Fundamental geometric characteristics for shading in PV power plants.⁵⁴⁵ Principle set-up of ensembles of modules is depicted in the left. Shading fraction (FS) in dependence of tilt angle (β), geometric dimension of module arrays (b) and distance to next row (l_{NS}) is depicted in the right. PV power plant design of 2-axes, 1-axis vertical and 1-axis optimally tilted north-south tracking PV systems can be described by the left schematic. 1-axis horizontal east-west tracking and fixed optimally tilted PV systems are constructed in long rows in east-west direction without spacing between arrays of modules. 1-axis horizontal north-south is identical to its east-west version by exchanging east-west and north-south directions. Shading occurs in either east-west or north-south direction or in both directions, depending on PV system: fixed tilted (N-S), 1-axis horizontal east-west (N-S), 1-axis horizontal north-south (E-W), 1-axis vertical (N-S and E-W), 1-axis optimally tilted north-south (N-S and E-W) and 2-axes (N-S and E-W).

Row to row shading and consequences for GCR is considered by rules described by Duffie and Beckmann⁵⁴⁶ and Narvarte and Lorenzo⁵⁴⁷ based on principle considerations in Figure 3.2-2 and Equation 3.2-4. Tilt angle of modules is directly joined to distance of adjacent rows, which is the driving factor for GCR and total PV power plant area. Electrical consequence of partial shading of rows is calculated by method of Narvarte and Lorenzo⁵⁴⁸, i.e. 0% - 33% fraction of shaded array leads to a power reduction of 33% and so on in steps of one third. Module arrangement per row is assumed to be in parallel association for three lines, each made up of series association of a certain number of PV modules. Thus, each time one line of a row gets shaded output, power reduces by one third. Identical to solar resource calculations in chapter 2, all coordinates are computed in a $1^\circ \times 1^\circ$ mesh of latitude and longitude in 1h intervals over the mean day of all months of the year for all considered PV systems. Shading is a phenomenon mainly in the early morning and late afternoon, but also in seasons of extreme positions of the sun. The calculation of only 1h values might be too rough for an exact description of shading effects, but limited computational power forced this rough

⁵⁴⁵ Narvarte L. and Lorenzo E., Tracking and Ground Cover Ratio, 2008

⁵⁴⁶ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

⁵⁴⁷ Narvarte L. and Lorenzo E., Tracking and Ground Cover Ratio, 2008

⁵⁴⁸ Narvarte L. and Lorenzo E., Tracking and Ground Cover Ratio, 2008

estimate. Outcome of irradiation on module surface in dependence on GCR and adapted optimal tilt angle of 1-axis optimally tilted north-south continuous tracking PV system is shown in Figures 3.2-3 and 3.2-4.

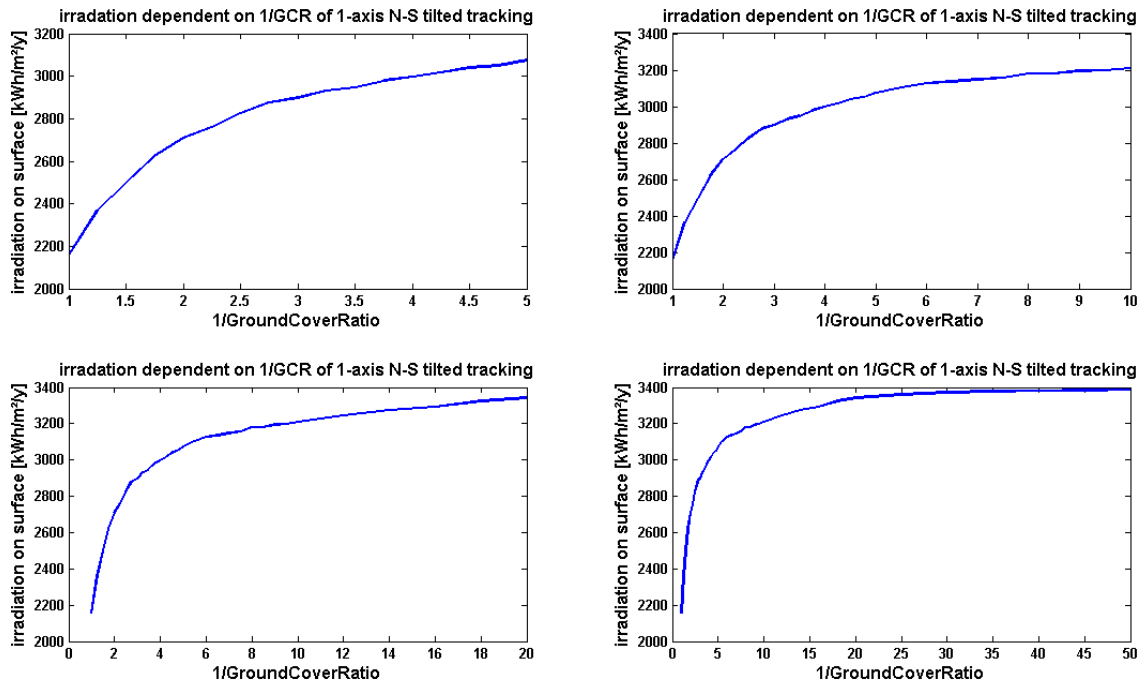


Figure 3.2-3: Irradiation on module surface in dependence on ground cover ratio. Depicted PV system is a 1-axis optimally tilted north-south continuous tracking one located in Sahara desert at 20.5°N/ 15.5°E. Calculations have been performed in a 1h time interval which might not be best adapted to shading effects, but characteristic is identical to results in literature.⁵⁴⁹

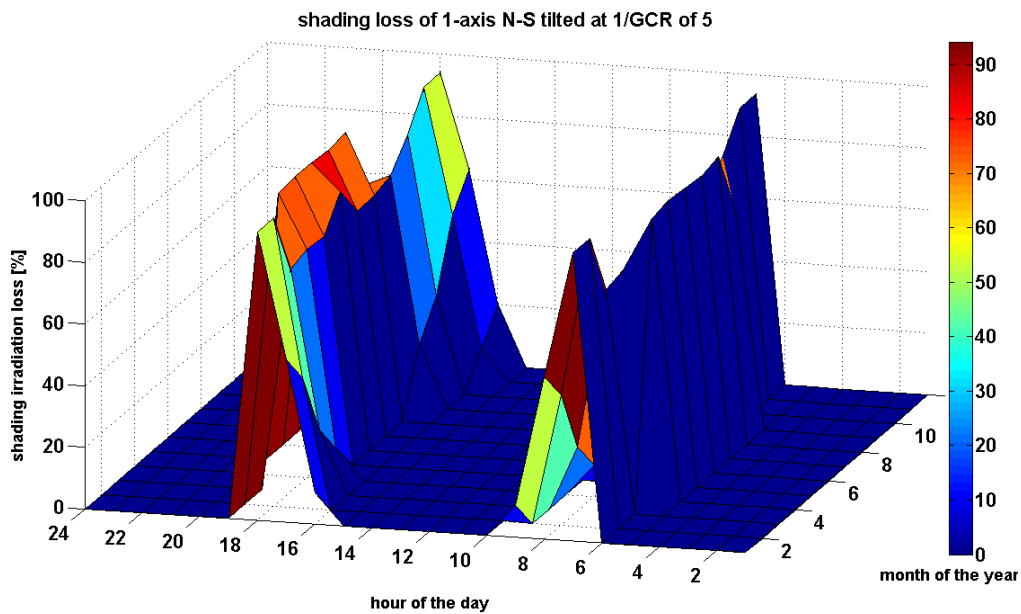


Figure 3.2-4: Shading loss characteristic of a PV system. Depicted PV system is a 1-axis optimally tilted north-south continuous tracking one, at a GCR of 20% located in Sahara desert at 20.5°N/ 15.5°E. Calculations have been performed in a 1h time interval which might not be best adapted to shading effects. Shading occurs in early

⁵⁴⁹ Narvarte L. and Lorenzo E., Tracking and Ground Cover Ratio, 2008

morning and late afternoon hours.

It is not possible to define an optimum relationship of GCR and shading by regarding irradiation on module surface. For finding optimised parameter settings for PV systems used for PV power plants the irradiation on module surface model needs to be combined with an economic model.

3.2.2.2 Financial Scenario Assumptions

It is highly debated in the market whether PV tracking of fixed tilted systems are and will be a good choice in regard to LCOE. For example Deutsche Bank noticed in a financial research report, that tracking systems allow high priced high efficiency modules to compete against low cost low efficiency modules.⁵⁵⁰ However, New Energy Finance concluded that tracking systems could not generate additional financial value for PV power plant operators.⁵⁵¹ Pacific Crest came to the result that low cost modules from First Solar eliminated the need for tracking systems⁵⁵² and that c-Si modules would be only competitive with tracking systems, however in the meantime First Solar decided to invest in a 1-axis tracking company⁵⁵³. Most large PV system manufacturers offer fixed optimally tilted systems as a standard but also at least one tracking system, typically the 1-axis horizontal north-south continuous tracking system.^{554,555,556,557} In this section a better understanding on competitiveness of PV system technology is in the main focus for performing further analyses on best optimised and locally adapted PV LCOE.

A database on the trade-off between GCR and shading for all respective PV systems is generated for selecting optimum parameter combinations. These parameters are GCR, shading loss, module efficiency, module cost per Wp and relative change of these parameters in the 2010s as a consequence of different learning rates for modules and inverters versus those of other BOS components. Scenario assumptions for calculating cost of PV power plants are summarized in Table 3.2-1. Three different scenario settings have been developed, which mainly differ in module cost, but also partly in cost for tracking systems, financing conditions, assumptions of PV industry growth rates and stability of learning rates. These scenarios assume well adjusted value chain management either internally in companies or externally by two or more companies. Main difference of the scenarios is a business-as-usual approach (realistic), tough competition, fast cost reduction and excellent bankable products (aggressive) and a crucial scenario with very high imbalanced and fierce competition but still excellent bankable products (bloody). Reality might be somewhere between the realistic and aggressive scenario.

		scenario realistic	scenario aggressive	scenario bloody
Capex_Module at efficiency of	10% [€/Wp]	1.40	1.00	0.87
Capex_Module at efficiency of	11% [€/Wp]	1.48	1.08	0.91

⁵⁵⁰ O'Rourke S., Solar Photovoltaic Industry, 2009

⁵⁵¹ Tringas T. and Ballardin G., Q3 Levelised Cost of Energy Outlook, 2009

⁵⁵² Bachmann M., Morning Note on First Solar, 2008

⁵⁵³ First Solar, First Solar Acquires RayTracker Inc., 2011

⁵⁵⁴ SunPower, Ground-Mounted Solar Trackers, 2011

⁵⁵⁵ Suntech Power, Introducing Reliathon: Lowering the LCOE of Multi-Megawatt Projects, 2011

⁵⁵⁶ First Solar, First Solar Acquires RayTracker Inc., 2011

⁵⁵⁷ BP Solar, BP Solar's EnergyMax solar electric ground systems, 2011

Capex_Module at efficiency of	12%	[€/Wp]	1.56	1.16	0.95
Capex_Module at efficiency of	13%	[€/Wp]	1.64	1.24	1.00
Capex_Module at efficiency of	14%	[€/Wp]	1.72	1.32	1.04
Capex_Module at efficiency of	15%	[€/Wp]	1.80	1.40	1.08
Capex_Module at efficiency of	16%	[€/Wp]	1.88	1.48	1.13
Capex_Module at efficiency of	17%	[€/Wp]	1.96	1.56	1.17
Capex_Module at efficiency of	18%	[€/Wp]	2.04	1.64	1.21
Capex_Module at efficiency of	19%	[€/Wp]	2.12	1.72	1.26
Capex_Module at efficiency of	20%	[€/Wp]	2.20	1.80	1.30
Capex_Inverter		[€/Wp]	0.18	0.15	0.15
Capex_Mounting_fixed		[€/m²mod]	25.00	25.00	25.00
Capex_Mounting_1-axis horizon		[€/m²mod]	52.50	37.50	37.50
Capex_Mounting_1-axis tilted		[€/m²mod]	55.00	40.00	40.00
Capex_Mounting_1-axis vertical		[€/m²mod]	80.00	52.50	52.50
Capex_Mounting_2-axes		[€/m²mod]	85.00	55.00	55.00
Capex_Gridconnection		[€/Wp]	0.08	0.08	0.08
Capex_Overhead		[€/Wp]	0.02	0.02	0.02
Capex_Civilworks		[€/m²site]	0.80	0.80	0.80
Capex_Cabbling_low1		[€/m²mod]	6.60	6.60	6.60
Capex_Cabbling_low2		[€/m²site@GCR3]	1.50	1.50	1.50
Capex_Cabbling_med		[€/Wp]	0.012	0.012	0.012
Capex_area		[€/m²site]	2.00	2.00	2.00
fin_RoE		[%]	10%	8%	8%
fin_interest		[%]	6%	5%	5%
fin_WACC		[%]	6.80%	5.60%	5.60%
fin_equityRatio		[%]	20%	20%	20%
plant_lifetime		[y]	25	30	30
plant_PerformanceRatio		[%]	80%	83%	83%
plant_degradation		[%/y]	0.4%	0.3%	0.3%
plant_Opex_basis		[%]	1.00%	0.80%	0.80%
plant_Opex_2add_1-axis horizon		[%]	0.13%	0.10%	0.10%
plant_Opex_2add_1-axis tilted		[%]	0.13%	0.10%	0.10%
plant_Opex_2add_1-axis vertical		[%]	0.21%	0.16%	0.16%
plant_Opex_2add_2-axis		[%]	0.28%	0.22%	0.22%
plant_roadFactor		[%]	20%	20%	20%
capacity_cumulated_2009		[GWp]	21	21	21
capacity_added_2009		[GWp]	6	6	6
PR_Module_Inverter_2009-2012		[%]	80%	80%	80%
PR_Module_Inverter_2013-2020		[%]	85%	80%	80%
PR_BOS_2009-2012		[%]	85%	80%	80%
PR_BOS_2013-2020		[%]	90%	85%	85%
growth_rate_2009-2012		[%]	40%	50%	50%
growth_rate_2013-2020		[%]	30%	40%	40%

Table 3.2-1: Scenario assumptions for PV power plant economics. The three scenarios cover a business-as-usual approach (realistic), highly optimised value chain composition (aggressive) and very high competition (bloody). Economic parameters are more cost than price oriented due to cost driven prices in competitive markets, which is the case for the PV industry. Power and area scaling of respective cost components is indicated. Numbers mentioned are for PV power plants of multi-10 MW starting in the end of the year 2009. Abbreviations stand for: capital expenditures (Capex), operational expenditures (Opex), return on equity (RoE), weighted average cost of capital (WACC), progress ratio (PR), balance of system (BOS). Data are taken from

various sources, but most relevant are price and cost for modules^{558,559,560,561,562,563}, price for tracking systems^{564,565}, or some BOS cost of PV power plant⁵⁶⁶. Other relevant factors discussed in other sections, like: plant lifetime and degradation (section 3.1.6), current global market data and PV industry growth rates (section 3.1.1), performance ratio of modules, inverters and BOS (section 3.1.2) and capital cost (section 3.3.2). Specific technology inherent characteristics like temperature coefficient and low light response are not explicitly parameterised but indirectly included in the performance ratio assuming a respective absolute error level of less than 10% in the resulting LCOE.

Outcome for capital expenditures (Capex) for the six relevant PV systems and as far as possible a technology independent consideration is shown for an exemplarily site in Figure 3.2-5. Capex for fixed optimally tilted PV systems in power plant scale of multi-10 MW are in the scenarios in 2010 about 1.80 €/Wp, 2.05 €/Wp and 2.40 €/Wp (realistic: 10%, 15% and 20% module efficiency), about 1.40 €/Wp, 1.70 €/Wp and 1.95 €/Wp (aggressive: 10%, 15% and 20% module efficiency) and about 1.30 €/Wp, 1.40 €/Wp and 1.50 €/Wp (bloody: 10%, 15% and 20% module efficiency). Prices of the realistic scenario have been signed in 2010. Prices of the aggressive scenario have not been seen in the market in 2010, but these potential prices would still be achievable due to respective fully loaded cost of leading companies in the PV industry. End of 2009 the fully loaded cost (EBIT of zero over the entire value chain) of leading PV companies for PV power plants have been about 1.45 €/Wp – 1.50 €/Wp for both CdTe PV and c-Si PV, i.e. 10% - 11% and 13% - 15% modules.⁵⁶⁷ Current growth rate and learning rate lead to annual cost reductions of about 10% - 15%, hence even the bloody scenario has been in reach for the cost leaders in the PV industry on a non profit level of EBIT of zero in 2010. In the realistic scenario fixed optimally tilted PV systems might cost about 1.0 €/Wp in 2020, which is fully inline with respective considerations for PV grid-parity analysis in Figure 3.3-10. For the aggressive and bloody scenario a PV system Capex of slightly below 0.60 €/Wp and 0.55 €/Wp might be possible in the year 2020. From today's point of perspective, the 1.0 €/Wp is absolutely feasible, whereas a PV system Capex of 0.60 €/Wp might be very aggressive, but ongoing evolutionary cost reductions could stabilize the learning rate at today's 20% and fast cost reductions might steadily trigger new fast growing markets, hence constant high PV industry growth rates are not totally unlikely. The author of this thesis expects a development better than the realistic case but may be not as outstanding excellent than the aggressive scenario. Nevertheless, financial PV market facts of the years 2010 and 2011 are more in favour of the aggressive scenario (section 3.2.2.3).

⁵⁵⁸ Siemer J., Leveled out, 2009

⁵⁵⁹ First Solar, 2009 Annual Report, 2010

⁵⁶⁰ Yingli Green Energy Holding, Annual Report, 2010

⁵⁶¹ Trina Solar, Annual Report 2009, 2010

⁵⁶² SMA Solar Technology, Geschäftsbericht 2009, 2010

⁵⁶³ Wacker Chemie, Geschäftsbericht 2009, 2010

⁵⁶⁴ Siemer J., Trackers Survey: An industry in transition, 2009

⁵⁶⁵ Wiser R. et al., Tracking the Sun II, 2009

⁵⁶⁶ Nissen H., private communications on BOS cost components, 2009

⁵⁶⁷ Breyer Ch., How favourable is PV?, 2010a

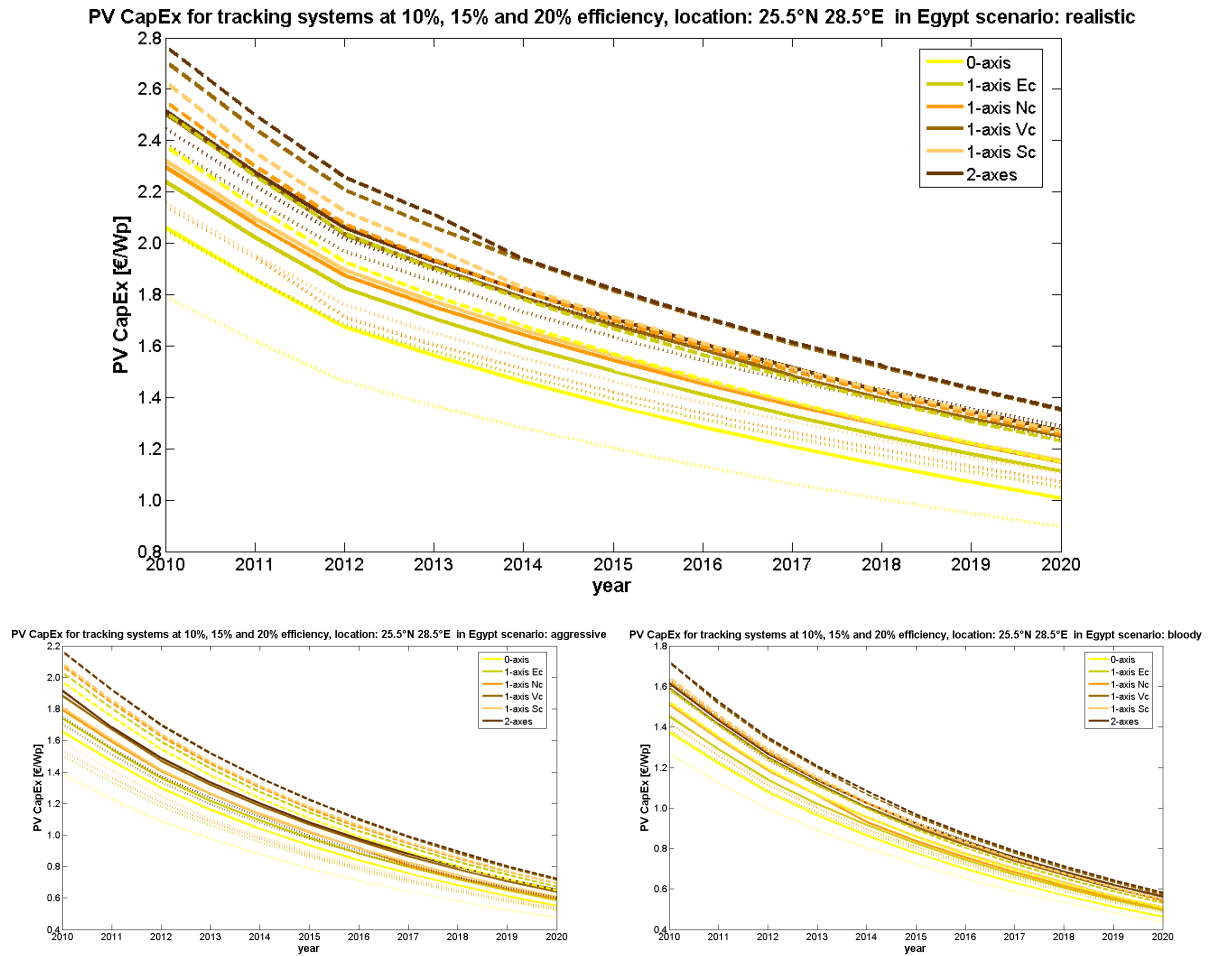


Figure 3.2-5: Capital expenditures (Capex) of PV systems in 2010s for the scenarios realistic (top), aggressive (bottom, left) and bloody (bottom, right). Capex depicted are for lowest local LCOE of respective PV systems. The exemplarily site is 25.5°N/ 28.5°E located in Egypt, however nearly all sites in the world show similar Capex. Capex curves are plotted for 10% efficient modules (dotted lines), 15% efficient modules (solid lines) and 20% efficient modules (dashed lines). Scenarios are defined in Table 3.2-1. Abbreviations stand for: fixed optimally tilted (0-axis), 1-axis horizontal east-west (1-axis Ec), 1-axis horizontal north-south (1-axis Nc), 1-axis vertical optimally tilted (1-axis Vc), 1-axis optimally tilted north-south (1-axis Sc) and 2-axes non-concentrating (2-axes) continuous tracking PV systems, respectively.

For calculating LCOE of respective PV systems (Eq. 3.2-1) Capex and irradiation on module surface are needed in dependence of module efficiency and GCR. Lowest LCOE per PV system defines the optimised parameter setting for multi-10 MW PV power plants within all the assumptions of the scenarios of Table 3.2-1 and the solar resources of chapter 2. An exemplarily Capex, insolation and LCOE characteristic for fixed optimally tilted and for 1-axis horizontal north-south continuous tracking PV systems is shown in Figures 3.2-6 and 3.2-7 in realistic scenario, respectively.

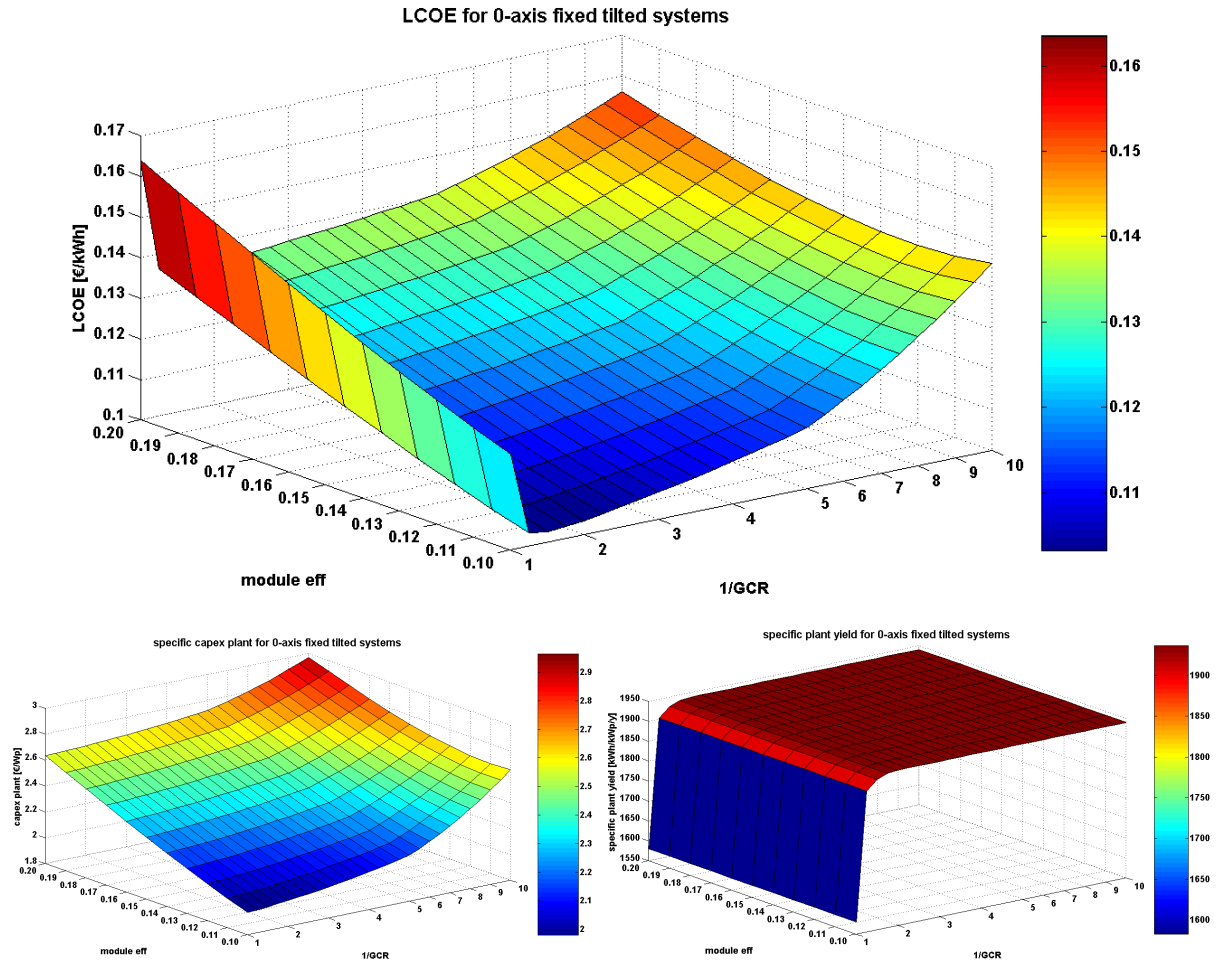
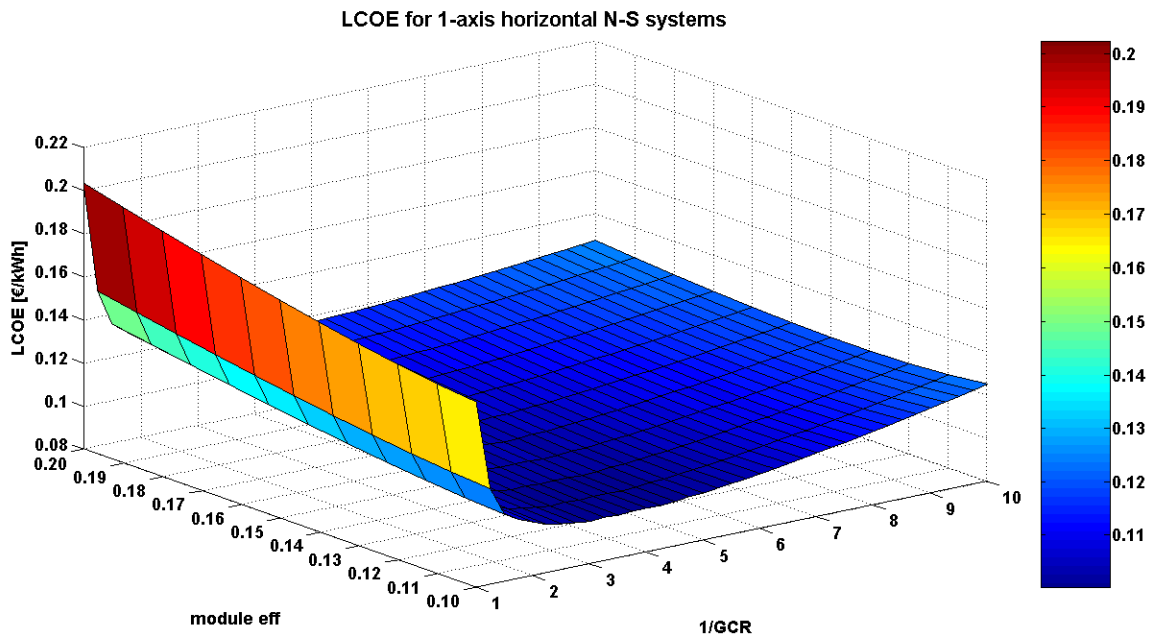


Figure 3.2-6: LCOE (top), Capex (bottom, left) and final yield (bottom, right) in dependence on module efficiency and GCR of a fixed optimally tilted PV system in realistic scenario assumptions. The exemplarily site is 20.5°N/ 15.5°E located in Sahara desert. LCOE and Capex increase due to higher module efficiencies is a consequence of heterogeneous module price. LCOE and Capex increase as a result of higher reciprocal GCR is a simple outcome of more BOS related Capex without respective final yield increase. Optimum GCR at that site close to the equator might be at about 50%. Parameter space is calculated for the year 2009.



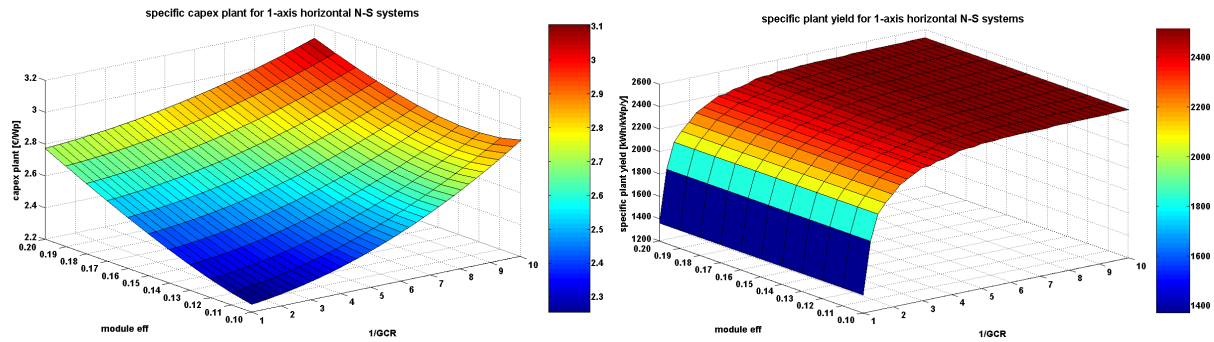


Figure 3.2-7: LCOE (top), Capex (bottom, left) and final yield (bottom, right) in dependence on module efficiency and GCR of a 1-axis horizontal north-south continuous tracking PV system in realistic scenario assumptions. The exemplarily site is 20.5°N/ 15.5°E located in Sahara desert. LCOE and Capex increase due to higher module efficiencies is a consequence of heterogeneous module price. LCOE and Capex increase as a result of higher reciprocal GCR is a simple outcome of more BOS related Capex without respective final yield increase. However this effect is much more damped for this tracking system than for fixed optimally tilted ones (Fig. 3.2-6). Optimum GCR at that site close to the equator might be at about 30%. Parameter space is calculated for the year 2009.

Both examples in Figures 3.2-6 and 3.2-7 show similar characteristics. Firstly, Capex and LCOE are increasing with module efficiency, i.e. true value of modules of higher efficiency is lower in PV power plant business than the prevailing average selling price for such modules. Secondly, Capex are increasing with higher reciprocal GCR, as a simple consequence of higher area related BOS expenditures. Thirdly, LCOE are decreasing, then stabilizing and finally increasing with higher reciprocal GCR, as a result of increasing final yield by lower GCR due to reduced shading. Parameter combination of lowest LCOE per PV system is defined as its optimum. Comparing all regarded six PV systems, the least cost system at a specific site can be found. Applying the scenario assumptions over the decade of the 2010s the dynamic can be analysed, as well. Irradiation on module surface and respective LCOE of six PV systems is depicted for the realistic scenario and the year 2010 in Figure 3.2-8. LCOE dynamics over the entire decade is shown in Figure 3.2-9.

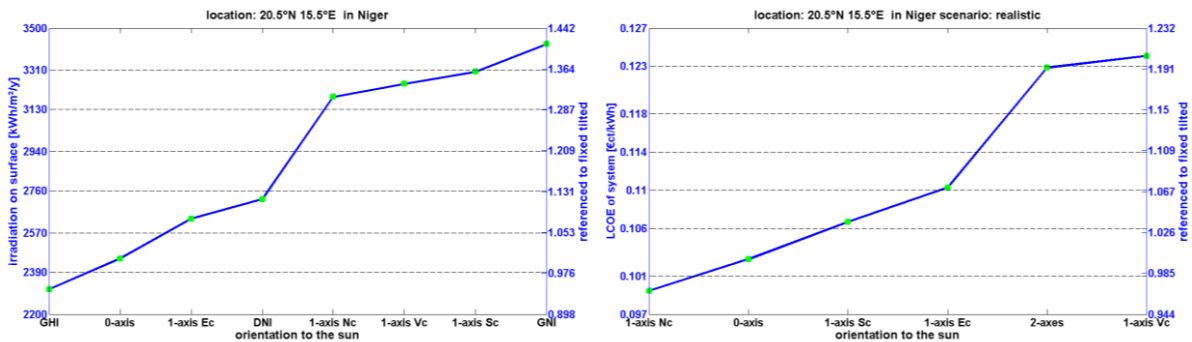


Figure 3.2-8: Highest irradiation on module surface (left) and lowest LCOE (right) of PV systems. The exemplarily site is 20.5°N/ 15.5°E located in Sahara desert. Realistic scenario setting of Table 3.2-1 is applied. Abbreviations stand for: global normal irradiation (GNI), fixed optimally tilted (0-axis), 1-axis horizontal east-west continuous tracking (1-axis Ec), 2-axes concentrating direct normal irradiation (DNI), 1-axis horizontal north-south continuous tracking (1-axis Nc), 1-axis vertical optimally tilted continuous tracking (1-axis Vc), 1-axis optimally tilted north-south continuous tracking (1-axis Sc) and 2-axes non-concentrating continuous tracking (2-axes/ GNI).

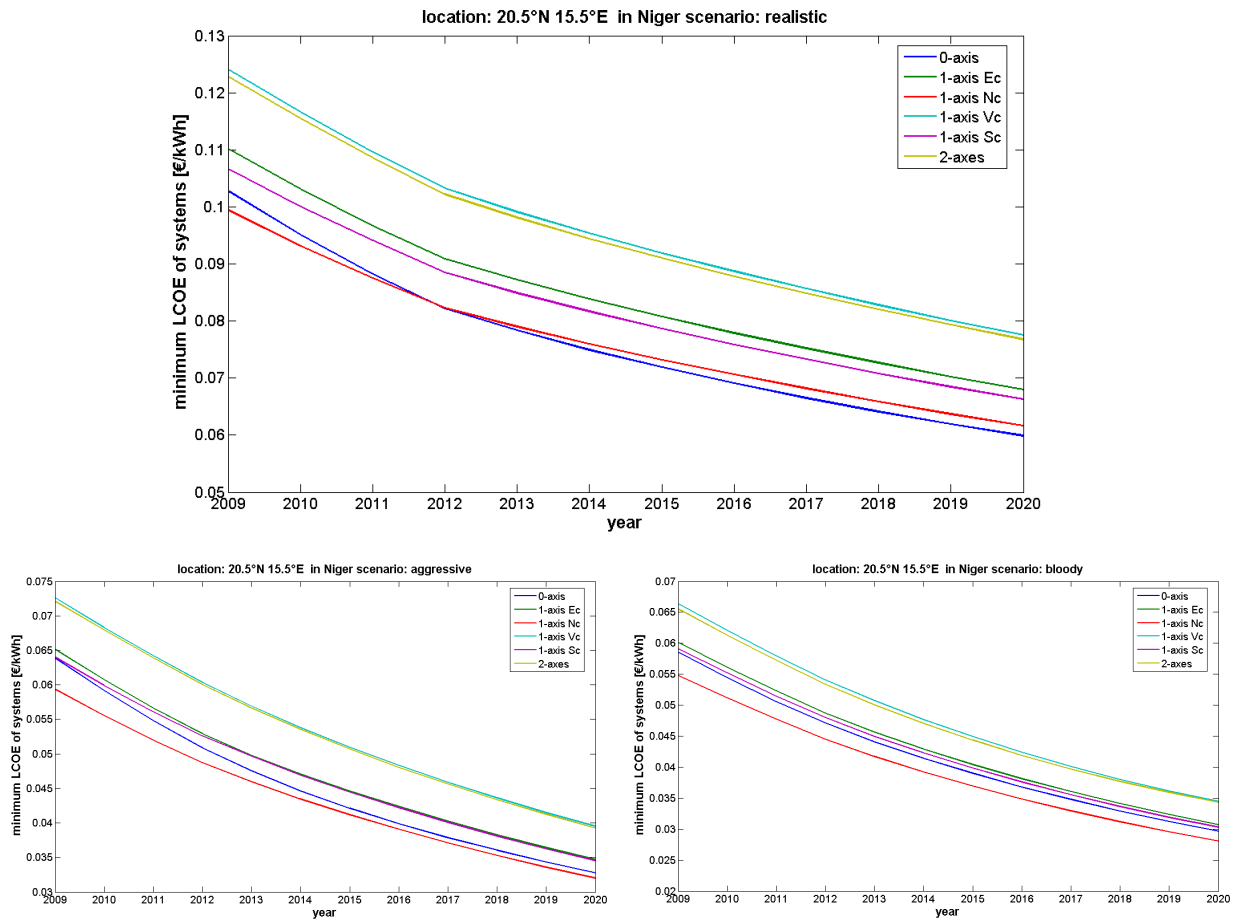


Figure 3.2-9: LCOE of PV systems in the 2010s for the scenarios realistic (top), aggressive (bottom, left) and bloody (bottom, right). LCOE depicted are for lowest local LCOE of respective PV systems. The exemplarily site is 20.5°N/ 15.5°E located in Sahara desert. The scenarios are defined in Table 3.2-1. Abbreviations stand for: fixed optimally tilted (0-axis), 1-axis horizontal east-west (1-axis Ec), 1-axis horizontal north-south (1-axis Nc), 1-axis vertical optimally tilted (1-axis Vc), 1-axis optimally tilted north-south (1-axis Sc) and 2-axes non-concentrating (2-axes) continuous tracking PV systems, respectively.

Difference in irradiation of the six PV systems is about 40% between reference PV system (fixed optimally tilted) and system of highest irradiation on module surface (2-axes). Difference in LCOE of the six PV systems is only 25% between least cost system (1-axis horizontal north-south) and system of highest LCOE (1-axis vertical). However, reference system (fixed optimally tilted) is also cost competitive and only 5% higher in LCOE than 1-axis horizontal north-south continuous tracking PV system. Such a low difference might not justify to use moving parts and to give up one of the most valuable advantages of PV power technology, except as many as possible PV full load hours (FLh) are needed, since about 30% more FLh could be expected. PV systems of two directional shading (section 3.2.2.1) and relative high Capex for tracking structure (Table 3.2-1) show an excellent irradiation on module surface but disappointing LCOE results, like for 2-axes non-concentrating and 1-axis vertical optimally tilted continuous tracking PV systems. The other two directional shading PV system, 1-axis optimally tilted north-south has comparable irradiation but significantly lower Capex for tracking structure enabling competitive LCOE. For sites of high global horizontal irradiation, low diffuse light fraction and being close to the equator, like in Sahara desert, 1-axis horizontal north-south continuous tracking and fixed optimally tilted seem to be the most attractive PV systems. In case of PV power FLh needed in the morning and the afternoon, the 1-axis tracking system might be the best system of all, without prejudice the disadvantage of moving parts.

Relative LCOE difference of the PV systems might be nearly stable over the entire decade, as a consequence of similar proportions of module and inverter to BOS Capex. Due to a lower learning rate of BOS components the relative fraction of BOS is increasing over time and LCOE trends of respective systems might lead to changes in the least cost system, as in Sahara desert, where fixed optimally tilted ones might be slightly lower in cost in the mid of 2010s. However, all the presented results are very sensitive to the input cost data of the PV modules, i.e. if modules of moderate and high efficiency had been priced more competitive to the modules of lower efficiency most tracking systems would perform much better in the economics. The LCOE trend in the realistic scenario leads to 0.10 €/kWh cost in 2010 and 0.06 €/kWh in 2020. The LCOE in the aggressive and bloody scenario would lead to about 0.06 €/kWh in 2010 and below 0.04 €/kWh in 2020.

These cost trends clearly reveal solar PV electricity to become a very cost competitive power technology. Results shown in this section have been for the example of Sahara desert. All the other coordinates are presented in an integrated form in section 3.2.3.

3.2.2.3 Global Industry Cost Curves for PV Systems

This section has been introduced after preliminary finalising this chapter. However, the relevance is quite high, due to the fact that fundamental cost assumptions in the previous sections and resulting consequences had been controversial discussed and assessed as too aggressive by some colleagues but the author of this thesis defends this numbers as the verified outcome of a broad and deep industry cost analysis.

Photon Consulting published in early 2011 the latest ‘Solar Annual’ report including PV industry cost curves for power plant and roof-top systems in all relevant markets in the world and for all relevant industry players.⁵⁶⁸ The global integrated industry cost curve for PV systems for the relevant markets in the year 2010 is visualised in Figure 3.2-10. A breakdown of the market focussed PV system cost into fully-loaded cost of the relevant c-Si and TF module manufacturers is depicted in Figure 3.2-11, whereas the market related non-module system cost are shown in Figure 3.2-12. These are the differentiated true cost of the relevant PV industry players in the different PV markets.

⁵⁶⁸ Bolman C. et al., Solar Annual 2010-2011: Cash In, 2011

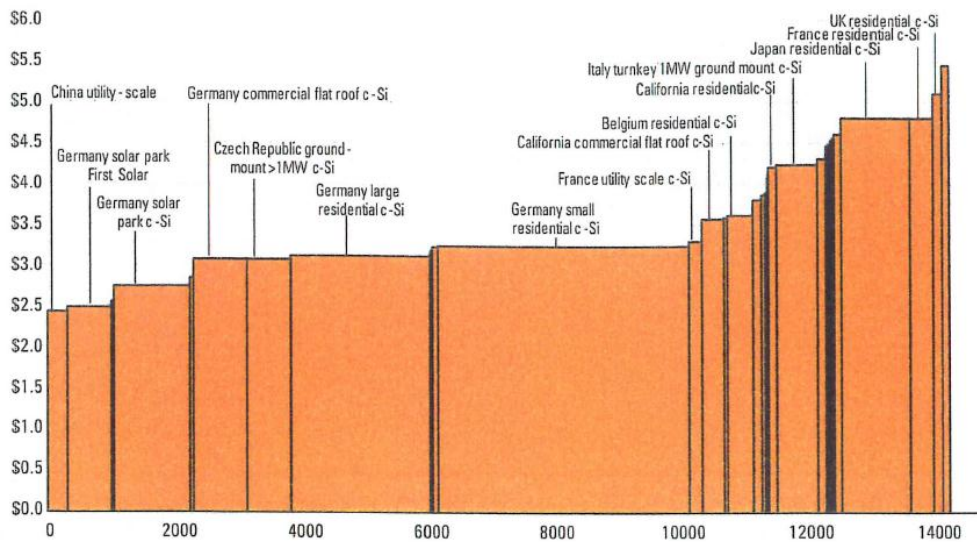


Figure 3.2-10: Global fully-loaded PV industry cost curve for utility-scale and roof-top systems in the year 2010. The system cost, i.e. Capex, is in units of USD/Wp (USD/€ exchange rate of 1.3) and the volume in MW. The diagram is taken from Photon Consulting.⁵⁶⁹

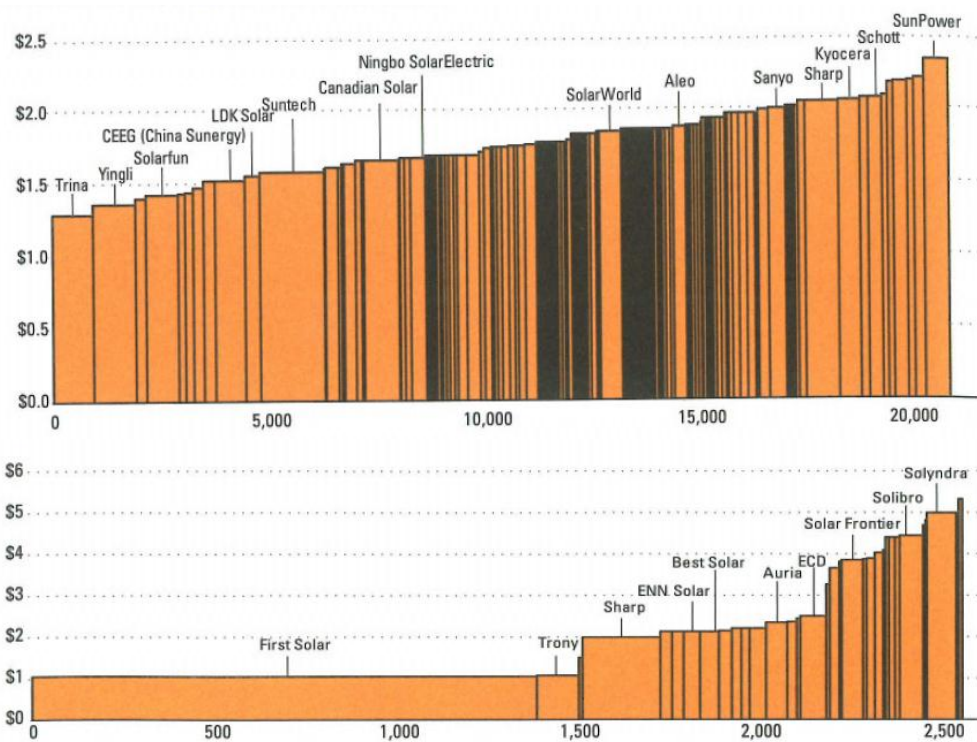


Figure 3.2-11: Global fully-loaded PV industry cost curve for c-Si (top) and thin-film (bottom) module manufacturers in the year 2010. The module cost, i.e. Capex, is in units of USD/Wp (USD/€ exchange rate of 1.3) and the volume in MW. The diagram is taken from Photon Consulting.⁵⁷⁰

⁵⁶⁹ Bolman C. et al., Solar Annual 2010-2011: Cash In, 2011

⁵⁷⁰ Bolman C. et al., Solar Annual 2010-2011: Cash In, 2011

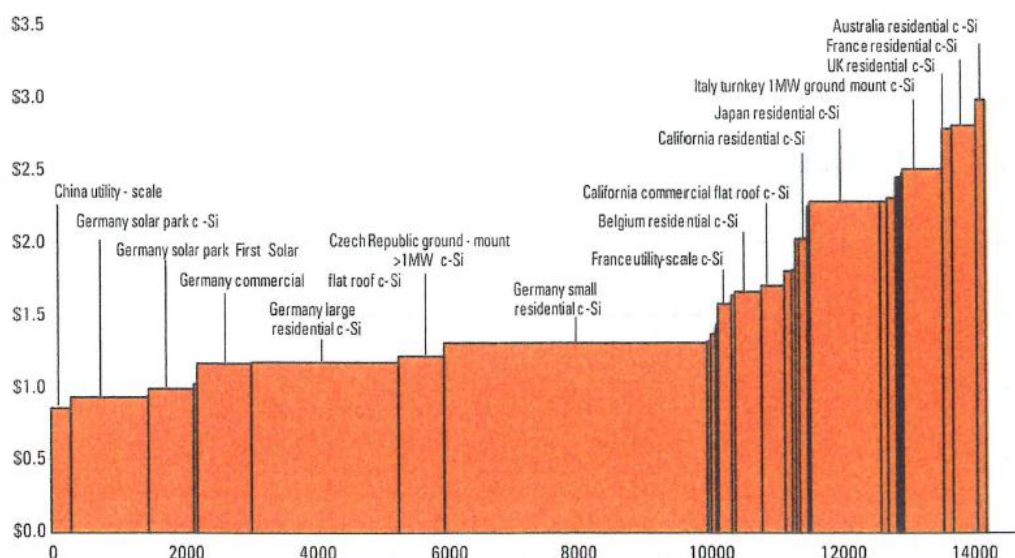


Figure 3.2-12: Global fully-loaded PV industry cost curve for non-module costs in the relevant PV markets in the year 2010. The non-module cost, i.e. Capex, is in units of USD/Wp (USD/€ exchange rate of 1.3) and the volume in MW. The diagram is taken from Photon Consulting.⁵⁷¹

The most competitive utility-scale market segments are China and Germany, which show average fully-loaded system cost of about 1.9 – 2.1 €/Wp in the year 2010 (Fig. 3.2-10) being in line with the realistic scenario assumptions in Table 3.2-1 leading to respective Capex of 1.8 – 2.05 €/Wp. This confirmation is very relevant since both China and Germany achieve this cost level, but the former as a low cost country which has not yet grown into the market size for substantial downstream scaling and the latter as a high cost country but being highly efficient due to downstream scaling.

Most competitive PV industry leaders achieve an even better cost level. True cost of PV power plants in Germany equipped with First Solar modules are found to be slightly below 1.6 €/Wp (Figures 3.2-11 and 3.2-12). The two c-Si module cost leaders achieve fully-loaded module cost in average of about 1.02 €/Wp (Figure 3.2-11). The fully-loaded average non-module cost in China and Germany for c-Si PV power plants are 0.67 and 0.72 €/Wp, respectively. As a consequence the fully-loaded system cost for very competitive c-Si PV power plants have been about 1.7 €/Wp, composed by c-Si module cost leaders and the two most cost efficient PV markets (Figures 3.2-11 and 3.2-12). In total leading PV industry players have been able to offer PV power plants for 1.6 – 1.7 €/Wp for the conditions of cost efficient PV markets. Therefore the leading industry players are able to offer 10% - 25% more cost competitive PV power plants in already cost efficient markets than the PV industry in average. This system cost range of 1.6 – 1.7 €/Wp is narrower and higher at the lower end than the assumed range of 1.4 – 1.7 €/Wp in the aggressive scenario assumptions in Table 3.2-1, however the upper end of the range is identical.

Photon Consulting presents an overview on discount rates and internal rates of return (IRR) for all relevant market segments.⁵⁷² The minimum discount rate for utility-scale systems in Germany and China are expected to be about 4.7% and 5.3%, whereas the total achievable IRR is assumed to be about 6.8% and 9.9%, respectively. The required minimum discount rate is in all market segments below 6.8% except Greece, India and Bulgaria. The majority of

⁵⁷¹ Bolman C. et al., Solar Annual 2010-2011: Cash In, 2011

⁵⁷² Bolman C. et al., Solar Annual 2010-2011: Cash In, 2011

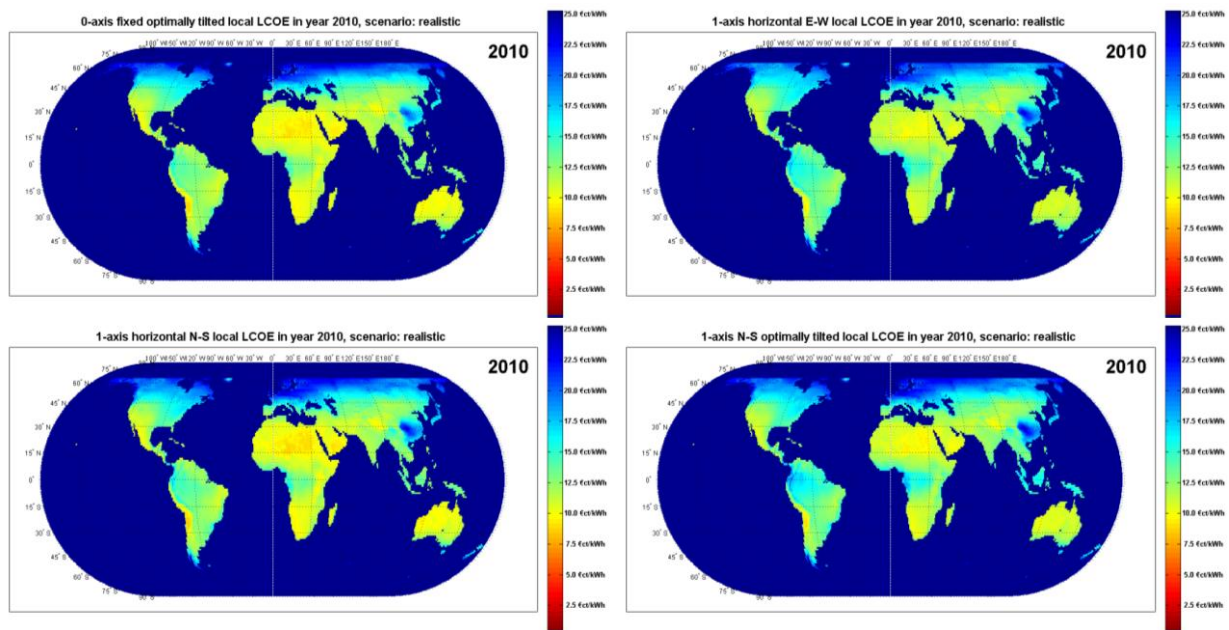
market segments show discount rates of 5.6% or lower. The assumed WACC in the realistic (6.8%) and aggressive (5.6%) scenario are achievable in many markets.

Summing up, comprehensive and differentiated market data confirm the assumptions for the realistic and aggressive scenario defined in Table 3.2-1. Nevertheless, the reduction of bureaucracy cost ⁵⁷³ and the accessibility of sustainable large market sizes are a very important precondition for low non-module cost in the different markets in the world. Moreover, it should be of utmost interest for policy-makers to guarantee low risk market conditions, e.g. stable FiT legislation or regulation frameworks reducing investment risks, for achieving respective low minimum capital cost being very relevant for both cost competitive PV LCOE and large volumes of annually new installed PV systems.

3.2.3 Least Cost of Systems

Routines for finding least cost of PV systems introduced in the last sections can be applied to all coordinates within the 1°x1° mesh of latitudes and longitudes for which all relevant solar resources (chapter 2) are available. Integrated assessment of least cost of all PV systems allows to identify the least cost PV system per coordinate and to depict the least cost of all systems in a world map. By applying the experience curve approach (section 3.1.2) scenario projection for the decade of the 2010s gives insights into the dynamic of PV cost trends. Specific trends among the six PV systems are analysed in the following section.

Global LCOE of the six PV systems for the realistic scenario and the year 2010 is shown in Figure 3.2-13.



⁵⁷³ Beneking A., Europas größte Solarbremser – So reibungslos wie in Deutschland läuft es nirgends, 2011

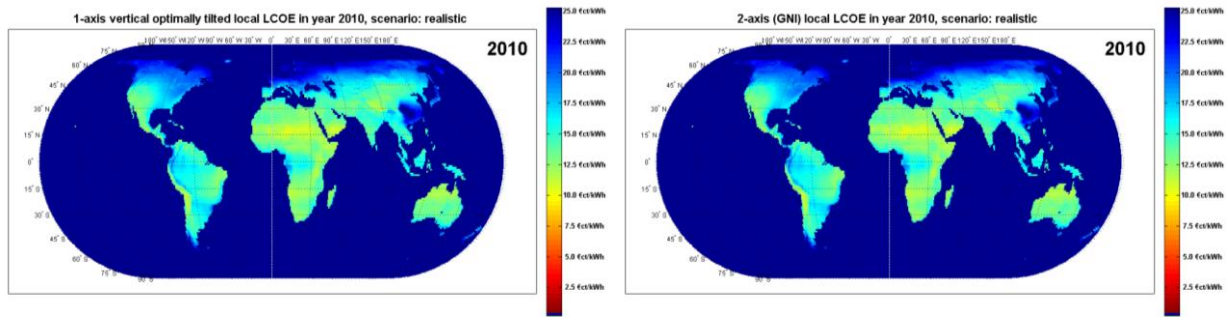


Figure 3.2-13: Global LCOE of relevant PV systems in the year 2010 for the realistic scenario. PV systems are: fixed optimally tilted (top, left), 1-axis horizontal east-west (top, right), 1-axis horizontal north-south (centre, left), 1-axis optimally tilted north-south (centre, right), 1-axis vertical (bottom, left) and 2-axes non-concentrating (bottom, right) continuous tracking, respectively.

Relative differences of PV systems are difficult to figure out in a plot of absolute LCOE. Thus, least LCOE of all systems and name of respective system per coordinate are shown in Figure 3.2-14 for the realistic scenario in the year 2010. In reference to this optimized LCOE landscape each system can be compared in its relative cost position for understanding relative competitiveness of all PV systems for all coordinates. Relative LCOE competitiveness for PV systems is summarized in Figure 3.2-15 for the realistic scenario in the year 2010.

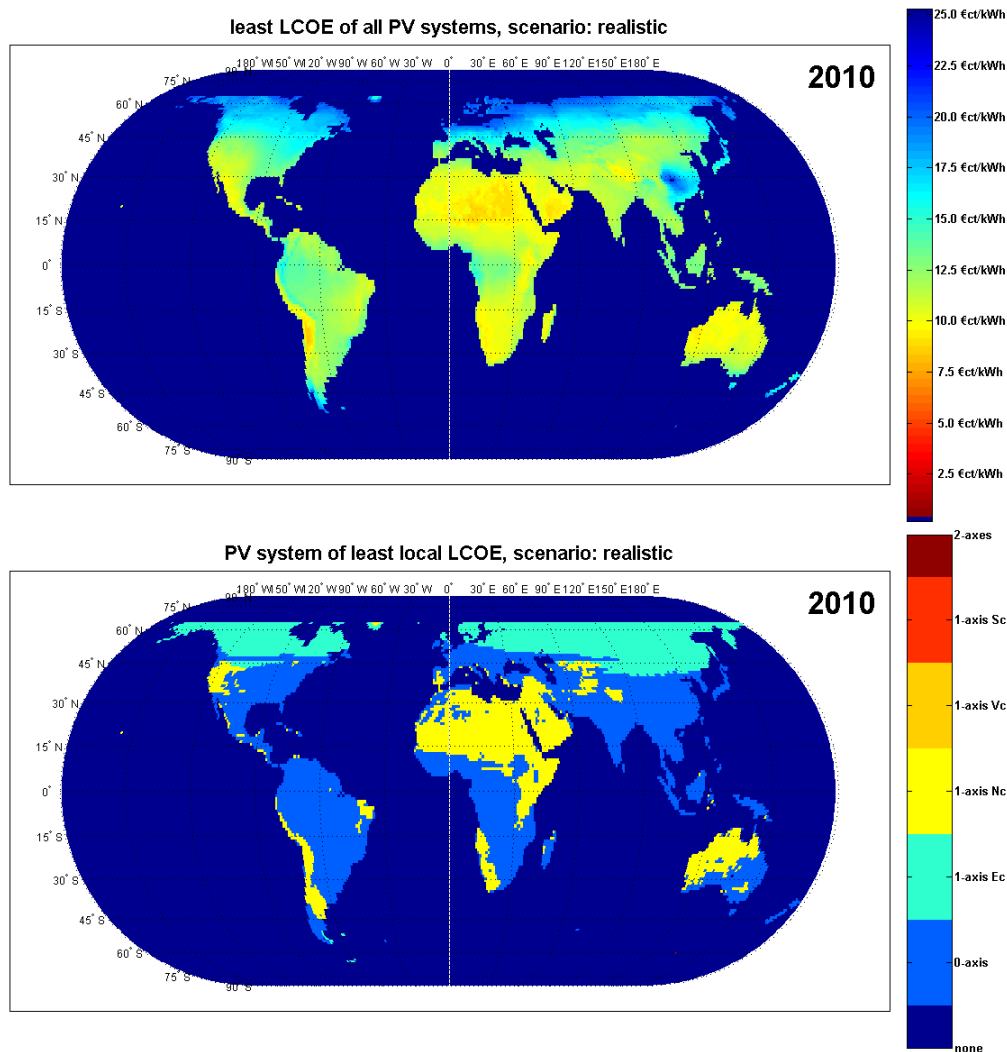


Figure 3.2-14: Least LCOE of all PV systems (top) and name of respective system (bottom) in the realistic scenario in year 2010. Regions of high GHI, low diffuse irradiation and not too far away from equator are best suited for 1-axis horizontal north-south systems, more than 30°N/S its optimally tilted tracking version is a better solution, whereas regions of large variation of solar zenith angle are best conditions for 1-axis horizontal east-west systems and for all other regions fixed optimally tilted systems are the most attractive PV system in terms of LCOE.

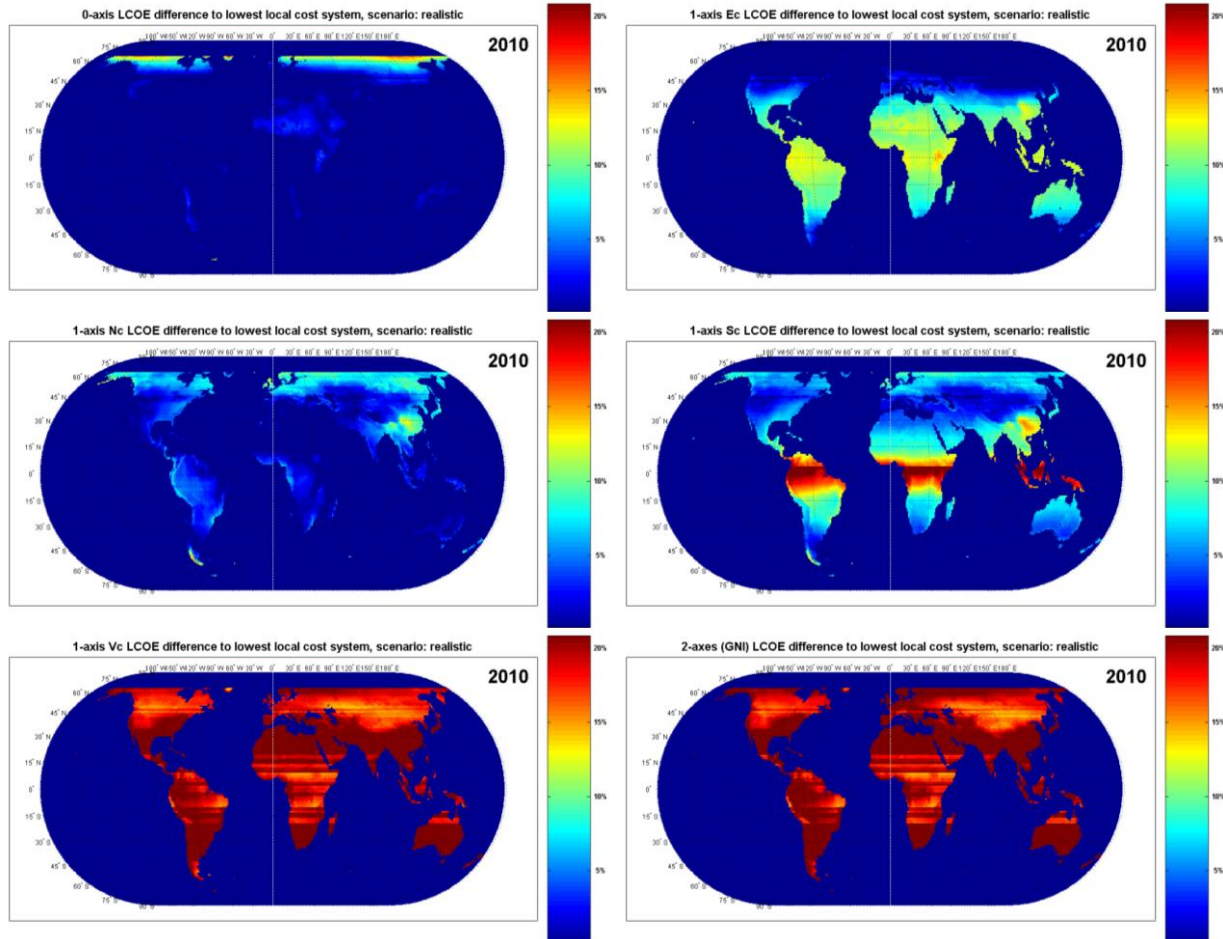


Figure 3.2-15: Relative difference of each PV systems to least LCOE of all PV systems in the realistic scenario in year 2010. PV systems are: fixed optimally tilted (top, left), 1-axis horizontal east-west (top, right), 1-axis horizontal north-south (centre, left), 1-axis optimally tilted north-south (centre, right), 1-axis vertical (bottom, left) and 2-axes non-concentrating (bottom, right) continuous tracking, respectively.

Least cost of all systems per coordinate shows regions best suited for best adapted PV systems for respective conditions (Fig. 3.2-14), i.e. high GHI, low diffuse irradiation and within 30°N/S is a good match for 1-axis horizontal north-south tracking system, whereas in the very north and south is a good solution the 1-axis horizontal east-west tracking system and for all other coordinates the fixed optimally tilted system. Relative differences of LCOE of each PV system to least cost of all systems (Fig. 3.2-15) confirms the results for most attractive systems, but show also the relative advantages and disadvantages of all systems either in general or for specific regions. For example 1-axis vertical optimally tilted and 2-axes non-concentrating continuous tracking PV systems are higher in LCOE for all coordinates and for most regions of more than 10%. Fixed optimally tilted PV system is very competitive, as it is either the least cost system or only a few percent higher in LCOE. Other 1-axis tracking systems have specific advantages for some regions in the world.

Cost dynamics in the 2010s for fixed optimally tilted PV systems (Fig. 3.2-16) and for least cost of all PV systems (Fig. 3.2-17) both in the realistic scenario show a steady cost reduction over the entire decade to 6 – 12 €/ct/kWh in the year 2020. LCOE dynamics for cost of all PV systems (Fig. 3.2-18) in the aggressive scenario result in 4 – 8 €/ct/kWh in 2020.

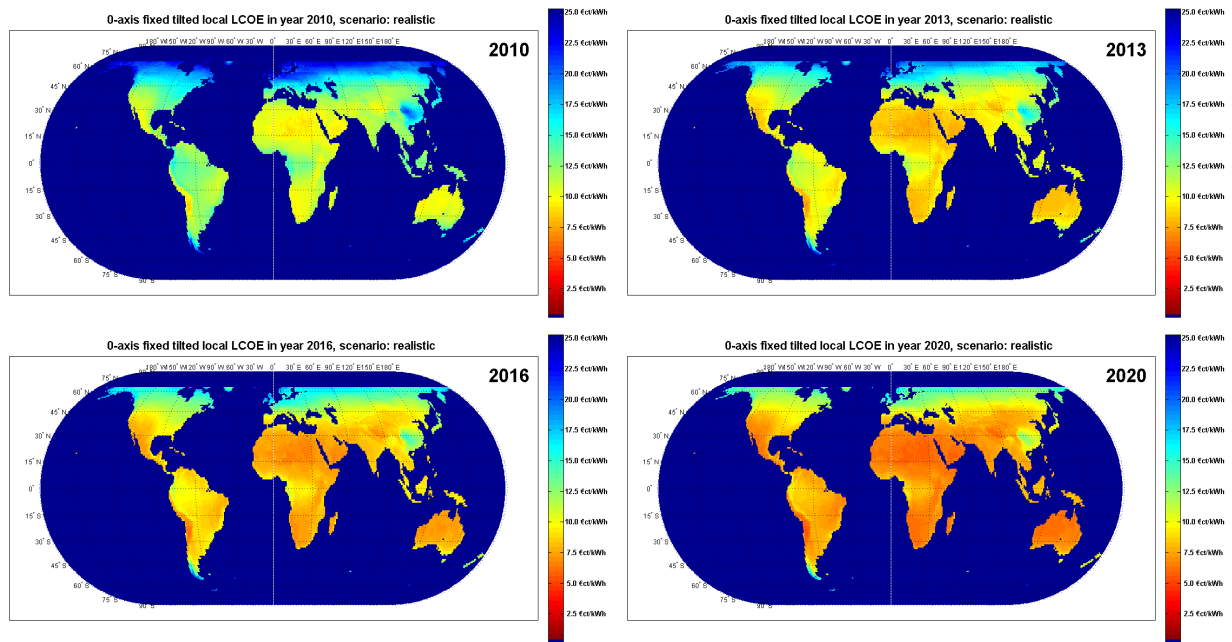


Figure 3.2-16: Least cost of fixed optimally tilted PV system in the 2010s for the realistic scenario. The realistic scenario is defined in Table 3.2-1.

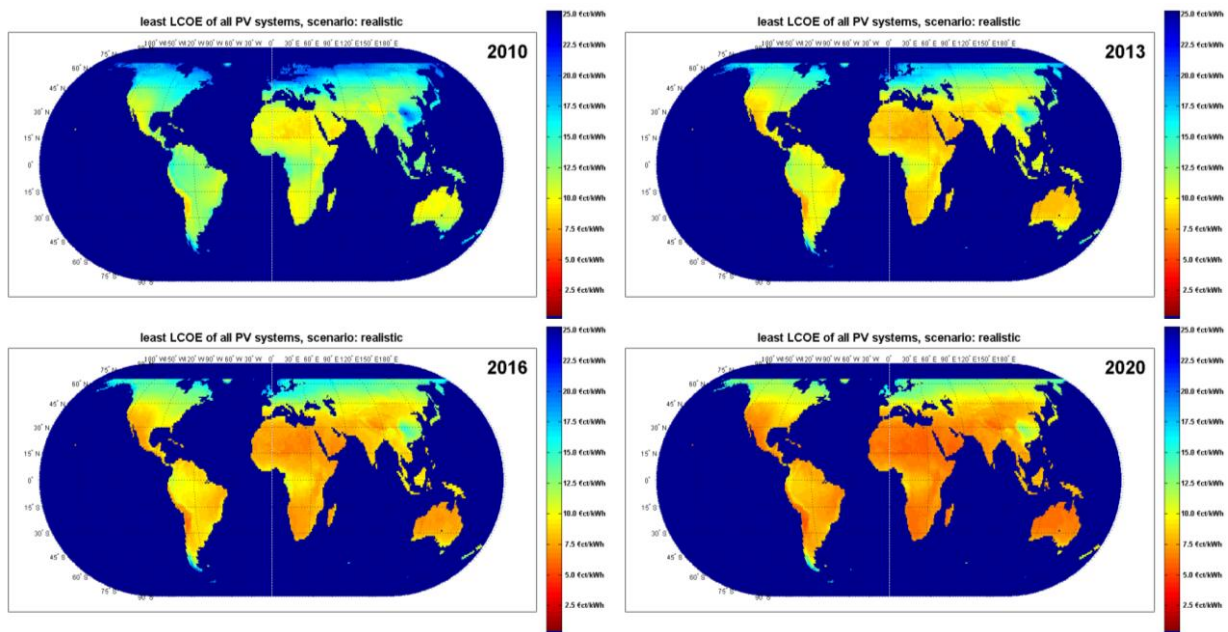


Figure 3.2-17: Least cost of all PV systems in the 2010s for the realistic scenario. The realistic scenario is defined in Table 3.2-1.

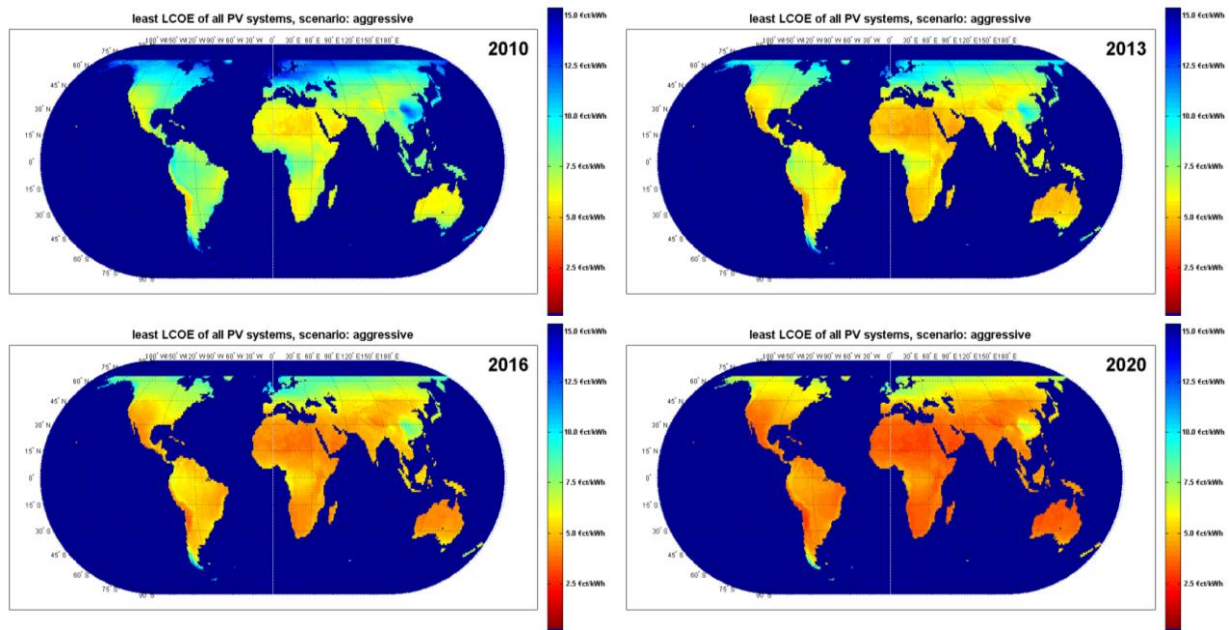


Figure 3.2-18: Least cost of all PV systems in the 2010s for the aggressive scenario. The aggressive scenario is defined in Table 3.2-1.

Both major scenarios, i.e. the realistic and the aggressive one, show a steady cost reduction for PV systems in the 2010s to a level of 4 – 5 €/kWh for sites of very good solar conditions and to a level of 8 – 12 €/kWh for moderate sites depending on PV system and cost scenario. In any case solar PV will become a very cost competitive power technology. Cost reductions will continue in the 2020s and consequently PV might become the most competitive power technology in the world for nearly all regions in the world. The LCOE difference of 10 €/kWh and a factor of two in the year 2010 in the realistic scenario might be significantly reduced in absolute numbers to a difference of 4 €/kWh in the year 2020 in the aggressive scenario, however the factor of two will remain, as a simple consequence of different solar resource levels (Fig. 2.2-3).

Aggregated LCOE dynamics show impressive improvements for the further market diffusion of PV. However, it is not obvious how the dynamics will be for the different PV systems. This will be emphasized in the following section.

3.2.4 Diffusion of Systems

In the last section economic results for the considered PV system technologies are shown on basis of the scenarios described in Table 3.2-1. Economic results indicate best adapted system technology in dependence of module efficiency, site location, solar resource availability, relative and absolute cost structure and therefore also in time. These dynamics are analysed and visualized more deeply in this section.

System technology of least LCOE in year 2010 for the realistic scenario assumptions in dependence of module efficiency is depicted in Figure 3.2-19.

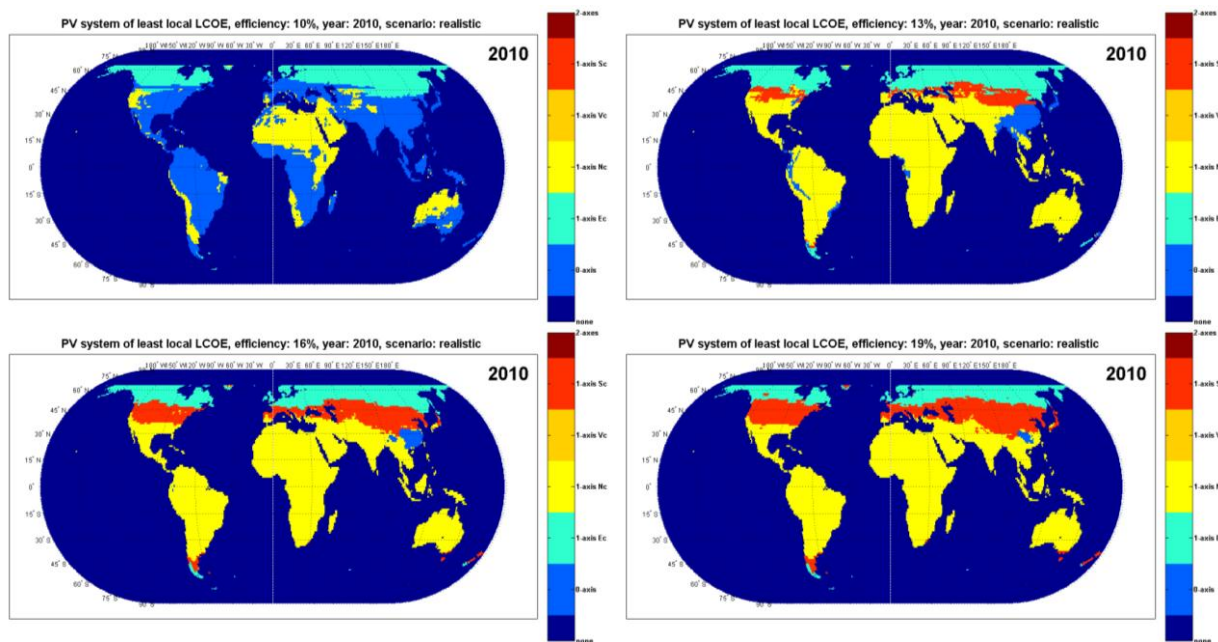


Figure 3.2-19: Least cost PV system technology in the year 2010 for the realistic scenario in dependence on module efficiency. The realistic scenario is defined in Table 3.2-1.

Results for least cost PV system technology show a significant dependence on module efficiency, as for 10% efficient modules the very sunny regions are dominated by 1-axis horizontal north-south systems, in moderate regions and regions of high diffusive horizontal irradiation (Fig. 2.1-3) is a fixed optimally tilted system best adapted and for latitudes of more than 45°N/S the 1-axis horizontal east-west system is the least cost solution. For modules of 13% efficiency and more, the results are in a equilibrium of nearly no fixed optimally tilted systems, 1-axis horizontal north-south systems for quasi all regions within latitudes of 40° N/S, 1-axis optimally tilted north-south systems within latitudes of roughly 40° - 50° N/S and 1-axis horizontal east-west systems for latitudes more than 50° N/S. These results are not absolutely strict, as local variations of solar resource conditions have an impact on the economics of respective system technologies, e.g. in Central Asia and the South-East of China.

Sensitivity of PV system technology to different scenario settings can be found by comparing results for the realistic (Fig. 3.2-19) to the aggressive scenario (Fig. 3.2-20). The scenarios defined in Table 3.2-1 differ in several assumptions, but mainly in module Capex, tracking system Capex cost of capital, Opex and industry growth rates. In the aggressive scenario there are nearly no least cost sites for fixed optimally tilted systems, independent on module efficiency. For modules of about 13% efficiency the share of least cost sites of 1-axis optimally tilted north-south is much lower than in the realistic scenario, however for 16% and 19% efficient modules the distribution of least cost systems in the world is more or less identical to the realistic case.

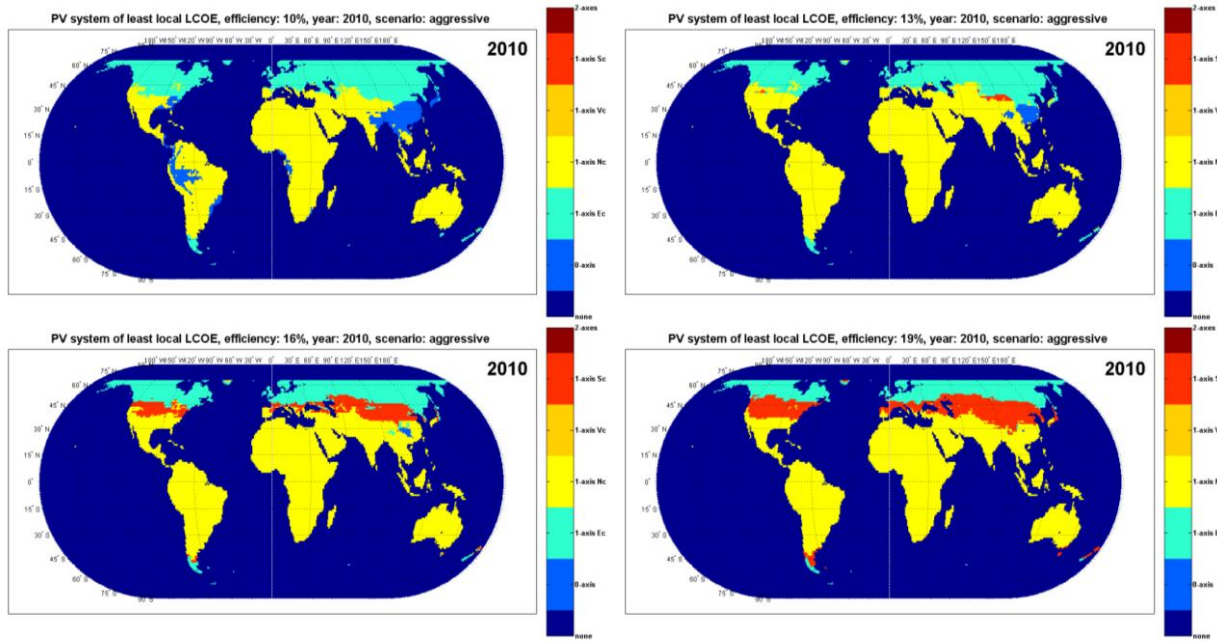
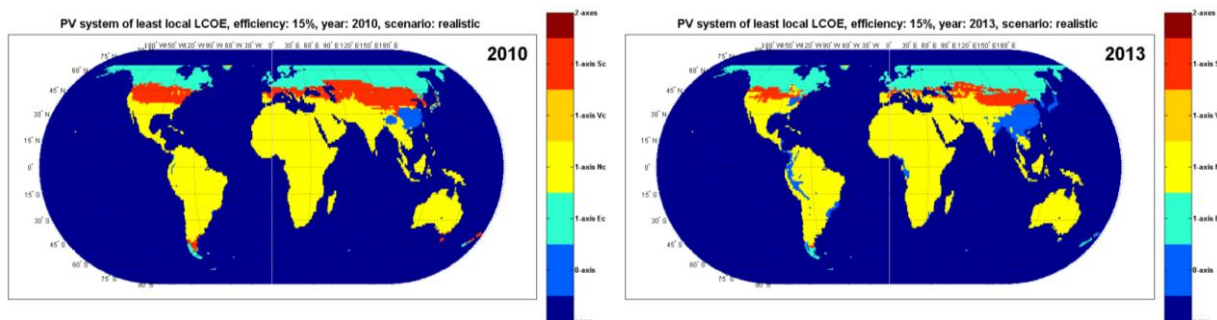


Figure 3.2-20: Least cost PV system technology in the year 2010 for the aggressive scenario in dependence on module efficiency. Aggressive scenario is defined in Table 3.2-1.

Dynamics in least cost system might be observed over the years 2010 to 2020, due to different learning rate assumptions for modules and inverters versus other BOS components, like mounting structure and tracking systems, in the scenario assumptions defined in Table 3.2-1. 15% efficient modules are taken as an example for analysing the expectation of dynamics in time (Fig. 3.2-21 and 3.2-22), as this efficiency class is very likely to be the industry standard in 2 to 4 years. Starting conditions in the year 2010 are those depicted in Figures 3.2-19 and 3.2-20. By mid 2010s all least cost sites for 1-axis optimally tilted north-south systems disappear in competition to 1-axis horizontal north-south and 1-axis horizontal east-west and fixed optimally tilted systems, dependent on absolute solar resource quality and diffuse horizontal irradiation. In fact 1-axis optimally tilted north-south system combines characteristics of these three systems, therefore the simulated transition of least cost sites is a direct consequence of relative cost structure and local solar resource conditions. At the end of the 2010s the dynamic is increasing, as more and more regions tend to the fixed optimally tilted system as least cost option. This dynamic is triggered by site conditions of higher ratio of diffuse horizontal irradiation, slightly lower global horizontal irradiation (Fig. 2.1-1 to 2.1-3) and a trend of increasing ratio of BOS Capex to total PV power plant Capex, which is a consequence of BOS learning rates lower than those of modules (Table 3.2-1). The differences of the realistic and aggressive scenario assumptions are mentioned in the previous sections.



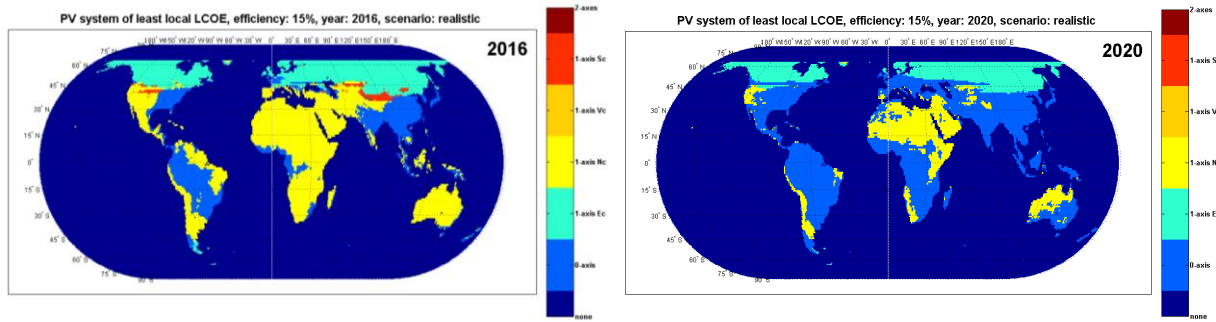


Figure 3.2-21: Least cost PV system technology for 15% efficient modules for the realistic scenario in the 2010s. The realistic scenario is defined in Table 3.2-1.

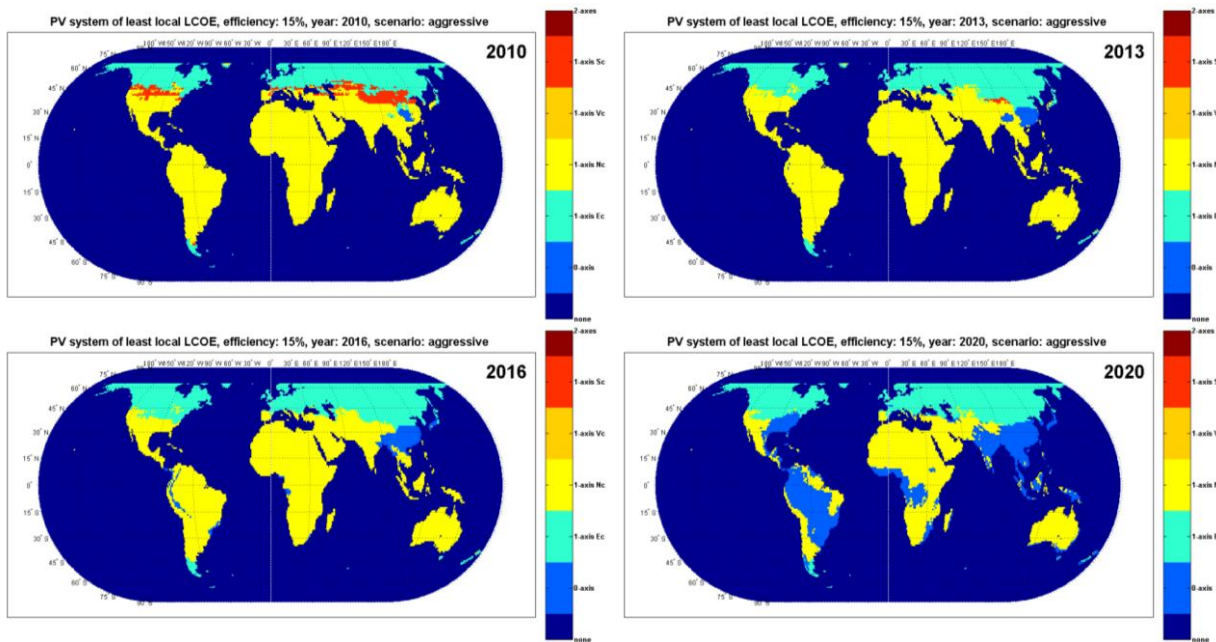


Figure 3.2-22: Least cost PV system technology for 15% efficient modules for the aggressive scenario in the 2010s. The aggressive scenario is defined in Table 3.2-1.

Last consideration in this section is the dynamic of least cost systems by the end of the decade under the applied scenario setting. The dependence on module efficiency is shown for the realistic (Fig. 3.2-23) and aggressive scenario (Fig. 3.2-24). In comparison to the situation for the year 2010 (Fig. 3.2-19 and 3.2-20) a significant shift can be expected in terms of the required module efficiency level needed for advantageous tracking LCOE versus the reference case of fixed optimally tilted systems. In both scenarios the results for 16% and 20% efficient modules in the year 2020 are very similar to those of 10% and 13% efficiency in the year 2010. This result is a consequence of assumed lower learning rates for BOS components than for those of modules. In both scenarios the least cost system for 10% modules is fixed optimally tilted except sites at high (aggressive scenario) and very high (realistic scenario) latitudes. Modules of 13% efficiency are again very similar in both scenarios, but in the aggressive one the regions in the world of both very high global but low diffuse horizontal irradiation, are in favour of least cost of the 1-axis horizontal north-south system. In both scenarios modules of 16% to 20% lead to least cost tracking systems in regions of high global horizontal irradiation, in particular for low diffuse irradiation in those regions.

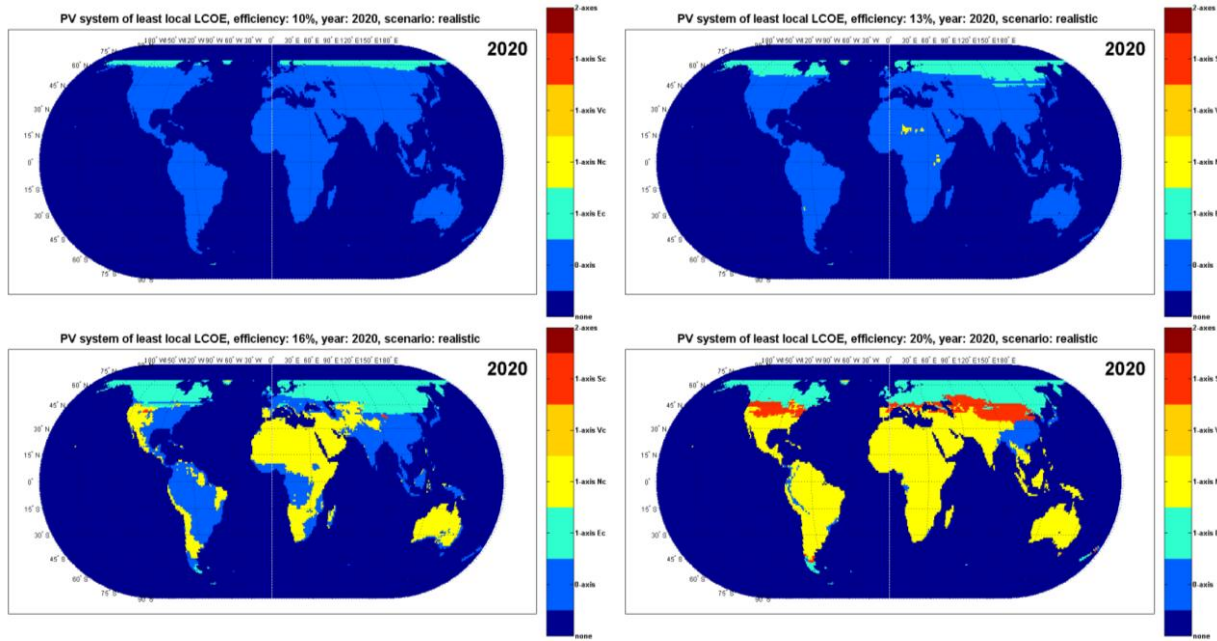


Figure 3.2-23: Least cost PV system technology in the year 2020 for the realistic scenario in dependence on module efficiency. The realistic scenario is defined in Table 3.2-1.

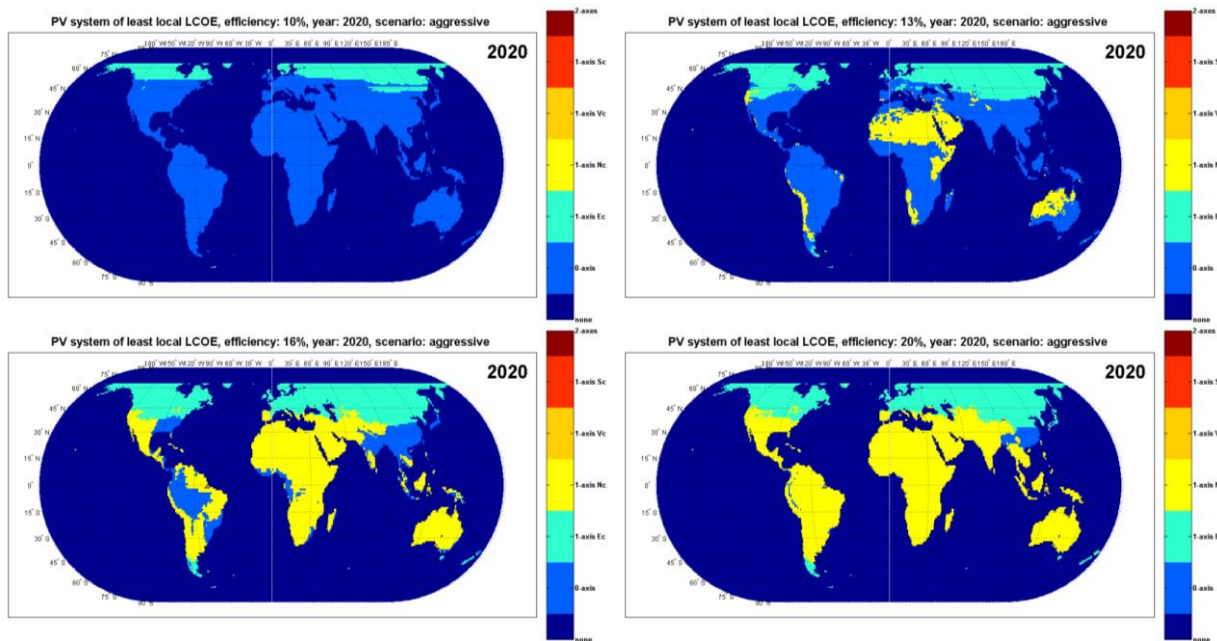


Figure 3.2-24: Least cost PV system technology in the year 2020 for the aggressive scenario in dependence on module efficiency. The aggressive scenario is defined in Table 3.2-1.

Results in this section clearly show there is no simple answer which PV system technology is the best one. However, no single parameter combination within the scenario assumptions for the years 2010 to 2020 leads to least cost for 2-axes non-concentrating and 1-axis vertical optimally tilted tracking systems. Interestingly, Götzerger and Stahl came to a very similar conclusion for 2-axes non-concentrating tracking versus fixed optimally tilted systems in 1985, i.e. this fundamental insight seems to be very stable over time.⁵⁷⁴ The findings for 2-axes and 1-axis vertical systems in this section might be a consequence of relatively high

⁵⁷⁴ Götzerger A. and Stahl W., Global Estimation of Available Solar Radiation and Cost of Energy for Tracking and Non-tracking PV-Systems, 1985

Capex for respective tracking systems, higher Opex and higher ground cover ratio related Capex due to two directional shading (section 3.2.2). Nevertheless, the results observed in the years to come might also deviate from analyses in this section due to uncertainties for tracking Capex, Opex and relative learning rates. Available data for a precise parameter setting are very limited, hence uncertainties are higher than desired.

Summarizing the results of this section, fixed optimally tilted, 1-axis horizontal north-south and 1-axis horizontal east-west are the most favoured least cost systems for all module efficiency classes in the 2010s. For sunny and very sunny sites within 40° N/S 1-axis horizontal north-south tracking is the most suited system for most parameter settings. In case of relative high area related BOS Capex versus module Capex sunny regions of a higher diffuse irradiation fraction tend to switch to fixed optimally tilted systems. Also in dependence of the aforementioned ratio, 1-axis optimally tilted north-south systems might be an excellent solution in regions of latitudes of about 40° - 50° N/S. In the very north and south 1-axis horizontal east-west tracking systems are a good solution, as this system is best adapted to high seasonal variations in the zenith angle. However, relative and absolute difference in LCOE is rather low (section 3.2.3) and often within only a few percent. Therefore LCOE should not be the only criteria, as the amount of full load hours deviate by about 30% between fixed optimally tilted and 1-axis horizontal north-south tracking systems for most regions of very good solar conditions in the world (section 2.2.5). PV power plant operators interested in low LCOE and highest appropriate full load hours might opt for 1-axis horizontal north-south systems in all regions in the world of at least good solar conditions.

3.3 On-grid End-user Systems: Grid-Parity

This section presents a detailed analysis of grid-parity dynamics based on the levelized cost of electricity (LCOE) concept (section 3.2.1) coupled with the experience curve approach (section 3.1.2) including a broad discussion of the key driving forces of the model (section 3.3.2). Results of the analysis are shown for Europe, the Americas, Africa and the Asia-Pacific region (section 3.3.3).

Some of this results for Europe had been a cornerstone that led to the 12% supply target of European electricity demand by 2020 of the European Photovoltaic Industry Association (EPIA) as announced on the 23rd EU PVSEC in Valencia in 2008.^{575,576} Results for the US had been published first in the US⁵⁷⁷ and together with all European Union member states on the 24th EU PVSEC in Hamburg in 2009.⁵⁷⁸ Results for Japan, India, Middle East and North Africa and Asia had been presented at respective regional conferences.^{579,580,581,582} In total results are obtained for 151 countries plus some regional aggregations of the US, India and China. It is now covered 98.0% of world population and 99.7% of global gross domestic product.

⁵⁷⁵ Milner A., The Solar Industry within the SET-Plan, 2008

⁵⁷⁶ EPIA, PV industry substantially revises its target to supply 12% of European electricity demand by 2020, 2008

⁵⁷⁷ Schubert B., Q-Cells presentation, 2008

⁵⁷⁸ Breyer Ch. et al., Grid-Parity Analysis for EU and US regions and market segments, 2009b

⁵⁷⁹ Klärner H. and Schulz M., SET for 2020, 2009

⁵⁸⁰ Kar M., Grid Parity of PV Power in India, 2010

⁵⁸¹ Breyer Ch., Value of Solar PV Electricity in MENA Region, 2010b

⁵⁸² Beckel O., Grid Parity in Asian Photovoltaic Markets, 2010

3.3.1 Grid-Parity Concept

Installations of PV systems have shown high growth rates around the world (section 3.1.1). As a consequence of this growth PV electricity generation cost continuously decreases. The contrary trend is shown by electricity prices for end-users. The intersection in time of these two trends is defined as PV grid-parity and indicates cost neutral PV installations on an annual basis. By applying PV and electricity cost dynamics one can perform a detailed analysis of global grid-parity event dynamics for nearly all countries in the world and respective residential and industrial market segments in the years to come. Key motivation of this analysis is to learn more about the geographic and temporal distribution in the occurrence of grid-parity in the world.

The grid-parity concept is a helpful tool for analysing the third PV market diffusion phase (section 3.1.1). The milestone of grid-parity enables sustainable PV markets as market introduction programmes like feed-in tariffs can be begun to be phased-out in a controlled manner.

3.3.2 Grid-Parity Model and its Assumptions

For analysing the third PV market diffusion phase a dynamic grid-parity model has been designed.⁵⁸³ The outcome is a time and geography dependent investigation method for sustainable market potentials of PV for the considered countries. Each country is represented by the two major market segments of residential and industrial customers (users). The dynamic grid-parity model enables estimates where and when sustainable market segments are created by implementing PV electricity generation. PV generation costs are calculated by the LCOE method⁵⁸⁴ (section 3.2.1) and compared to the electricity prices of market segments in respective countries. Scenario assessment is applied for the years 2010 to 2020. It has to be mentioned, that no subsidies for PV are taken into account, i.e. real PV costs are regarded. It was neither possible nor intended to exclude various subsidies in the global electricity markets. These direct financial subsidies for fossil fuels are estimated to about 560 bnUSD in 2008, most of it in non-OECD countries.⁵⁸⁵

The input parameters for LCOE model are mainly dependent on circumstances regarding geography, time, energy and financial markets. Major assumptions and respective key driving forces of the dynamic grid-parity model are the experience curve approach, PV industry growth, PV system cost and electricity prices. Capital expenditures for PV systems are derived from the empirical experience curve for PV (section 3.1.2), which depends on the growth rate of global PV markets (section 3.1.1) and hence, on time and the general energy markets. Net PV generated energy is a function of local solar irradiance (sub-chapter 2.2). For analysing the grid-parity dynamics in time (section 3.3.3) the critical input parameters are the learning rate (progress ratio) of PV, the growth rate of the global PV industry, both key drivers of the experience curve, and the electricity price trends.

The empirical law of experience curves (section 3.1.2) drives the levelized cost of electricity of PV systems (section 3.2.1) which has to compete against local electricity prices in

⁵⁸³ Gerlach A., Wirtschaftlichkeit von Photovoltaik in nicht subventionierten Märkten, 2009

⁵⁸⁴ Short W. et al., A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, 1995

⁵⁸⁵ IEA, World Energy Outlook 2010, pp. 569-591

respective markets. Electricity prices differ strongly in different markets and even for different players in the same market segment as a consequence of market forces. Nevertheless, average electricity prices can be derived for market segments. In general, electricity prices are a function of fuel cost, capital cost, labour cost, grid cost, energy taxes, energy subsidies, greenhouse gas (GHG) emission cost and profit margins of generation companies and transmission and distribution service operators.

The model is based on the effective average PV system price in Germany in 2010 of 2.70 €/Wp and 2.40 €/Wp for residential roof-top systems and industrial large-scale roof and accordingly PV power plants, respectively. These market segments take over a global price setting function due to the sheer size of the German market.⁵⁸⁶ System price assumptions are based on consensus view of several financial PV industry analysts all published in 2010.^{587,588,589,590,591,592,593} The empirical observed experience curve (section 3.1.2) correctly describes the cost reduction of PV systems for the last 30 - 50 years. Over the last three decades the learning rate of PV has been on a stable 20% level. Mature industries show a flattening of experience curves, therefore the decrease of LCOE for PV was calculated by a progress ratio of 0.80 and 0.85 as well, i.e. a learning rate of 20% and 15%, respectively. The learning rate is a very sensitive parameter in the entire work, thus detailed work on historic and current PV R&D investments is considered for best possible insights on the further development of the learning rate (section 3.1.3). As a consequence, both consensus results of different studies on learning rates in PV industry led to a well accepted learning rate of 20% and research results for PV R&D investments indicate a continued learning rate of 20% in the years to come.

Cost reductions are indirectly driven by PV industry growth. Growth rates of PV seem not to be limited for at least the next one to two decades (section 3.1.1 and 6.6.2). The assumption in this section of an average annual 30% growth rate of PV industry in the scenario period of the years 2010 to 2020 is considered to be conservative. Annual growth trend for the last 15 years has been 45%. Nevertheless, consensus of scientific researchers and financial analysts is a growth rate of about 30%.^{594,595,596,597,598,599,600,601} However, it has been very common to underestimate both near and long-term growth rates of PV⁶⁰², as it could be in this section.

Further assumptions for important PV related parameters are taken into account. PV system performance ratio is assumed to constantly increase for residential and industrial systems

⁵⁸⁶ EPIA, Global Market Outlook for Photovoltaics until 2014, 2010, pp. 5-6

⁵⁸⁷ Aycicek E. et al., Sector Analysis Photovoltaics 2010, 2010

⁵⁸⁸ Bumm P., Solar Power, 2010

⁵⁸⁹ O'Rourke S. et al., Solar Photovoltaic Industry 2010 global outlook Déjà vu?, 2010

⁵⁹⁰ Photon, Finanzierung: Entwicklung der Anlagenpreise, 2010

⁵⁹¹ Shah V. et al., Solar-Investor Guide 2010, 2010

⁵⁹² Gupta S. et al., Global Solar: Sovereign Debt Concerns ... Not a Solar Eclipse, 2010

⁵⁹³ Reuter M. and Gruse A.K., European PV Module Price Monitor: First Quarter Results 2010, 2010

⁵⁹⁴ EPIA, Global Market Outlook for Photovoltaics until 2014, 2010

⁵⁹⁵ IEA Technology Roadmap: Solar photovoltaic Energy, 2010

⁵⁹⁶ Bumm P., Solar Power, 2010

⁵⁹⁷ O'Rourke S. et al., Solar Photovoltaic Industry 2010 global outlook Déjà vu?, 2010

⁵⁹⁸ Shah V. et al., Solar-Investor Guide 2010, 2010

⁵⁹⁹ Krewitt W. et al., Globale Energieszenarien - Bedeutung der Erneuerbaren Energien und der Energieeffizienz, 2008

⁶⁰⁰ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

⁶⁰¹ Mints P., First Markets and Applications for OPV, 2009

⁶⁰² Gredler C., Das Wachstumspotenzial der Photovoltaik und der Windkraft – divergierende Wahrnehmungen zentraler Akteure, 2008

from 75% and 78% in 2010 to 80% and 82% in 2015, respectively, and remain constant afterwards. Weighted average cost of capital is set to 6.4%, as in several markets PV investments start at about 5% average cost of capital. Annual PV operation and maintenance expenditures (Opex) are estimated to be 1.5% of initial PV system investments (Capex). PV system lifetime is assumed to steadily increase from 25 years in 2010 to 30 years in 2015 and stay constant afterwards. There are indications that PV module lifetime is longer than the assumed 25 years ^{603,604} (section 3.1.6.2) which will further improve LCOE. Better performance and longer lifetimes of key components will improve the performance ratio and lower operation and maintenance, hence improve LCOE. Solar irradiation on modules at fixed optimally tilted angle for each location is averaged by population distribution for respective countries and aggregated regions (sections 2.2.3 and 2.3.1).

Concerning electricity prices, initial market sizes for the year 2010 and average annual market growth rates of the market segments in the different regions are taken from various sources ^{605,606,607,608,609,610,611} depicted in Figure 3.3-1. The prices are assumed to increase in the same manner as in the last years by 5%, 3% and 1% per year for electricity price levels of 0 – 0.15 €/kWh, 0.15 – 0.30 €/kWh and more than 0.30 €/kWh, respectively. The scenario setting for future electricity price escalation rates is very likely to be conservative, as illustrated in the following.

Real electricity price escalation for residential market segments has been on average 4.3% p.a. in the years 2000 to 2007 in the EU ⁶¹² and on average 3.6% p.a. in the years 2000 to 2006 in the US ⁶¹³. Cost trends in other regions in the world are dependent on local electricity subsidies or taxes, vulnerability to oil and natural gas price volatility, increase in environmental standards and stranded power plant investments.

In liberalized electricity markets, like in the EU and the US, electricity prices are coupled to respective electricity wholesale prices. These wholesale prices are typically a function of available supply and demand and are dependent on the last class of power plants which is needed to cover supply (merit-order). Therefore, the cost structure of natural gas power plants strongly influences wholesale prices. The cost structure of gas power plants itself is dominated by gas fuel cost. It has been observed for the last three decades that gas prices are correlated to crude oil prices (sections 1.3.2 and 6.1.4), thus in the end the global crude oil price determines end-users electricity prices in liberalized electricity markets. Probability is high that historical peak-oil occurs right now which is and will be accompanied by high crude oil prices and consequently high electricity prices. Regulated markets in the world also face increasing electricity cost due to rising fuel prices.

⁶⁰³ Grunow P. and Lehmann S., General assessment of the reliability of crystalline silicon photovoltaic modules, 2009

⁶⁰⁴ Schott Solar, Power ohne Ende: Nach 26 Jahren noch über 90% Leistung, 2010

⁶⁰⁵ EC, Eurostat, 2010

⁶⁰⁶ EIA, Electricity U.S. Data, 2010

⁶⁰⁷ EIA, International Electricity Prices and Fuel Costs, 2010

⁶⁰⁸ MED-ENEC, Electricity Price Data, 2010

⁶⁰⁹ UPDEA, Comparative study of electricity tariffs used in Africa, 2009

⁶¹⁰ CERC, Electricity Price Data, 2010

⁶¹¹ Q-Cells Research, Electricity Price Data, 2010

⁶¹² EC, Eurostat, 2010

⁶¹³ EIA, Electricity U.S. Data, 2010

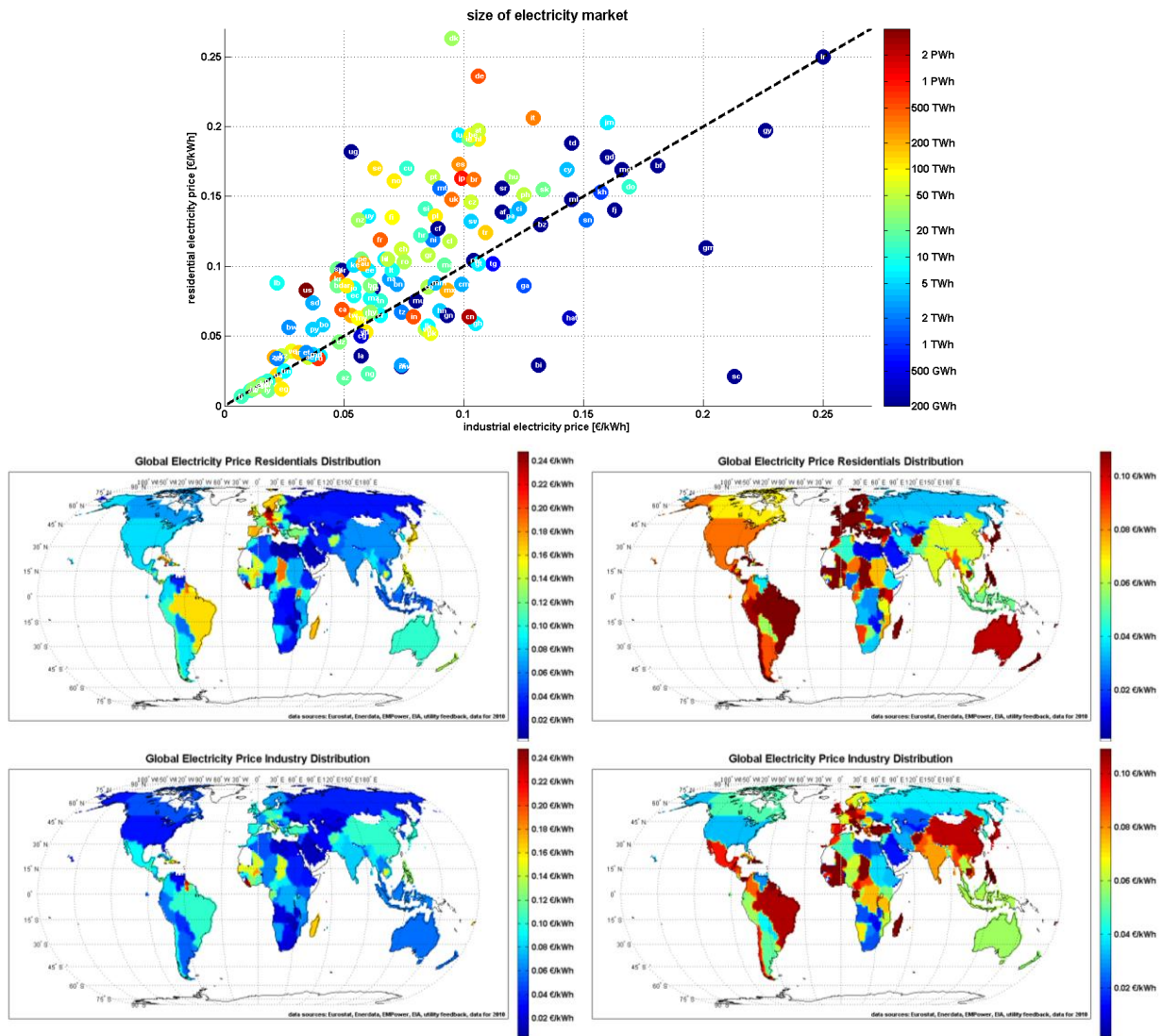


Figure 3.3-1: Global overview on residential and industrial electricity prices for the year 2010. Almost all countries are rated by their residential and industrial prices including indication for the final electricity consumption (top) and the residential and industrial prices are depicted for the full (center, left and bottom, left) and focussed on the low price regime (center, right and bottom right). The dataset comprises almost all countries in the world being named in the top by respective country codes of top level web domain (Appendix Table 4). Data are taken from various sources described above. Detailed data for depicted countries can be found elsewhere ⁶¹⁴ and is partly given in Appendix Table 3.

Social cost of climate change mitigation (sub-chapter 1.2) will have to be internalized in energy cost for having real price signals of energy use. Conservative estimates clearly show that social cost of climate change are in the order of 70 €/tCO₂. Electricity prices outside the EU reflect no CO₂ cost and respective prices in the EU started to internalize GHG emissions in the mid 2000s, but on a subcritical low level of 10 – 25 €/tCO₂. Maybe marginal cost of GHG emissions to tackle climate change will be even higher than 70 €/tCO₂. Regions dependent on fossil fuel fired power plants, in particular coal, will be affected by high escalation rates of true electricity cost. Other social cost of electricity supply are also not internalised in electricity prices, but have to be paid. Such cost are for instance: higher mortality and multiple illnesses due to heavy metal emissions of coal and oil power plants (section 3.1.7.2), military conflicts due to diminishing energy resources, reduced ecological value of destroyed ecosystems by use and exploitation of conventional energy and insecurity

⁶¹⁴ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

due to nuclear proliferation, nuclear terrorism and unclear nuclear waste disposal.

Prerequisite for grid-parity analysis is access to an electricity grid. This is not the case for about 1.4 billion people in the world (sub-chapters 1.4 and 3.4). Most of them live in rural areas in Sub-Sahara Africa (about 590 million), India (about 400 million) and other developing Asia (about 390 million). However grid-parity concept makes no sense for people without access to electricity, but most of them live in areas of excellent solar conditions, hence highly economic off-grid PV systems are a best adapted and the least cost solution for their energy needs. These PV system solutions are discussed in sub-chapter 3.4.

3.3.3 Results of Grid-Parity Analysis

Main result of dynamic grid-parity analysis is a constant market diffusion potential of PV all around the world (Fig. 3.3-2 to 3.3-9). Starting between 2010 and 2012, the share of all addressable residential electricity market segments increases towards the end of the decade to 86%, 99%, 28% and 83% in Europe, the Americas, Africa and Asia (Fig. 3.3-8), corresponding to 1,490, 2,750, 60 and 1,250 TWh, respectively. The same addressable share for all industrial electricity market segments reaches at the end of the decade to 75%, 93%, 27% and 88% in Europe, the Americas, Africa and Asia at the end of the decade (Fig. 3.3-9), corresponding to 2,100, 2,110, 90 and 1,750 TWh, respectively.

In Europe grid-parity events of large residential market segments occur first, quickly followed by Asia-Pacific and succeeded by the Americas in the mid of the decade (Fig. 3.3-8). Most segments in Africa reach grid-parity early in the 2010s, but the largest markets, South Africa and Egypt, heavily subsidize their electricity markets and therefore reach grid-parity only beyond 2020. Grid-parity events of large industrial market segments start between 2011 and 2013 and are synchronous in Europe, the Americas and Asia to a large extent of the entire decade (Fig. 3.3-9). The characteristics of the industrial segments in Africa are quite similar to the residential ones. As an important remark, it should be pointed out that a flattening of the progress ratio from 0.80 to 0.85 and significantly higher profit margins of PV industry would slow down grid-parity events by one to two years in maximum ⁶¹⁵.

Regions with high solar irradiation and high electricity prices reach grid-parity first, whereas regions with high electricity prices and moderate solar irradiance will quickly follow. LCOE of PV electricity generation in regions of high solar irradiance will decrease from 16 to 6 €/kWh in the years 2010 to 2020, respectively.

3.3.3.1 Europe

Figure 3.3-2 depicts grid-parity dynamics in the 2010s for 75 market segments in Europe. First grid-parity market segments are the residential segment in Italy and the residential and industrial segments in Cyprus. This market segments combine best combination for early grid-parity: good solar conditions and high electricity prices. Generally, islands show early grid-parity events all over the world, for which Cyprus is an excellent example. Fundamental reason for this are high electricity generation costs on islands as a consequence of usually oil (diesel) fired power plants, suffering high fuel prices.

⁶¹⁵ Breyer Ch. et al., Grid-Parity Analysis for EU and US regions and market segments, 2009b

Nevertheless, grid-parity can be achieved equally in time via very good solar conditions and moderate electricity prices or moderate solar conditions and high electricity prices. This characteristic can be observed for residential market segments in Portugal and Denmark, respectively. By the mid 2010s about 70% of residential and 30% of industrial market segments in Europe will be beyond grid-parity (Fig. 3.3-2, 3.3-8 and 3.3-9). By the end of the 2010s the great majority of all electricity market segments (80% for residential and 75% for industrial) in Europe will be beyond grid-parity. In the year 2010 total electricity consumption is about 4,400 TWh. As a consequence of PV capacity factors in Europe and grid restrictions, an overall share of PV electricity in Europe of 6% - 12% in the 2020 can be achieved.

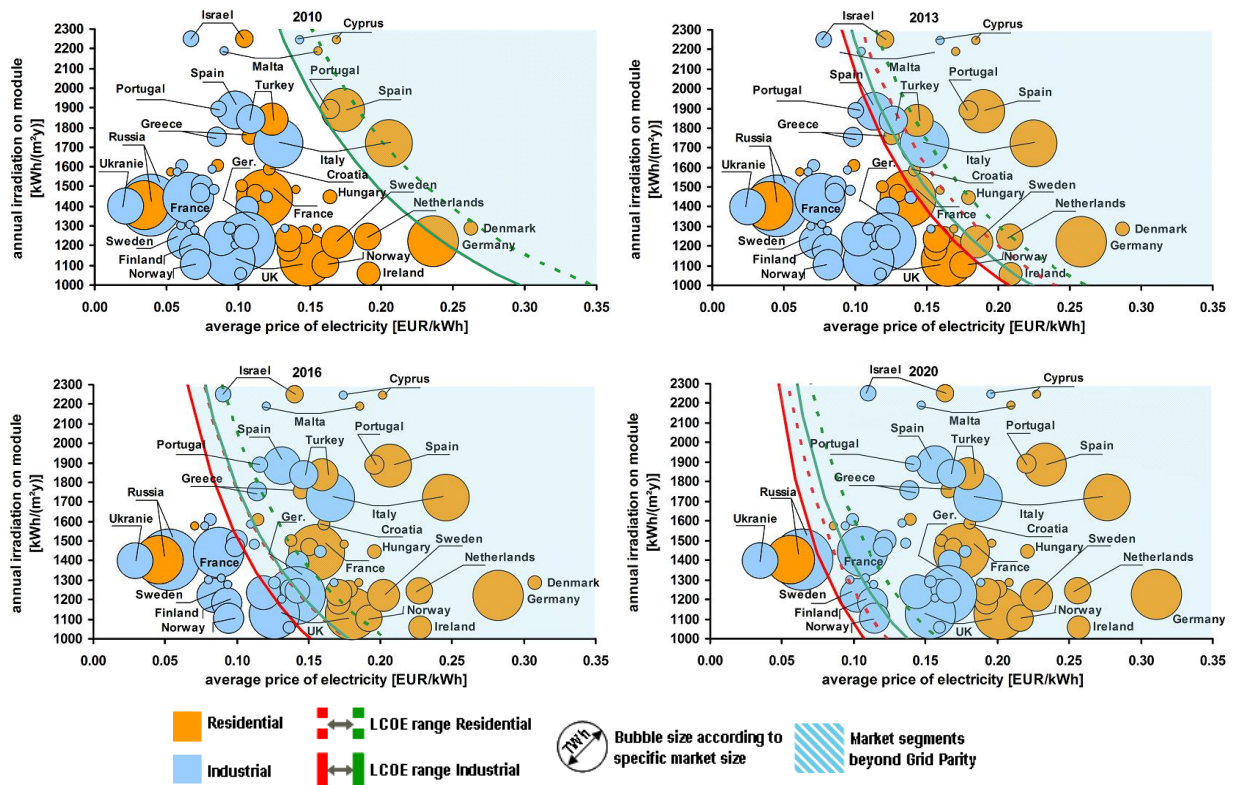


Figure 3.3-2: Grid-parity analysis for Europe in 2010 (top, left), 2013 (top, right), 2016 (bottom, left) and 2020 (bottom, right). European countries are rated by their population weighted solar irradiation (section 2.3.1 and Appendix Table 1) and electricity prices (Fig. 3.3-1) of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Detailed data for depicted countries can be found elsewhere⁶¹⁶ and is partly given in Appendix Table 3.

Clear outcome of grid-parity analysis for Europe is a fast reduction in LCOE of PV and therefore market introduction cost will decline as a consequence. Market deployment of PV is essential for a fast reduction of PV LCOE and hence large contribution of PV to European electricity supply. A significant electricity supply in the EU by PV will help to lower social cost of diminishing fossil fuel resources and GHG emission as discussed in sub-chapters 1.2 and 1.3.

⁶¹⁶ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

3.3.3.2 The Americas

Figure 3.3-3 plots grid-parity dynamics in the 2010s for 64 market segments in the Americas. The characteristics of commercial and industrial market segments can be regarded as very similar to those of Europe (section 3.3.3.1). First grid-parity market segments are in the Caribbean, consequence of excellent solar conditions and costly oil (diesel) fuel for power supply on islands. Such market segments show best combinations for early grid-parity, as good solar conditions and high electricity prices are given. Nevertheless, grid-parity can be achieved equally in time via very good solar conditions and moderate electricity prices or moderate solar conditions and high electricity prices. This characteristic can be observed for residential market segments in El Salvador and Guyana, respectively. Further examples for last finding would be California and Massachusetts for states of the US.⁶¹⁷

By the mid 2010s about 30% of residential and 22% of industrial market segments will be beyond grid-parity (Fig. 3.3-3, 3.3-8 and 3.3-9). By the end of the 2010s the great majority of all electricity market segments (99% for residential and 93% for industrial) in the Americas will be beyond grid-parity. In the year 2010 total electricity consumption is about 8,900 TWh. As a consequence of PV capacity factors in the Americas and grid restrictions, an overall share of PV electricity in the Americas of 8% - 16% in the year 2020 can be achieved.

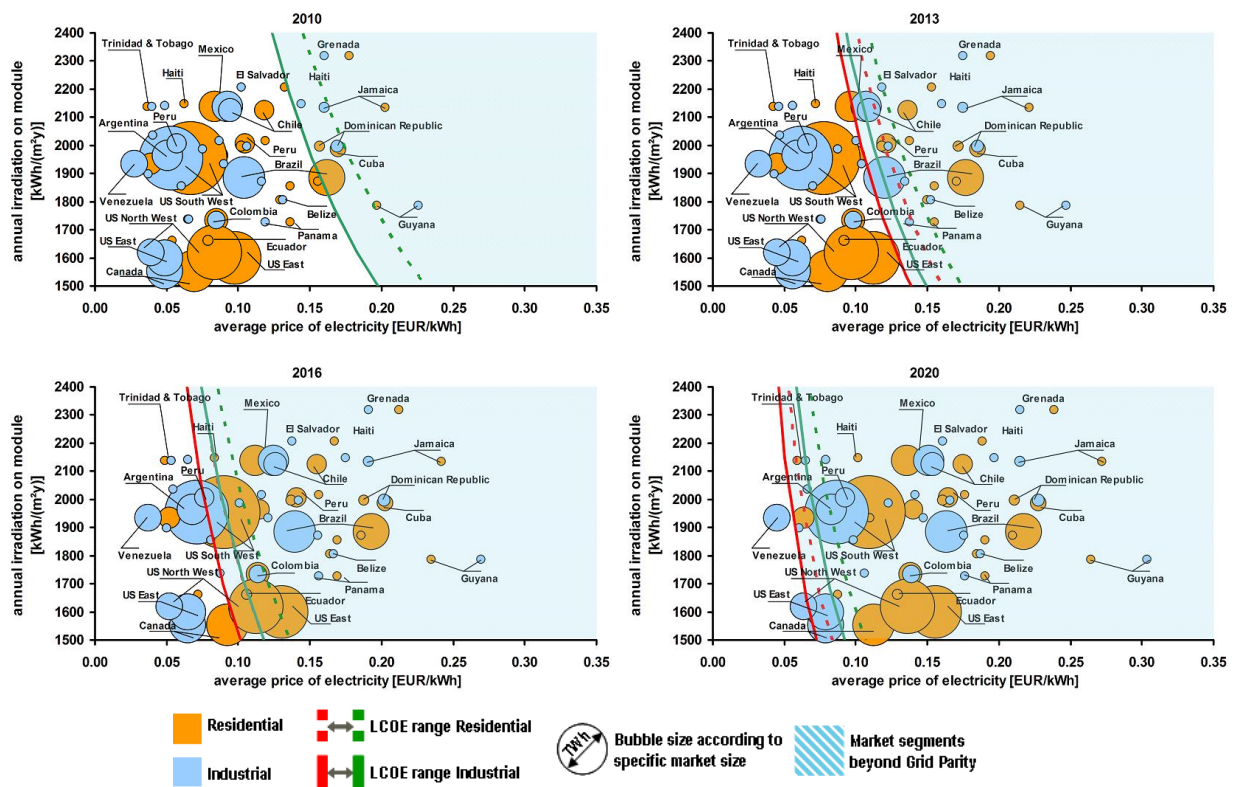


Figure 3.3-3: Grid-parity analysis for the Americas in 2010 (top, left), 2013 (top, right), 2016 (bottom, left) and 2020 (bottom, right). American countries are rated by their population weighted solar irradiation (section 2.3.1 and Appendix Table 1) and electricity prices (Fig. 3.3-1) of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and 10% margin, respectively.

⁶¹⁷ Breyer Ch. et al., Grid-Parity Analysis for EU and US regions and market segments, 2009b

conservative 15% learning rate, respectively. Detailed data for depicted countries can be found elsewhere ⁶¹⁸ and is partly given in Appendix Table 3.

An assessment of the outcome for the Americas is quite similar to that of Europe (section 3.3.3.1). PV will be also a highly important energy technology for the Americas to tackle depletion of fossil fuel resources and climate change. The faster a broad market introduction of PV is started the faster the highly positive effects of significant PV electricity supply can be realized in the Americas.

3.3.3.3 Africa

Figure 3.3-4 depicts grid-parity dynamics in the 2010s for 81 market segments in Africa. First grid-parity market segments are the residential and mostly industrial segments on the Seychelles and Madagascar and in The Gambia, Burkina Faso, Senegal, Mali and Chad. These market segments show the best combination for early grid-parity: excellent solar conditions and high electricity prices. Similar to Europe and the Americas (sections 3.3.3.1 and 3.3.3.2), islands are again among the first grid-parity regions. Several West African countries reach grid-parity early. However, grid-parity should not be overestimated for Sub-Saharan countries, as most people living there do not have access to electricity, particularly in rural areas (sub-chapters 1.4 and 3.4).

Most residential and industrial market segments reach grid-parity in this decade, except South Africa and Egypt (both account together for 64% of total African electricity generation) which heavily subsidize their energy markets with 4 and 17 bnUSD in 2009, respectively.⁶¹⁹ Countries allocate enormous public spending to energy subsidies, e.g. Iran, Saudi Arabia, Russia, India, China, Venezuela, Indonesia and United Arab Emirates, might enter a vicious circle. In a world faced with rising energy prices (sub-chapter 1.3) rapidly increasing subsidies are needed for stabilising local prices, whereas only very limited resources are left for investments for inexpensive and price stabilizing renewable energy technologies, like solar PV and wind power. Energy subsidy induced destabilized national budgets might become an enormous burden for further economic development of these countries.

By the mid 2010s about 8% of residential and 7% of industrial market segments will be beyond grid-parity (Fig. 3.3-4, 3.3-8 and 3.3-9). By the end of the 2010s the majority of all electricity market segments (which only account for 28% for residential and 27% for industrial electricity consumption) in Africa will be beyond grid-parity. In the year 2010 total electricity consumption is about 500 TWh, whereas about 320 TWh are generated in South Africa and Egypt. As a consequence of PV capacity factors in Africa and grid restrictions, an overall share of PV electricity in Africa of 16% - 32% could be achieved by the year 2020.

⁶¹⁸ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

⁶¹⁹ IEA, World Energy Outlook 2010, pp. 569-591

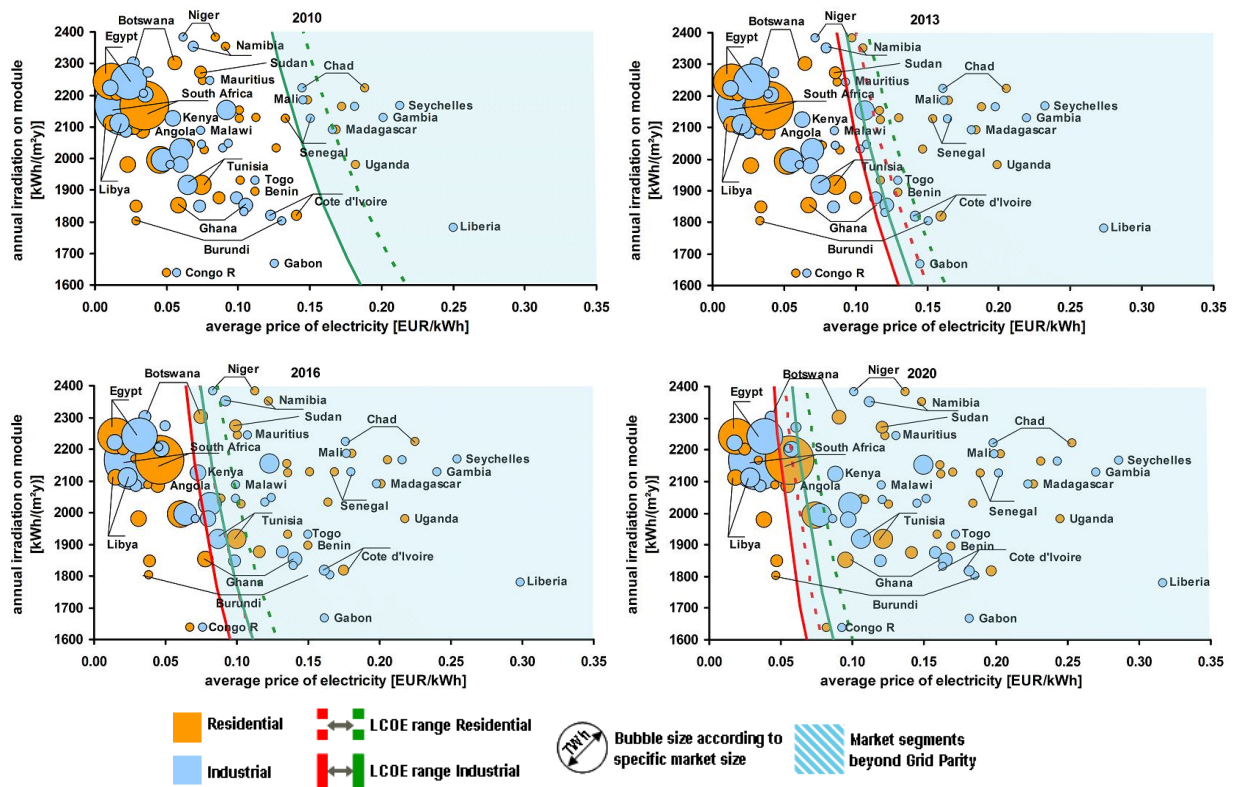


Figure 3.3-4: Grid-parity analysis for Africa in 2010 (top, left), 2013 (top, right), 2016 (bottom, left) and 2020 (bottom, right). African countries are rated by their population weighted solar irradiation (section 2.3.1 and Appendix Table 1) and electricity prices (Fig. 3.3-1) of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Detailed data for depicted countries can be found elsewhere ⁶²⁰ and is partly given in Appendix Table 3.

About 1.4 billion people do not have access to electricity of whom a large fraction live in Africa. The grid-parity concept is not applicable to those people. However, off-grid PV is a very economic option for them due to very low financial amortization periods for complete PV systems ranging between 6 - 18 months (pico systems) and 12 - 36 months (solar home systems) but strongly dependent on individual energy consumption patterns (sub-chapters 1.4 and 3.4). ⁶²¹

3.3.3.4 Asia-Pacific

Figure 3.3-5 depicts grid-parity dynamics in the 2010s for 85 market segments in Asia-Pacific. First grid-parity market segments are the residential segment in Cambodia, Fiji, Japan and the Philippines and industrial segments in Western China and the Philippines. These market segments show the best combination for early grid-parity: good solar conditions and high electricity prices. Similar to other world regions islands show early grid-parity events.

⁶²⁰ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

⁶²¹ Breyer Ch. et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 2011c

Nevertheless, grid-parity can be achieved equally in time via very good solar conditions and moderate electricity prices or moderate solar conditions and high electricity prices. This characteristic can be observed for industrial and residential market segments in Western China and Japan, respectively. By the mid 2010s about 45% of residential and 36% of industrial market segments will be beyond grid-parity (Fig. 3.3-5, 3.3-8 and 3.3-9). By the end of the 2010s the great majority of all electricity market segments (83% for residential and 88% for industrial) in Asia-Pacific will be beyond grid-parity. In the year 2010 total electricity consumption is about 8,180 TWh. As a consequence of PV capacity factors in Asia-Pacific and grid restrictions, an overall share of PV electricity in Asia-Pacific of 11% - 22% in the year 2020 can be achieved.

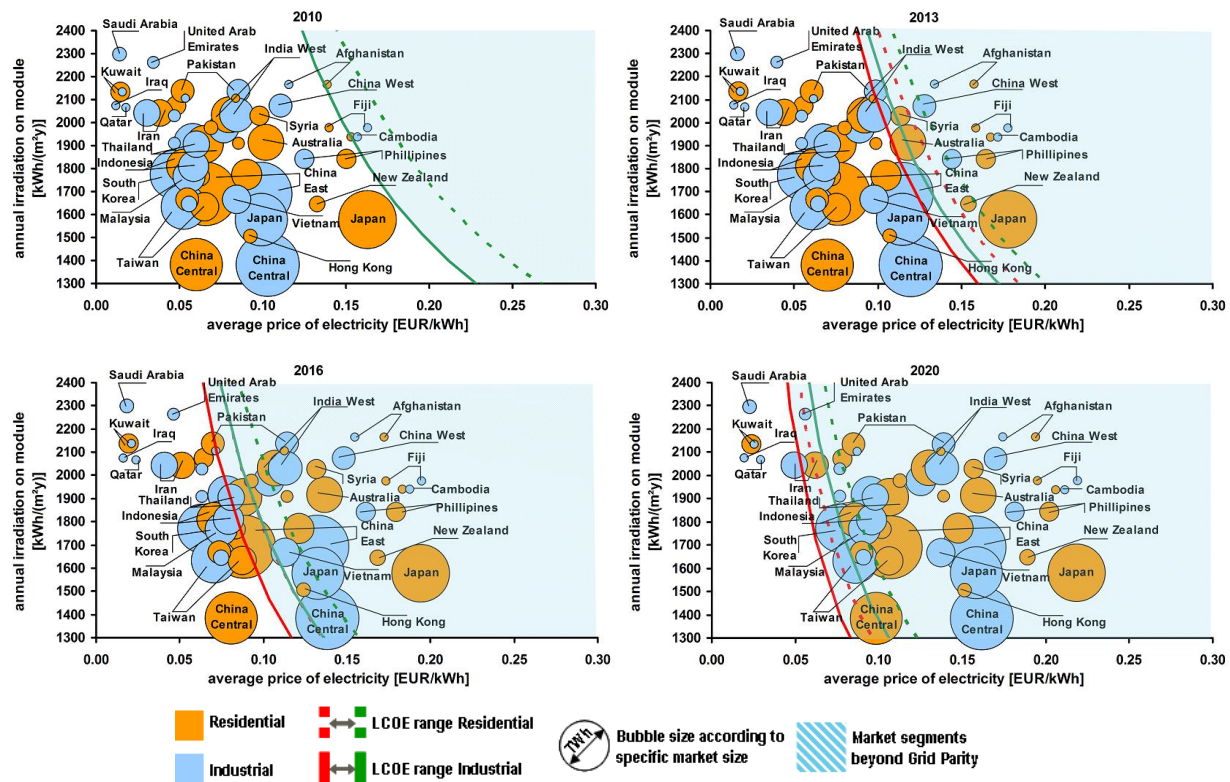


Figure 3.3-5: Grid-parity analysis for Asia-Pacific in 2010 (top, left), 2013 (top, right), 2016 (bottom, left) and 2020 (bottom, right). Asian countries are rated by their population weighted solar irradiation (section 2.3.1 and Appendix Table 1) and electricity prices (Fig. 3.3-1) of the major market segments: residential (orange) and industrial (blue). The electricity market volume is indicated by the size of the respective circle. The levelized cost of electricity (LCOE) for PV electricity generation is indicated for smaller residential systems by dashed lines and for larger commercial systems by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Detailed data for depicted countries can be found elsewhere ⁶²² and is partly given in Appendix Table 3.

Clear outcome of grid-parity analysis for Asia-Pacific is a fast reduction in LCOE of PV and therefore market introduction cost will decline as a consequence. A significant PV electricity supply in Asia-Pacific will help to lower social cost of current electricity supply, e.g. increasing health cost due to coal related emissions (section 3.1.7.2), increasing political insecurity as a consequence of diminishing fossil fuel resources (sub-chapter 1.3) or destabilizing of fragile ecosystems induced by GHG emissions (sub-chapter 1.2).

Oil producing Asian countries reach grid-parity at the end of the 2010s or even later, which is

⁶²² Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

directly related to very high energy subsidies in these countries.⁶²³ However, high social costs have to be paid, due to very high opportunity cost. For these countries, a much better economic outcome could be realised by shifting opportunity costs into renewable investments, like large-scale solar PV power plants. Currently, historic first fuel-parity events can be observed in Middle East, i.e. generating electricity by burning oil in oil power plants is higher in LCOE than the same amount of electricity in solar PV power plants (section 3.4.2 and sub-chapter 6.2).^{624,625} Consequently, enormous local economic benefits could be created by switching from one domestic energy source, fossil fuels, to another: solar photovoltaic energy.

3.3.3.5 Development over Time of Total Addressable Grid-Parity Market Segments

As shown in the last four sections a fast market diffusion of PV can be expected all around the world. These fast growing market potentials for PV due to grid-parity events are complemented by highly economic off-grid PV markets in rural areas of developing countries (section 3.4) and fuel-parity events which will create highly profitable utility-scale solar PV markets (chapter 6), in particular in sunny oil producing countries and best analysed for MENA region.^{626,627} In the year 2008 global electricity generation has been about 20,200 TWh⁶²⁸ and is expected to increase to about 27,400 TWh by the end of the 2010s. Population weighted mean irradiation on fixed optimally tilted module surface for Europe, the Americas, Africa and Asia-Pacific is 1,450, 1,890, 2,070 and 1,830, kWh/m²/y, respectively (section 2.3.1). An overview on the global grid-parity dynamics is shown in Figure 3.3-6.

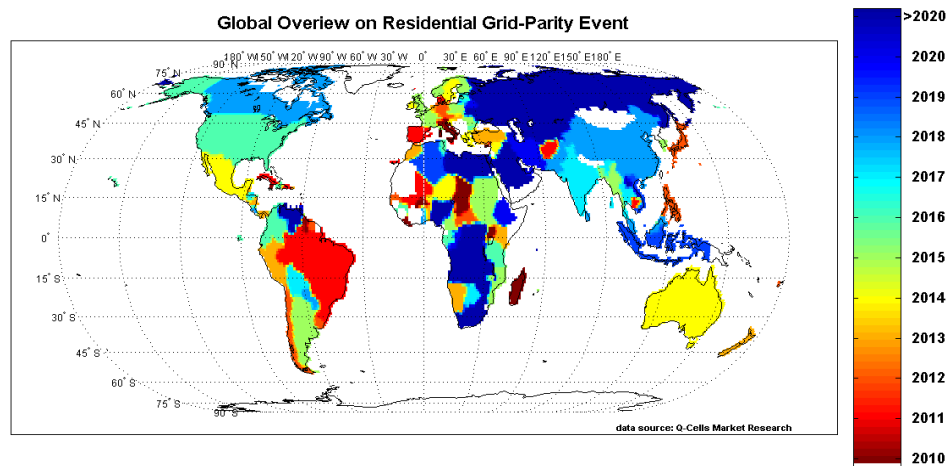


Figure 3.3-6: Global overview on residential grid-parity for the years 2010 to 2020. Data are based on results visualised in Figures 3.3-2 to 3.3-5. Detailed data for depicted countries can be found elsewhere⁶²⁹ and is partly given in Appendix Table 3.

The economics of PV are often expected to be closely related to the local solar resource.

⁶²³ IEA, World Energy Outlook 2010, pp. 569-591

⁶²⁴ Breyer Ch. et al., Value of Solar PV Electricity in MENA Region, 2010d

⁶²⁵ Breyer Ch. et al., Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, 2010e

⁶²⁶ Breyer Ch. et al., Value of Solar PV Electricity in MENA Region, 2010d

⁶²⁷ Breyer Ch. et al., Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, 2010e

⁶²⁸ IEA, World Energy Outlook 2010, p. 620

⁶²⁹ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

However, the analysis of the 150 countries clearly reveals a significant higher dependence of the grid-parity on the local electricity prices than on the local irradiation (Fig. 3.3-7). The residential electricity prices in 2010 vary between less than 0.01 and more than 0.26 €/kWh (factor of about 30), whereas the population weighted solar irradiation on fixed optimally tilted modules varies only between 1,050 and 2,380 kWh/m²/y (factor of about 2.5) in the world (Fig. 3.3-7 and Appendix Table 3).

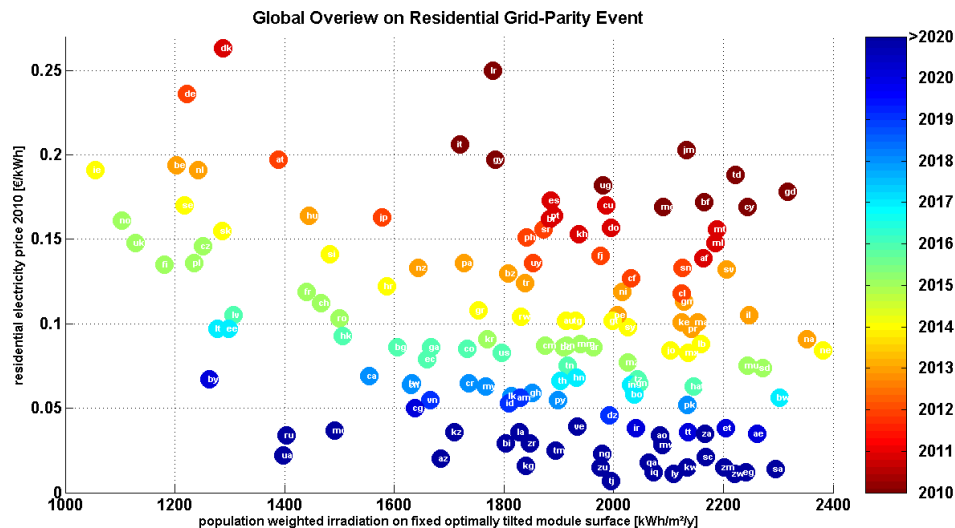


Figure 3.3-7: Overview on residential grid-parity event dynamics in dependence on local electricity prices and solar irradiation. The colour code indicates the year of grid-parity and the countries can be identified by their global code of top level web domain (Appendix Table 4). Detailed data for depicted countries can be found elsewhere ⁶³⁰ and is partly given in Appendix Table 3.

Total electricity consumption is about 4,390, 8,940, 500 and 8,180 TWh in Europe, the Americas, Africa and Asia-Pacific in the year 2010 and might grow to a global total of about 27,400 TWh in the year 2020.

The development over time for absolute and relative grid-parity market segments in the world is depicted for residential (Fig. 3.3-8) and industrial (Fig. 3.3-9) market segments.

First residential grid-parity events occur today in all regions in the world and continue throughout the entire decade (Fig. 3.3-8). Very early grid-parity showing market segments are Cyprus, Italy, the Caribbean and West Africa. At the end of this decade more than 80% of market segments in Europe, the Americas and Asia-Pacific are beyond residential grid-parity. Exception is given for Africa, due to energy subsidies in South Africa and Egypt, which represent more than 60% of electricity generation in Africa. Residential grid-parity is complemented by highly economic off-grid PV in rural regions of developing countries. This is the case for about 1.4 billion people in the world, mostly living in Africa and South Asia.

⁶³⁰ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

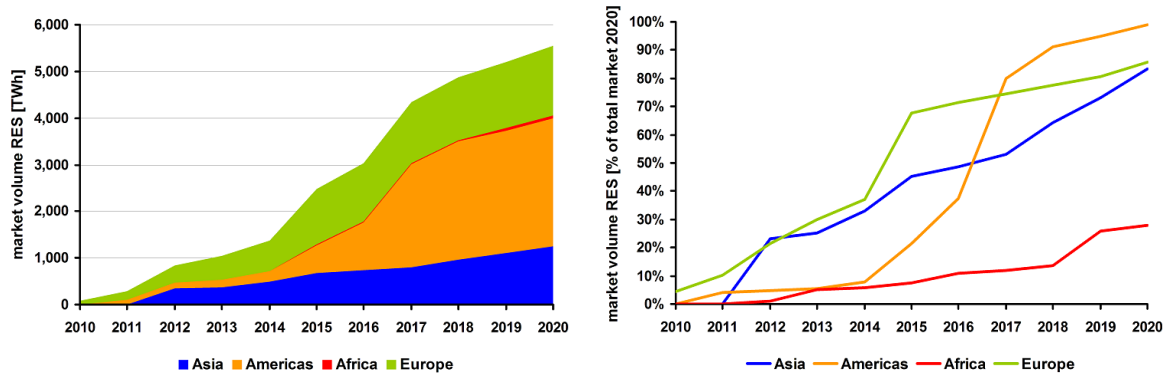


Figure 3.3-8: Grid-Parity market volume for residential segments in absolute (left) and relative (right) numbers for all regions in the world in the years 2010 to 2020.

Residential grid-parity analysis (Fig. 3.3-2 to 3.3-5 and 3.3-8) is performed for 154 countries in the world. These countries account for 98.0% of world population ⁶³¹, 99.7% of global gross domestic product ⁶³², 99.5% of global electricity consumption ⁶³³ and 99.2% of global greenhouse gas emissions ⁶³⁴. Detailed data are given in Appendix Table 3.

First industrial grid-parity events occur today in all regions in the world and often on islands. They continue throughout the entire decade (Fig. 3.3-9). Very early market segments are Cyprus, West Africa, Seychelles, Caribbean, Cambodia and Fiji. Europe, the Americas and Asia-Pacific show quite similar characteristics of industrial grid-parity events throughout the entire decade. At the end of the decade more than 75% of market segments in Europe, the Americas and Asia-Pacific are beyond industrial grid-parity. Exception is given for Africa, due to energy subsidies in South Africa and Egypt. Further exception are mainly oil producing countries used to substantially subsidizing their energy markets, e.g. Russia, Saudi Arabia, Libya, Venezuela, Iran, Iraq, Kuwait, Qatar, Oman and Angola.

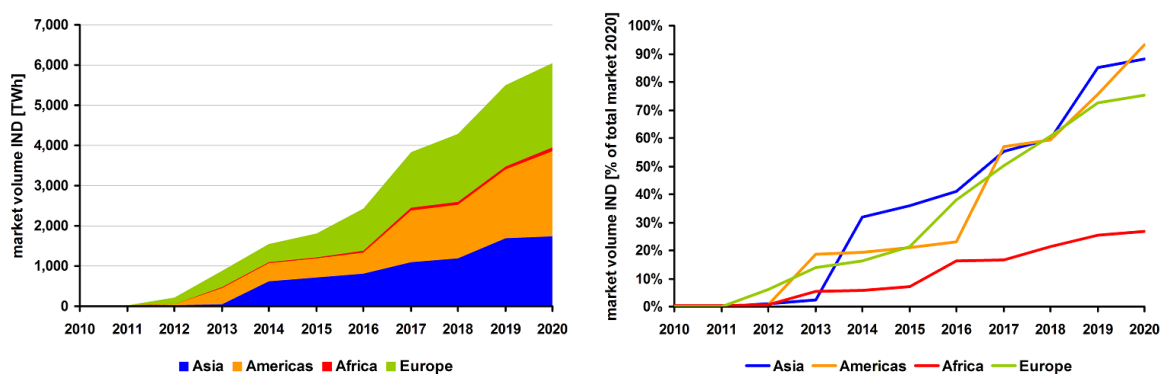


Figure 3.3-9: Grid-Parity market volume for industrial segments in absolute (left) and relative (right) numbers for all regions in the world in the years 2010 to 2020.

Nevertheless, significant opportunity cost might become a pressing burden for these countries, as most could substitute substantial amounts of currently burnt oil and natural gas resources by renewable energy sources like solar PV. As consequence of fuel-parity in these countries fast growing utility-scale solar PV power plant markets are very likely (chapter 6).

⁶³¹ UN, World Population Prospects: The 2008 Revision Highlights, 2009

⁶³² World Bank, Gross domestic product 2008, 2009

⁶³³ IEA, Key World Energy Statistics 2009, 2009

⁶³⁴ UN, Carbon Dioxide Emissions (CO₂), 2009

PV power plants can be used as fuel saving technology. Dynamics and impact of fossil fuel-parity are discussed in sub-chapter 3.4 and chapter 6.

Industrial grid-parity analysis (Fig. 3.3-2 to 3.3-5 and 3.3-9) is performed for 151 countries in the world. These countries account for 97.7% of world population⁶³⁵, 99.3% of global gross domestic product⁶³⁶, 99.6% of global electricity consumption⁶³⁷ and 99.1% of global greenhouse gas emissions⁶³⁸. Detailed data are given in Appendix Table 3.

Key driving force of PV LCOE and therefore for all results presented in this section is system cost. Consensus expectation of financial analysts is 2.70 and 2.40 €/Wp for residential and commercial/ industrial PV systems in Germany in 2010.^{639,640,641,642,643,644,645} Most parts of PV systems are globally traded and produced to similar world market cost. Furthermore, all PV markets in the world comprising several hundred MWp installations per year will show similar distribution cost. Hence a global average sales price is applicable reflecting similar global PV cost. The most competitive and by far largest PV market is Germany. Therefore German PV prices are used as price benchmark in the world (Fig. 3.3-10). Experience curve of PV and market growth rates are key factors for ongoing cost reductions of PV systems (sections 3.1.1 and 3.1.2).

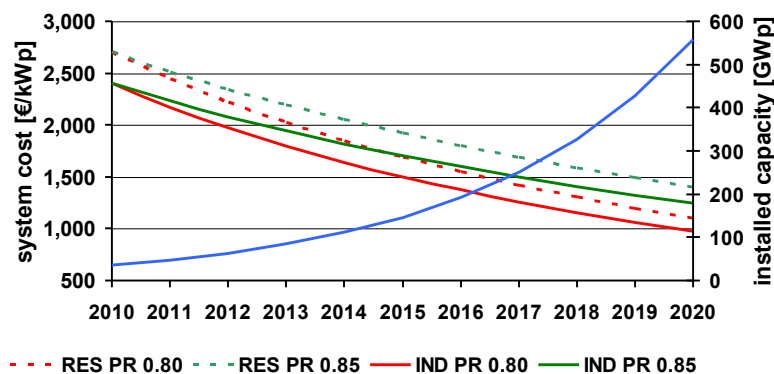


Figure 3.3-10: PV system prices in the 2010s assumed for grid-parity analysis. PV system price includes module, inverter, land and all necessary balance of system components. PV system price of 2.70 €/Wp is indicated for smaller residential systems by dashed lines and for larger commercial systems of 2.40 €/Wp by full lines. Red and green lines represent a normal 20% and conservative 15% learning rate, respectively. Growth rate of global PV markets is assumed to be 30% p.a. PV system price is the major contributor to levelized cost of electricity (LCOE). Further assumptions for LCOE are weighted average cost of capital of 6.4%, lifetime of 25 up to 30 years, operation and maintenance cost of 1.5% of PV system price and performance ratio of 75% up to 82%.

Assumptions for underlying PV system cost might be too conservative. Growth rates of

⁶³⁵ UN, World Population Prospects: The 2008 Revision Highlights, 2009

⁶³⁶ World Bank, Gross domestic product 2008, 2009

⁶³⁷ IEA, Key World Energy Statistics 2009, 2009

⁶³⁸ UN, Carbon Dioxide Emissions (CO₂), 2009

⁶³⁹ Aycicek E. et al., Sector Analysis Photovoltaics 2010, 281ß

⁶⁴⁰ Bumm P., Solar Power, 2010

⁶⁴¹ O'Rourke S. et al., Solar Photovoltaic Industry 2010 global outlook Déjà vu?, 2010

⁶⁴² Photon, Finanzierung: Entwicklung der Anlagenpreise, 2010

⁶⁴³ Shah V. et al., Solar-Investor Guide 2010, 2010

⁶⁴⁴ Gupta S. et al., Global Solar: Sovereign Debt Concerns ... Not a Solar Eclipse, 2010

⁶⁴⁵ Reuter M. and Gruse A.K., European PV Module Price Monitor: First Quarter Results 2010, 2010

global PV installations have been 45% for the past 15 years, which is much higher than expected 30%. Lower future cost potential is also indicated by today's best practice cost for large PV power plants of about 1.5 – 1.6 €/Wp, including all manufacturing, sales, general administration and research cost, excluding cost for debt and equity and value chain inefficiencies, which can be achieved for both CdTe PV and crystalline silicon PV technology.⁶⁴⁶ First PV industry players plan to reach fully-loaded PV power plant cost of about 1.20 – 1.35 €/Wp in 2014⁶⁴⁷ (numbers include 0.20 €/Wp additional cost before excluded and an USD/€ exchange rate of 1.4), which is far below expectations in Fig. 3.3-10 used in this model and provides a further indication of conservative assumption.

In regions reaching grid-parity in the early 2010s, e.g. Spain, PV installations will generate a significant benefit for system owners in the following years (Fig. 3.3-11). New PV solutions, like decentralised storage of PV electricity, will arise due to an enormous financial scope. First insights for 13 different markets in the world roughly indicate a PV plus storage grid-parity about four years after the net metering grid-parity as indicated in Figure 3.3-11.⁶⁴⁸ The very successful feed-in tariffs in Europe will have to be supplemented by new legal frameworks to further enable a fast diffusion of PV and respective social benefits.

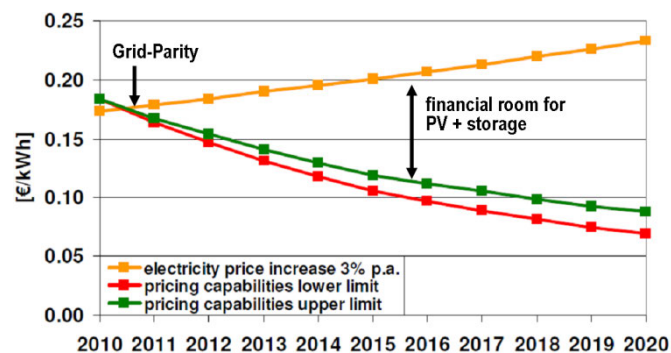


Figure 3.3-11: Grid-parity dynamics in Spain – residential segment. Large difference in expected levelized PV cost and electricity supplied by grid may result in stand-alone PV solutions.

Results presented in this sub-chapter clearly show the enormous potential of PV to become a major source of electricity in the next two decades. Solar energy is available all over the world and distributed more or less homogenously (chapter 2). Based on rapidly improving economics, low technological complexity and excellent resource accessibility solar PV has the potential to become the most democratic source of energy with various beneficial social impacts all over the world.

Grid-parity as the third major PV diffusion phase will be observed in the next years in several countries around the world. First grid-parity events occur right now. The 2010s are characterized by ongoing grid-parity events throughout the most regions in the world, reaching an addressable market of about 75% up to 90% of total global electricity market. It poses a question: what will occur beyond grid-parity? Grid-parity events will trigger development of new business models, like PV-storage applications, and will induce progress in electric grid management, like PV induced locally temporarily reversed power flows. In consequence, new political frameworks for maximizing social benefits will be required. Finally, it can be stated that PV electricity generation will achieve grid-parity in most market

⁶⁴⁶ Breyer Ch., How favourable is PV?, 2010a

⁶⁴⁷ Asali K., Value of PV for Large Scale Solar Power Plants in MENA, 2010

⁶⁴⁸ Werner C., Grid-Parity für Photovoltaik mit Energiespeicher, 2011

segments in the world and will become a very competitive source of energy.

3.4 Off-grid End-user Systems: Fuel-Parity

Prerequisite for grid-parity analysis of the last sub-chapter is access to an electricity grid. This is not the case for about 1.4 billion people in the world (Fig. 1.4-1).⁶⁴⁹ Most of them live in rural areas in Sub-Sahara Africa (about 590 million), India (about 400 million) and other developing Asia (about 390 million). An overview on global access to electricity is depicted in Figure 3.4-1. Detailed description and figures for numbers of people without access to electricity, local electrification rates and further data on a country basis can be found elsewhere^{650,651}.

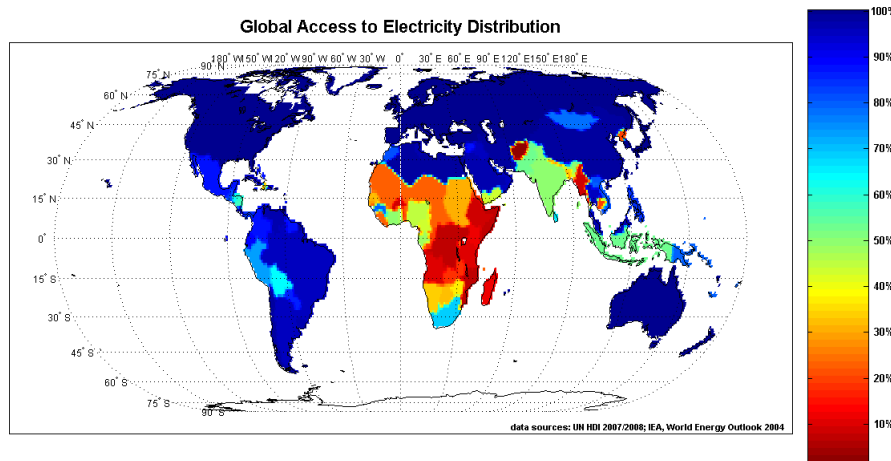


Figure 3.4-1: Global access to electricity in percent of local population. Dark blue colour coding represents up to 100% electricity access of local population, whereas dark red is an indication for very low electrification rate of local population of 10% or even less. Dependence of electrification rates on final electricity consumption on a country basis is given in Figure 1.4-5. Data are taken from United Nations Development Programme⁶⁵² and International Energy Agency⁶⁵³.

By far the most people having no access to modern forms of energy live in sunny regions (Fig. 2.2-3 and 3.4-1). Detailed analysis of georeferenced location of world population⁶⁵⁴, location of people without access to electricity (Fig. 3.4-1) and local irradiation on module surface of fixed optimally tilted PV systems (Fig. 2.2-3) clearly shows excellent solar conditions for most of the 1.4 billion people having no access to electricity of about 1,800 – 2,200 kWh/m²/y (Fig. 3.4-2). Most people without access to electricity live in developing countries of gross domestic product (GDP) per capita of less than 2,500 USD.⁶⁵⁵

⁶⁴⁹ IEA, World Energy Outlook 2010, 2010

⁶⁵⁰ Werner C. et al., Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, 2011

⁶⁵¹ Breyer Ch. et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 2011c

⁶⁵² UNDP, Human Development Report 2007/2008, 2008

⁶⁵³ IEA, World Energy Outlook 2006, 2006

⁶⁵⁴ Balk D. and Yetman G., The Global Distribution of Population: Gridded Population of the World, 2005

⁶⁵⁵ Breyer Ch. et al., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 2011c

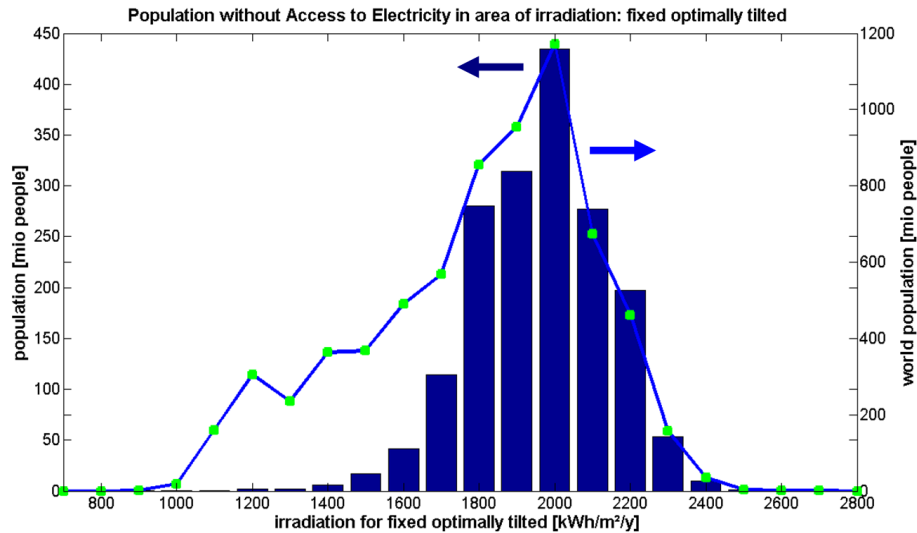


Figure 3.4-2: Population without access to electricity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents distribution of world population. The bars are referred to the left axis and represent population without access to electricity.

Grid-parity concept (sub-chapter 3.3) makes no sense for people without access to electricity, but most of them live in areas of excellent solar conditions, hence highly economic off-grid PV systems are a best adapted and the least cost solution for their energy needs (following sections). Concepts of best describing attractiveness of PV solutions for those people are dependent on the specific situation. Very poor people have to spend a high fraction of their income for kerosene fuelled lamps, for dry cell battery powered radios and tape recorders and for charging mobile phones, hence cost for kerosene and dry cell batteries are the reference for evaluating economic attractiveness of PV systems (section 3.4.1). The former energy cost are paid week by week, or month by month, whereas the latter ones have to be bought in total but can be used for years. Attractiveness of PV applications is distinguished by their financial amortization period. People on higher standard of living, who are not grid-connected, are much more dependent on fossil fuel prices. Mainly diesel cost is the major driver of energy related end-user cost for those people without access to electricity (section 3.4.2). Parity of off-grid PV LCOE to fuel LCOE is the most appropriate measure for the economics of off-grid PV systems, therefore the so-called fuel-parity well describes this segment.

A sustainable off-grid market development in developing countries often dominated by small off-grid PV solutions has to consider several key success factors for rural electrification. Similar success patterns have been observed around the world: adequate system design, training of installers and end-users, financing, service and institutional cooperation^{656,657,658,659,660} and in case of hybrid mini-grids tariff structuring⁶⁶¹.

⁶⁵⁶ Arkesteijn K.M. and Maaskant A.E., Small is beautiful: Solar product and market development should be scaled to the actual needs of end-users in the developing world, 2007

⁶⁵⁷ Merten J. et al., Seven key points for successful rural electrification programmes with solar energy, 2007

⁶⁵⁸ Müller H. and Siepker B., Awareness – Training – Financing: The way to a sustainable dissemination of stand-alone PV systems for rural electrification, 1998

⁶⁵⁹ Argaw N., The role of institutions for sustainable development of rural communities using PV systems, 1998

⁶⁶⁰ Breyer Ch. et al., Electrifying the Poor: Highly economic off-grid PV Systems in Ethiopia – A Basis for sustainable rural Development, 2009a

⁶⁶¹ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

3.4.1 Solar Home Systems

Standard PV system for rural off-grid electrification of family homes is a solar home system (SHS). An excellent overview on SHS diffusion in practice is given by Damian Miller for many developing countries.⁶⁶² In the following the economics of SHS are exemplarily described for the case of Ethiopia (section 3.4.1.1), because of its typical characteristics for a classical SHS market. The analysis for Ethiopia will be the reference for estimating the attractiveness of SHS for all countries in the world of less than 80% electrification (section 3.4.1.2).

3.4.1.1 Economics of Solar Home Systems for the Case of Ethiopia

Ethiopia is a landlocked country situated in the Horn of Africa with a population estimated at over 83 million by 2007. Its annual population growth rate of 2.5% ranks it 28th fastest growing of 229 countries and regions in the world.⁶⁶³ In terms of gross domestic product (GDP) per capita Ethiopia is rated 174th of 179 and in terms of human development index it is rated 169th of 177.⁶⁶⁴ These numbers indicate Ethiopia as one of the poorest countries in the world. More country specific data can be found elsewhere.⁶⁶⁵ Most Ethiopians live in rural areas (84%) and only 1% of those have access to electricity. Nevertheless, solar irradiation on fixed optimally tilted module surface is between 1,930 – 2,360 kWh/m²/y leading to a population weighted mean value of 2,205 kWh/m²/y (sections 2.2.3 and 2.3.1 and Appendix Table 1), providing an excellent basis for PV applications. Due to its conditions, Ethiopia is an excellent example for most of the least developed countries in the sunbelt, hence several results achieved for Ethiopia might be transferred to countries comprising about one billion people around the world.

Currently Ethiopia generates its power from its vast hydro power potential and supplemented diesel power plants. 647 MW or 89% of the installed grid connected capacity comes from hydro power plants.⁶⁶⁶ Economically feasible hydro power potential would be up to 30 GW.⁶⁶⁷ Due to seasonal rainfalls the generation capacity significantly depends on the amount of rain water during the raining season. This results in power shedding during periods with low water levels. Such periods regularly force the Ethiopian Electricity Power Company (EEPCo) to cut off customers from power supply, even in the capital. Ethiopia has launched construction of several new hydro power plants to prevent power shortages and meet the demand growth.⁶⁶⁸

Ethiopia exhibits excellent prerequisites for a nearly 100% renewable energy supply. Superb hydro and solar resources offer the chance of renewable energy supply in an economically, ecologically and socially sustainable way. Such PV-hydro potentials have been already

⁶⁶² Miller D., *Selling Solar – The Diffusion of Renewable Energy in Emerging Markets*, 2009

⁶⁶³ UN, *World Population Prospects: The 2006 Revision Highlights*, 2007

⁶⁶⁴ UNDP, *Human Development Report 2007/2008*, 2008

⁶⁶⁵ Solar Energy Foundation, *Country Data for Ethiopia*, 2009

⁶⁶⁶ EEPCo, *Electricity Power Industry Master Plan Program*, 2007

⁶⁶⁷ GTZ, *Energy-policy Framework Conditions for Electricity Markets and Renewable Energies*, 2007

⁶⁶⁸ EEPCo, *Electricity Power Industry Master Plan Program*, 2007

analysed for Ethiopia ⁶⁶⁹ and might lead to utility-scale PV power plants. These enormous renewable energy potentials might be connected to the DESERTEC plan in EU-MENA region ⁶⁷⁰ (section 7.4.4) and further document the enormous energy supply potential of renewable energy sources.

Nevertheless, more than 80% of the Ethiopian population has no access to electricity, in particular in rural areas where more than 80% of the Ethiopians live. Overcoming this obstacle is a key for sustainable rural development. Like everywhere in the world, consumers in Ethiopia have a need for light, communication (e.g. radio, TV, cell phone) or mechanical energy (e.g. cooling, water pumping) but not electricity as an end in itself. In Ethiopia conventional rural energy usage is based on kerosene lamps for light and dry cell batteries for radios and tape recorders. Electric light is more easy and comfortable to handle, brighter, less expensive, cleaner and much safer than kerosene lamps.

Typical off-grid PV solar home systems in Ethiopia consist of a 10 Wp PV module (in contrast to 50 Wp system typically used in most countries), charge and remote controller, 18 Ah gel lead acid battery, two 50 lm/W LED lamps and one plug for a radio or tape recorder. Commonly two kerosene lamps are used by one family plus optionally one radio or tape recorder powered by dry cell batteries.

A simple financial tool for comparing alternative options is the calculation of payback periods.⁶⁷¹ Knowing all cash flows for investment, spare parts, service, financing cost and available budgets for energy needs, one can derive the payback period in which the investment pays off. If the lifetime of an investment is longer than the payback period, a financial benefit will be generated.

All necessary data are available in local currency, therefore the calculation is performed in Ethiopian Birr (ETB). As of March 2009, currency exchange rate was set to 14 ETB/€. Major assumptions are for the average energy budget of an Ethiopian family, cost of the SHS and its components, which have to be exchanged in regular intervals: complete 10 Wp PV system including all components (3,200 ETB), fuel cost for one kerosene lamp (45 ETB/month), dry cell batteries for one radio (24 ETB/month), dry cell batteries for one tape recorder (48 ETB/month), reinvestment for new PV battery (440 ETB/every 4 years), reinvestment for new charge and remote controller (600 ETB/every 10 years), reinvestment for 4 new LED lamps (400 ETB/every 7 years), inflation 10% p.a. and credit cost 3% p.a. over inflation rate.

⁶⁶⁹ KfW, PV-Hydro Initiative: Stages 1 & 2 – Assessment of the Potential for the Commercialization of Conjunctive Photovoltaic – Hydro Power Generation, 2001

⁶⁷⁰ Knies G. Clean Power from Deserts – The Desertec Concept for Energy, Water and Climate Security, 2009

⁶⁷¹ Short W. et al., A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, 1995

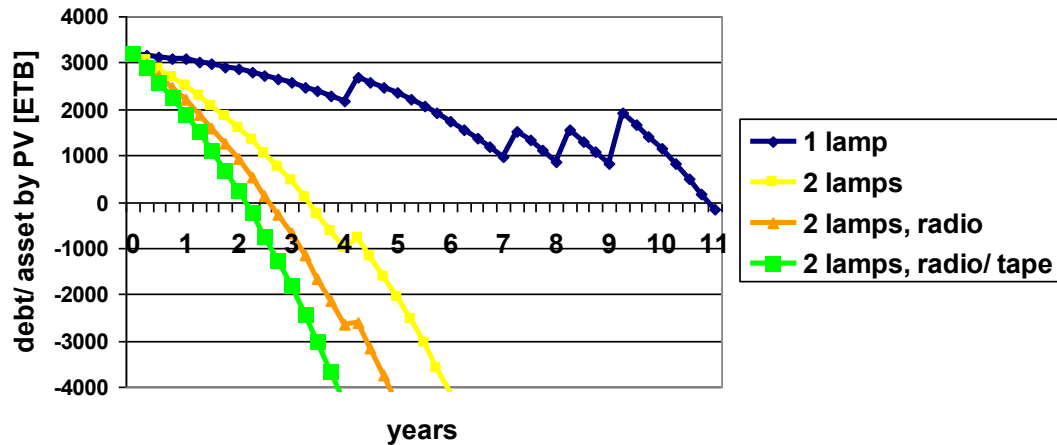


Figure 3.4-3: Payback period of small off-grid PV systems in Ethiopia. A today's 10 Wp PV system is compared to conventional energy consumption in rural areas. Replacement needs for battery, LED lamp and charge controller are the reason for the discontinuous shape of the graphs.

The payback period (Fig. 3.4-3) of a standard 10 Wp SHS is between 2 - 4 years, depending on energy consumption habits of the users. Families using two kerosene lamps reach break-even of their investment in a 10 Wp SHS in about 3.5 years. After break-even there are only regular replacement costs of some components which add up to a significant monthly reduction of energy cost by about 80%. This 80% cost reduction is equivalent to a present value⁶⁷² in the year of break-even of about 8,500 and 20,000 ETB for assumed system lifetimes of 10 and 20 years, respectively. Families with larger energy budgets, for the given example of two lamps and dry cell batteries for radio and tape recorder, reach break-even in 2.2 years, benefit from a 90% cost reduction of their energy budget in the year of break-even and achieve a present value in the year of break-even of about 15,500 and 32,000 ETB for assumed system lifetimes of 10 and 20 years, respectively. Notably, these present values approximately equal 9 and 18 times the GDP/capita, respectively. Saved energy spending can be used for increasing the standards of living, e.g. better energy supply, education, medical aid, improved houses and much more.

Financial benefit for SHS owners is obvious, in particular in respect to an expected system lifetime of 15 - 20 years. Profitability of rural off-grid SHS is considerably higher than on-grid PV installations in most developed countries (sub-chapter 3.3). A comparable metric would be the internal rate of return (IRR), which indicates the profitability of an investment.⁶⁷³ Inflation corrected IRR for on-grid PV installations are about 5% - 7%, whereas IRR for the two lamps and the two lamps plus dry cell batteries case reaches 28% and 45%, respectively. Main reasons for this remarkable economic outcome are: high energy prices for rural population, which correlate to world market prices for fossil fuels, and ineffective use of the energy.

Standard power supply for rural areas in emerging and developed countries is a diesel generator (section 3.4.2). However, this is no suitable solution for the case of rural areas in Ethiopia, simply due to the low amount of electricity an Ethiopian family needs. A typical Ethiopian SHS of 10 Wp generates about 13 kWh electricity per year being sufficient for lighting the home, powering a radio and a limited use of a tape recorder. Energy losses in low

⁶⁷² Short W. et al., A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, 1995

⁶⁷³ Short W. et al., A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, 1995

voltage distribution networks would be higher than the finally needed amount of electricity. Furthermore, in poor rural areas it is rather difficult to maintain a diesel generator because of the lack of essential spare parts and fuel availability or for maintenance reasons. As a result of this lacking maintenance, some villages own a generator, being out of operation and not able to supply reliable electricity. Another problem is the aforementioned low voltage connection of the houses. In some cases the villagers cannot afford to connect their house to the central generator. Finally, air and noise pollution of a diesel generator is not negligible.

The last paragraphs showed that small off-grid SHS are highly beneficial for rural population in Ethiopia. Village power supply by diesel generators is no real alternative. Based on this insight, together with Ethiopian energy experts a rough estimate of today's addressable market for SHS in Ethiopia has been derived (Table 3.4-1).⁶⁷⁴ A good overview on market trends in Ethiopia and evaluations of local strategies can be found elsewhere^{675,676}.

Currently, typical off-grid PV home systems in Ethiopia consist of a 10 Wp PV system. An estimate of Ethiopian PV experts led to PV system demand in power units of 2 Wp for light for one house 4 h/day, 10 Wp for light and music, 20 Wp, 50 Wp and 100 Wp which is sufficient for a little cinema or a health station with refrigerators. This estimate is close to similar analyses of other Ethiopian experts⁶⁷⁷ and is based on today's GDP/capita. Optimised PV systems are expected to be sold at a significantly lower price than today, including scaling effects in distribution channels in Ethiopia. These effects are known from other markets and are reflected in local prices.^{678,679} Assumptions for the calculation below are: addressable rural households in Ethiopia (10 million), specific off-grid PV SHS price (150 ETB/Wp), currency exchange rate (14 ETB/€) and several years of market development. Markets for commercial off-grid and on-grid PV systems are not considered but would significantly increase the market potential.

PV systems	distribution	households	PV demand	market for optimised systems	
[Wp]	[%]	[mio]	[MWp]	[mETB]	[m€]
2	20%	2	4	600	43
10	20%	2	20	3,000	214
20	30%	3	60	9,000	643
50	20%	2	100	15,000	1,071
100	10%	1	100	15,000	1,071
total	100%	10	284	42,600	3,043

Table 3.4-1: Ethiopian cumulated off-grid PV addressable markets for solar home systems.

Remarkably, nearly all Ethiopians in rural areas could have access to electricity and they could afford it. These estimates show that 70% of rural population would significantly improve their standards of living and effectively save money for energy needs if they had access to SHS in the power range of not more than 20 Wp. The market segments for SHS

⁶⁷⁴ on the occasion of the "Solar Energy Training for Energy Sector Decision Makers and Experts", organized by Solar Energy Foundation, Addis Ababa, Ethiopia, 2008, September 15-25

⁶⁷⁵ Villers De T., Terminal Evaluation of the project 'Building Sustainable Commercial Dissemination Networks for Household PV Systems in Eastern Africa', 2007

⁶⁷⁶ Shanko M. et al., Rural solar PV market potential: A case for Jima region in Ethiopia, 2006

⁶⁷⁷ Shanko M. et al., Rural solar PV market potential: A case for Jima region in Ethiopia, 2006

⁶⁷⁸ Gabler H., Photovoltaik zur netzfernen Energieversorgung, 2008

⁶⁷⁹ Adelmann P., Wireless Power, Maputo Workshop for SSA Electrification Experts, 2009

larger than 20 Wp might offer an addressable volume of about 2,000 million €. As shown in Figure 3.4-3 investments in SHS would pay off within 2 - 4 years and reduce energy budgets by 80% – 90% after this payback period. Imagine a fast and nationwide diffusion of privately financed SHS, an enormous boost in private financial capabilities in rural areas can be expected. Rural villagers can decide which needs they may cover first, e.g. enlargement of their SHS, education, investments in their houses, medical aid, communication technologies and much more. These options and further beneficial social impacts are discussed in more detail elsewhere^{680,681}.

3.4.1.2 Global Market for Solar Home Systems

Ethiopia is an excellent reference for most SHS markets in the world. This is caused by several factors, mainly the irradiation level in Ethiopia which is comparable to the most countries of low electrification rates (Fig. 3.4-1 and 2.2-3), the cost for diesel as an indicator for kerosene prices is comparable or even higher in most other SHS markets (Fig. 3.4-5) and the GDP/capita in Ethiopia is one of the five lowest in the world, hence purchasing power is higher in nearly all other countries in the world (Fig. 3.4-4).

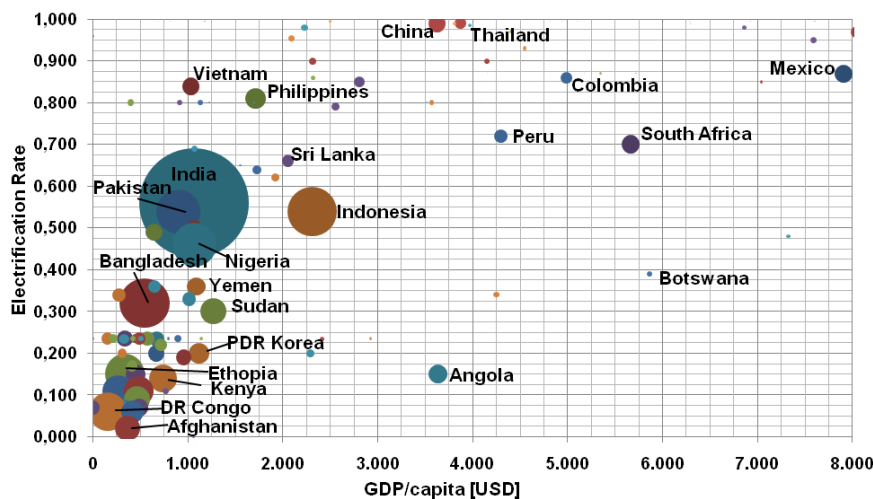


Figure 3.4-4: Electrification rate in dependence on GDP per capita for developing countries. The bubble size is according to the quantity of people without access to electricity. Data are taken from United Nations⁶⁸², International Energy Agency⁶⁸³ and the World Bank⁶⁸⁴.

For estimating the attractiveness of small PV off-grid applications all countries have been selected for electrification rates of less than 80% (Fig. 3.4-1 and 3.4-4). A check of their population weighted mean irradiation on fixed optimally tilted module surface (section 2.3.1 and Appendix Table 1) confirms that typical small PV applications do not need to be adapted in size, as the solar resource in all other selected countries is within a maximum relative deviation of 20%. Kerosene expenditures for lighting purposes have been translated to all other relevant countries by local diesel prices depicted in Figure 3.4-5, which is an excellent cost indicator.

⁶⁸⁰ Breyer Ch. et al., Electrifying the Poor: Highly economic off-grid PV Systems in Ethiopia – A Basis for sustainable rural Development, 2009a

⁶⁸¹ Dany C., Light for Ethiopia, 2009

⁶⁸² UNDP, Human Development Report 2007/2008, 2008

⁶⁸³ IEA, World Energy Outlook 2006, 2006

⁶⁸⁴ World Bank, Gross Domestic Production 2009, 2010

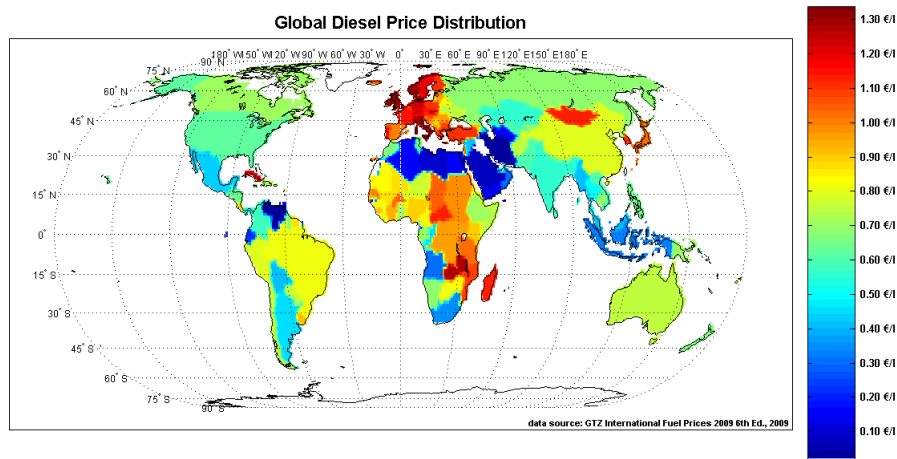


Figure 3.4-5: Global diesel price distribution. Crude oil price had been 48 USD/barrel at time of survey in mid November 2008. This translates to a crude oil cost of about 0.25 €/l for a USD/€ exchange rate of 1.265 for November 2008. Further refinery cost for conversion of crude oil into diesel are about 0.09 €/l, hence minimum diesel cost for the time of survey had been 0.34 €/l. Prices below 0.34 €/l are subsidised and prices above include partly significant taxes. These prices translate into 0.37 €/l and 0.51 €/l for crude oil content and diesel cost, respectively on a crude oil price of about 80 USD/barrel and a USD/€ exchange rate of 1.4.⁶⁸⁵ More details on the cost structure of fossil fuel prices can be found in sections 3.4.2.2 and 6.1.4. Data are taken from GTZ.⁶⁸⁶

Attractiveness of small PV applications investments is indicated by their amortization period as shown for the case of Ethiopia in Figure 3.4-3. As reference systems are chosen: a 2 Wp pico system (PS), a 10 Wp SHS and a 50 Wp SHS and respective energy related expenditures on kerosene for one or more lamps and dry cell batteries for a radio and a tape recorder comparable to the calculation in Figure 3.4-3 and summarized in Table 3.4-2. For calculating the financial amortization of SHS and PS their specific cost need to be calculated and compared to the substituted energy cost (Table 3.4-2). The replacement cost of key components like battery, charge controller or LED lamps have to be considered as well. The substituted energy costs are composed by the aforementioned kerosene and dry cell batteries. Results are shown for all countries in the world of electrification rates less than 80% in Figure 3.4-6.

		PS	SHS	SHS
system size	[Wp]	2	10	50
system cost	[€/Wp]	23	23	8
reinvest				
battery	[€/Wp]	3.15	3.15	0.96
	[y]	4	4	4
charge controller	[€/Wp]	4.30	4.30	0.80
	[y]	10	10	10
LED	[€/Wp]	2.85	2.85	0.64
	[y]	7	7	7
energy need				
kerosene	[l/month]	5	10	20
radio battery	[€/month]	-	1.70	1.70
tape rec battery	[€/month]	-	-	3.40

⁶⁸⁵ Breyer Ch. et al., Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, 2010e

⁶⁸⁶ Ebert S. et al., International Fuel Prices 2009 6th Edition, 2009

Table 3.4-2: Cost and lifetime assumptions for PS and SHS and typical local energy needs in off-grid regions. Data are taken from section 3.4.1.1, Breyer et al.⁶⁸⁷, Gabler⁶⁸⁸ and the World Bank⁶⁸⁹.

Depending on the prevailing energy consumption patterns the respective solar system size is taken into account (Table 3.4-2). The diesel prices (Fig. 3.4-5) in rural areas of developing countries are substantial higher than at urban locations, hence the so-called distance to port factor is linearly varied between 20% (> 2,000 USD GDP/capita) and 50% (< 300 USD GDP/capita) in rough dependence on the local infrastructure availability and the efficiency of distribution channels.

Price assumptions for PS and SHS are in the range of international market conditions in smaller and larger off-grid markets as well as the energy cost substitution potential of these systems according to energy consumption patterns of the users. Amortization of complete PV systems ranges between 6 - 18 months for PS and 12 – 36 months for SHS but strongly depending on energy consumption patterns (Fig. 3.4-6). Thus, small PV applications are the least energy cost option for people without access to electricity in rural areas. Analysis shows that upfront investment seems to be less of a financial burden than anticipated. The capitalized value of the various small PV systems range between 10 - 45 for PS and 5 – 20 for SHS times the original capital expenditures in most countries (Fig. 3.4-7).

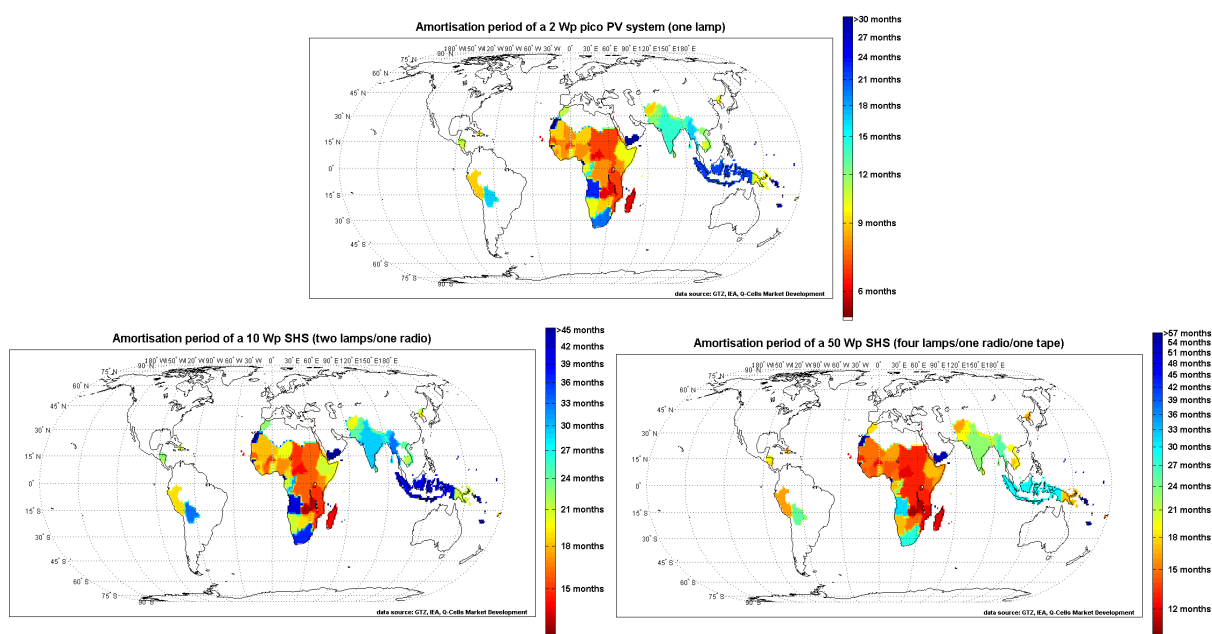


Figure 3.4-6: Amortization period for 2 Wp PS (top), 10 Wp SHS (bottom, left) and 50 Wp SHS (bottom, right). Coloured countries show electrification rates of less than 80%. Economics are based on assumptions in Table 3.4-2 and Figure 3.4-5 and inflation of 10% plus a real interest rate of 3%.

⁶⁸⁷ Breyer Ch. et al., Small Photovoltaic Applications in Regions of low Electrification: High Demand, fast financial Amortization and large Market Potential, 2011b

⁶⁸⁸ Gabler H., Photovoltaik zur netzfernen Energieversorgung, 2008

⁶⁸⁹ Cabraal A., Photovoltaics in the World Bank Group Portfolio, 2010

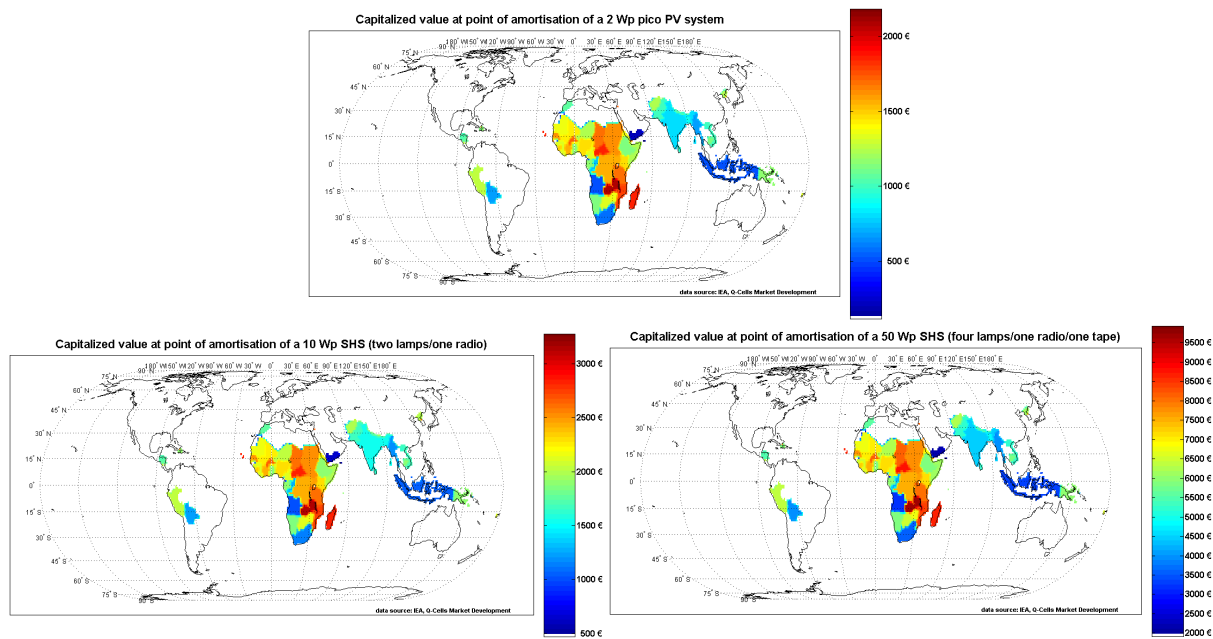


Figure 3.4-7: Capitalized value of 2 Wp PS (top), 10 Wp SHS (bottom, left) and 50 Wp SHS (bottom, right) at the point in time of full amortization till the end of lifetime. Assumptions for the calculations are based on data given in Table 3.4-2, Figures 3.4-5 and 3.4-6 plus a 20 years lifetime.

Insights on solar resource conditions and local cost of current energy supply presented in this section are used for a rough estimate of market potential for small PV applications. A market evaluation for Ethiopia, one of the poorest countries in the world, has led to a total market potential of 284 MWp valued by about 3 bn€ for roughly 70 mio people without electricity access (Table 3.4-1). These numbers correspond to about 30 Wp per small PV system. The market for the 1.4 billion people without access to electricity⁶⁹⁰ might be evenly addressed by small PV systems of the average size of 30 Wp for very poor regions, larger scale small PV systems of an average size of about 100 Wp for less poor regions and mini-grid applications (section 3.4.2) providing annually about 300 kWh/user. Markets for PV powered mini-grids are not considered. The such derived global market potential for PS and SHS in very poor rural regions for residential purposes might be about 1.9 GWp and 20.0 bn€, whereas the market potential for less poor rural regions might represent about 6.3 GWp and 66.7 bn€. These numbers are excluding PV powered mini-grids. However, advanced commercial applications and public services lead to an even higher market potential. Most well emerging and developed countries in the world show a residential fraction of total final electricity consumption of roughly one third, i.e. commercial, industrial and public consumption is two times higher than the residential one. Therefore, the commercial and public (schools, health centres, lanterns, water pumping, telecommunication, etc.) small PV off-grid market might be two times higher than the residential one. These numbers still exclude PV powered mini-grids. In 2007, the global market for rural PV off-grid applications in developing countries has been estimated to about 50 MW⁶⁹¹ growing on a roughly 20% growth rate, but could expand much faster due to excellent fundamental economics. However, financing gap might still be a dramatic hurdle for a fast diffusion of SHS in these countries. New developments in the field of pico systems^{692,693,694}, i.e. solar systems in the

⁶⁹⁰ IEA, World Energy Outlook 2010, 2010

⁶⁹¹ Gabler H., Photovoltaik zur netzfernen Energieversorgung, 2008

⁶⁹² Gabler H., Photovoltaik zur netzfernen Energieversorgung, 2008

⁶⁹³ Adelman P., Pico PV – An Overview, 2011

⁶⁹⁴ Chaurey A. and Kandpal T.C., Solar lanterns for domestic lighting in India: Viability of central charging station model, 2009

range of 2 Wp – 5 Wp could reduce the amortization period to less than 12 months, which should be less enough for a full upfront payment for the system by most end-users.

Summing up the results of the section 3.4.1, most people without access to electricity live in regions of very good or excellent solar conditions and have to pay significant amounts of their income for conventional energy supply. Attractive prices for PS and SHS lead to short financial amortization periods and enable people without access to electricity to cover their energy needs in a sustainable manner. Moreover, small PV applications are the least cost energy option. Fast growing global on-grid PV markets and scaling effects in local distribution channels will further reduce system cost for off-grid applications. Based on enormous demand for sustainable energy supply of still not electrified people and excellent economics of small PV applications, the respective total global market potential is expected to be in the order of 80 - 90 bn€ (residential) up to more than 250 bn€ (residential, commercial and public). Excellent economics of small PV applications might significantly accelerate respective growth rate of off-grid PV markets in the years to come.

3.4.2 Hybrid PV Systems

The combination of PV component with other electrical components, like diesel generators, batteries or wind turbines, forms hybrid PV systems. An overview on the fundamentals of hybrid power systems is given in section 6.1.1. In the following a general overview is given on small scale hybrid PV systems (section 3.4.2.1), which is regarded more deeply in its economics for the case of hybrid PV-Diesel and PV-Battery systems (section 3.4.2.2).

3.4.2.1 General Overview on Small Scale Hybrid PV Systems

Hybrid PV-Diesel systems are in operation for decades and typically used in off-grid power supply.^{695,696,697,698} Many of these hybrid PV-Diesel systems are key component of a mini-grid (Fig. 3.4-8), i.e. an electrical grid infrastructure of only a small geographic extent (Fig. 3.4-9) like a village, a small town or parts of an island. Standard design of hybrid PV-Diesel systems includes batteries, therefore fuel demand is limited and often used only as a backup component for periods of low irradiation. Solar PV electricity fraction in PV-(Wind-Battery)-Diesel systems is typically between 10% - 60%⁶⁹⁹, but can also reach very high proportions, as for a reported system in Morocco where 95% of entire electricity were provided by PV⁷⁰⁰. A large commercial market for hybrid PV-Diesel solutions has been established for applications in the telecommunications industry, in particular for wireless communication transmission stations.⁷⁰¹ Annual market size of such smaller sized hybrid PV systems is estimated to be about 50 MWp.⁷⁰²

⁶⁹⁵ Aulich H.A., et al., Rural Electrification with PV Hybrid Plants – State of the Art and Future Trends, 1998

⁶⁹⁶ Schmid A.L. and Hoffmann C.A.A., Replacing diesel by solar in the Amazon: short-term economic feasibility of PV-diesel hybrid systems, 2004

⁶⁹⁷ Mitra I., Optimum Utilization of Renewable Energy for Electrification of Small Islands in Developing Countries, 2008

⁶⁹⁸ Perlin J., From Space to Earth – The Story of Solar Electricity, 1999, pp. 125-145

⁶⁹⁹ Shrestha G. et al., Case Studies of PV-Diesel Hybrid Systems in Operation in Rural Asia: Experiences and Conclusions from China, Thailand and Vietnam, 2008

⁷⁰⁰ Vallvé X. et al., PV Hybrid Micro-Grid Experience in Morocco, 2008

⁷⁰¹ Müller M., Sustainable operation experience in PV-Hybrid Systems, 2008

⁷⁰² Müller M., Sustainable operation experience in PV-Hybrid Systems, 2008

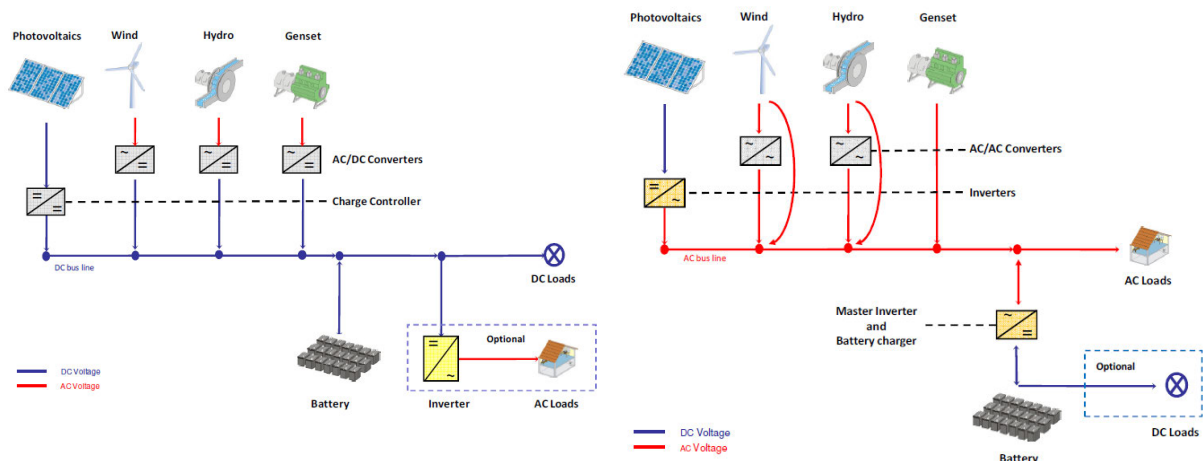
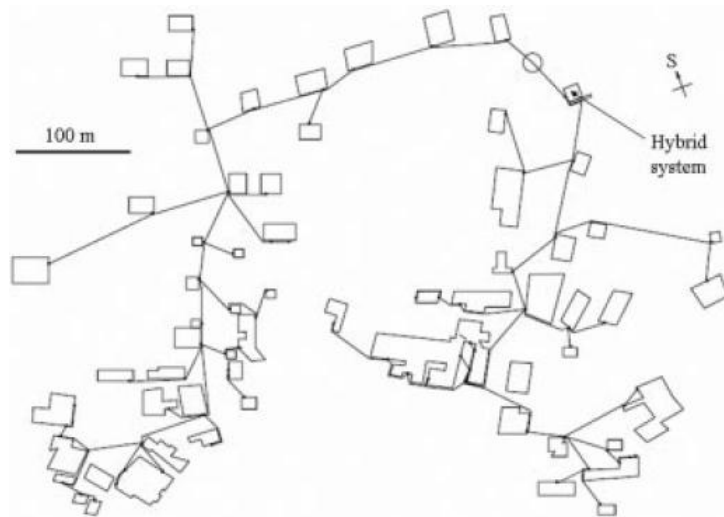


Figure 3.4-8: Electric design of a hybrid PV-Wind-Hydro-Battery-Diesel system coupled at a direct current (DC) bus bar (left) and an alternating current (AC) bus bar (right).⁷⁰³ There are also combinations of both standard types in operation.

The design depicted in Figure 3.4-8 might be the economic optimum for good wind conditions, otherwise a system without wind and hydro power would be a hybrid PV-Battery-Diesel system. Without a fossil fraction a hybrid PV-Battery system (section 3.4.2.2) could also power a mini-grid, depending on the number and spatial extent of the users and the wiring. However, a properly sized hybrid PV-Diesel system would be sufficient for powering the mini-grid or a group of users. For analysing which specific topology is best adapted to local conditions a broad set of simulation tools have been developed for hybrid PV systems.^{704,705} The diesel as a fossil balancing fuel might be substitutable by locally produced biogas and thus guaranteeing a full decoupling from fossil fuel prices. Such an option has been proposed for rural areas in Brazil but might be applicable in many rural areas in the world.⁷⁰⁶



⁷⁰³ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

⁷⁰⁴ Bopp G. and Lippkau A., Overview about design and simulation tools for hybrid PV systems, 2008

⁷⁰⁵ Schwunk S. et al., Simulation of Hybrid PV Systems, 2008

⁷⁰⁶ Borges Neto M.R. et al., Biogas/PV hybrid power system for decentralized energy supply of rural areas, 2011

Figure 3.4-9: Typical layout of a hybrid PV-Diesel mini-grid.⁷⁰⁷ The depicted hybrid PV-Diesel system powers the village of Iferd in Southern Morocco.

An exemplarily overview on existing and proposed hybrid PV-(Wind-Battery)-Diesel systems is given in Table 3.4-3. Such systems can be found all around the world, whereas typical electricity cost are much higher than electricity supply by large grids.

Region/ Country	Average electricity demand per user	Electricity cost	References
	[kWh/y/user]	[€/kWh]	
Africa			
Angola			⁷⁰⁸
Egypt			⁷⁰⁹
Libya			⁷¹⁰
Mauritania	475	0.42	⁷¹¹
Morocco	90 – 200	0.48 - 0.54	^{712,713,714}
Senegal	100	0.70 – 0.83	^{715,716}
Tunisia	400		⁷¹⁷
Asia-Pacific			
Antarctica			⁷¹⁸
China	156	0.67 – 0.81	^{719,720}
India	155 – 240		^{721,722}
Laos	10 – 40; 550	0.60 – 0.80	^{723,724; 725}
Micronesia	700 – 1100		⁷²⁶
Nepal	75 – 140		⁷²⁷
Oman			⁷²⁸
Samoa	120 – 1900		⁷²⁹
Thailand	130 – 560		^{730,731}

⁷⁰⁷ Munoz J. et al., Experience With PV-diesel Hybrid Village Power Systems in Southern Morocco, 2007

⁷⁰⁸ Müller M., Sustainable operation experience in PV-Hybrid Systems, 2008

⁷⁰⁹ Papadakis G. et al., Hybrid Renewable Energy Systems for the Supply of Services in Rural Settlements of Mediterranean Partner Countries – The Case Study of the Hybrid System – Micro-grid in Egypt, 2010

⁷¹⁰ Kershman S.A. et al., Hybrid wind/PV and conventional power for desalination in Libya – GECOL's facility for medium and small scale research at Ras Ejder, 2005

⁷¹¹ Marcel J.-C. and Sauvage E., Various rural electrification design for 7 villages in Northern Mauritania, 2008

⁷¹² Vallvé X. et al., PV Hybrid Micro-Grid Experience in Morocco, 2008

⁷¹³ Munoz J. et al., Experience With PV-diesel Hybrid Village Power Systems in Southern Morocco, 2007

⁷¹⁴ Munoz J. et al., First Operating Year of Two Village PV-Diesel Plants in the South of Morocco, 2004

⁷¹⁵ Peterschmidt N. et al., Taking the step from Solar-Home-Systems to Micro-Grids, 2008

⁷¹⁶ Schmidt-Reindahl J. et al., Market development for economically viable off-grid power supply in Senegal, 2008

⁷¹⁷ Linares A. et al., Hybrid RE System: Minigrid Set-Up, First Results and Lessons Learned, 2010

⁷¹⁸ Broe De A. et al., The Belgian Antarctic Research Station runs on Wind and Sun, 2008

⁷¹⁹ Shrestha G. et al., Case Studies of PV-Diesel Hybrid Systems in Operation in Rural Asia: Experiences and Conclusions from China, Thailand and Vietnam, 2008

⁷²⁰ Gorn M., Most Economic Design for Profitable Investment and Experiences during Implementation of Solar PV-Diesel Hybrid Systems: The case of Remote Villages in Central China Gansu, 2008

⁷²¹ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

⁷²² Roth-Deblon A. and Mitra I., PV-Wind Hybrid Power on the Roof of the World, 2008

⁷²³ Ortiz B. et al., Sustainable RE Projects for Intelligent Rural Electrification in Laos, 2010

⁷²⁴ Schroeter A. and Martin S., Profitable and affordable energy services for remote areas in Lao PDR: Private – Public Partnership as mutual leverage for Hybrid Village Grids in areas off the national grid, 2008

⁷²⁵ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

⁷²⁶ Konings P. et al., PV Mini-Grids for Yap State: Sustainable design for remote Pacific islands, 2008

⁷²⁷ Bhandari R., Role of Grids for Electricity and Water Supply with Decreasing Costs for Photovoltaics, 2010

⁷²⁸ Perlot G. and Mostafa M., YOUNICOS Company Overview, 2009

⁷²⁹ Walter J. et al., A Trail PV Mini-Grid Installation for Small Islands, 2008

⁷³⁰ Shrestha G. et al., Case Studies of PV-Diesel Hybrid Systems in Operation in Rural Asia: Experiences and Conclusions from China, Thailand and Vietnam, 2008

Vanuatu			⁷³²
Vietnam			⁷³³
Europe			
Azores			^{734,735}
Spain	270 – 4,200		^{736,737,738}
Sweden	6,000		⁷³⁹
Scotland	6,300	0.23	⁷⁴⁰
Americas			
Brazil	320		^{741,742}
Ecuador	1,900		⁷⁴³
Peru	335		⁷⁴⁴
USA			⁷⁴⁵

Table 3.4-3: Examples for existing and proposed hybrid PV-(Wind-Battery)-Diesel systems in the world. Many of the mentioned installations are part of a local mini-grid.

European educated engineers typically advice the construction of mini-grids due to their scalability to higher loads and AC voltage design. Nevertheless, this approach might be oversized for the very poor people in the world. The upfront costs of such a system are typically out of scope of financing for a local community. Capex for grid related investments are typically in the order 600 € - 1000 € per dwelling ⁷⁴⁶ but can also reach 1,500 € - 4,000 € ⁷⁴⁷, i.e. a substantial electricity consumption per year and user is an integral prerequisite for acceptable mini-grid economics. In the case of Ethiopia (section 3.4.1.1) the annual electricity consumption of a typical family is about 13 kWh. Typical PV based mini-grids are designed for an annual electricity consumption of 100 kWh – 500 kWh per user which is equivalent to LCOE of about 0.40 - 0.80 €/kWh as shown in Table 3.4-3. These costs are by a factor of two to four higher than electricity provided by the grid (sub-chapter 3.3), but might be justified due to no cost for the capital intensive grid extension. Thus, economy of mini-grids also depends on the distance to the electricity grid. Solar home systems are a much better start for the poorest, due to the fact that their economics are excellent (section 3.4.1). However, increasing electricity demand of SHS powered villages might result in the need for a local mini-grid, for the case of no connection to the national grid. The transformation of local power supply from SHS to a PV based mini-grid might be an appropriate solution ⁷⁴⁸

⁷³¹ Ketjoy N. et al., First Year Investigation of PV Mini Grid System in Chiangria Province of Thailand, 2004

⁷³² Mohns W. and Stein D., Community Powerhouse: A Rural Electrification Model for Vanuatu, 2008

⁷³³ Shrestha G. et al., Case Studies of PV-Diesel Hybrid Systems in Operation in Rural Asia: Experiences and Conclusions from China, Thailand and Vietnam, 2008

⁷³⁴ Perlot G. and Mostafa M., Younicos Company Overview, 2009

⁷³⁵ Sollmann D., Eine Insel mit drei Akkus, 2009

⁷³⁶ Müller M., Sustainable operation experience in PV-Hybrid Systems, 2008

⁷³⁷ Vallvé X. et al., First Experiences From the Electrification of Rural Villages in Spain with Multi-User Solar Hybrid Grids, 2001

⁷³⁸ Vossler I. et al., PV Hybrid Village Electrification in Spain: 6 Years Experience with MSG (Multi-User Solar Hybrid Grids), 2004

⁷³⁹ Fiedler F. et al., PV-Wind hybrid Systems for Swedish Locations, 2008

⁷⁴⁰ Thim F. et al., Conception and Operation of a Unique Large-Scale PV Hybrid System on a Hebridean Island, 2010

⁷⁴¹ Borges Neto M.R. et al. Biogas/PV hybrid power system for decentralized energy supply of rural areas, 2010

⁷⁴² Pinho J. T. et al., Wind-PV-diesel hybrid system for the electrification of the village of São Tomé – municipality of Maracana – Brazil, 2004

⁷⁴³ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

⁷⁴⁴ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

⁷⁴⁵ Martin G. and Kroposki B., Assessment of Photovoltaic Hybrid Power Systems in the Unites States, 2010

⁷⁴⁶ Munoz J. et al., Experience With PV-diesel Hybrid Village Power Systems in Southern Morocco, 2007

⁷⁴⁷ Gabler H., Photovoltaik zur netzfernen Elektrifizierung, 2008

⁷⁴⁸ Peterschmidt N. et al., Taking the step from Solar-Home-Systems to Micro-Grids, 2008

and after connection to the national grid the already installed SHS could be used as backup systems in case of grid failures⁷⁴⁹.

Several hybrid PV systems in Table 3.4-3 consist of further renewable energy technologies, like hydro power or biogas^{750,751}, but mainly hybrid PV-Wind-Battery-Diesel systems are in operation in case of sufficient wind resource. The fundamental reason are the better economics, due to lower LCOE for hybrid PV-Wind systems (plus batteries and Diesel generators) compared to hybrid PV-alone or hybrid Wind-alone systems for average conditions.^{752,753} Least cost system type in dependence of wind resource, solar resource and diesel price is depicted in Figure 3.4-10 being calculated by using the Software Homer⁷⁵⁴. In case of excellent wind conditions a hybrid Wind-Battery-Diesel systems is least cost option, whereas a PV-Battery-Diesel system is least cost system for excellent solar resource but weak wind conditions. In case of high diesel prices, least energy cost option for good wind conditions and good solar resource would be a hybrid PV-Wind-Battery system. Summary of relevant criteria for hybrid solar-wind generation projects is given by Chen et al.⁷⁵⁵.

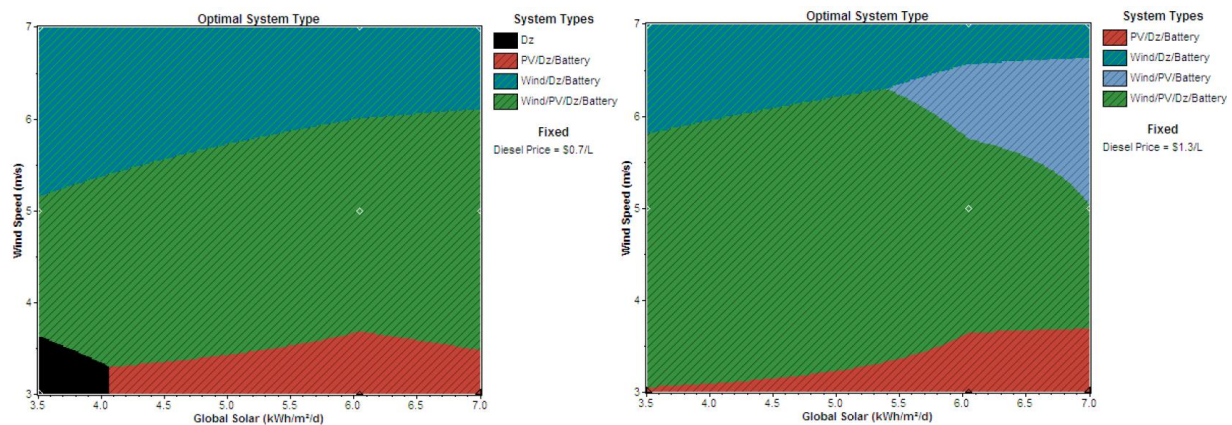


Figure 3.4-10: Optimal system type at different natural conditions with fixed diesel price of about 0.55 €/l (left) and about 1.00 €/l (right).⁷⁵⁶ Diesel prices of 0.55 €/l and 1.00 €/l equal crude oil prices of about 85 USD/barrel and 155 USD/barrel (Fig. 3.4-15), respectively, without any taxation and excluding typical 50% distribution cost in rural areas of developing countries, i.e. real equivalent would be rather 55 USD/barrel and 105 USD/barrel. Abbreviation stands for: diesel (Dz). Key assumptions are genset Capex of 310 €/kW, small wind turbine Capex of 1,630 €/kW, PV Capex of 2,170 €/Wp, battery Capex of 175 €/kW and converter Capex of 1,110 €/kW.

Figure 3.4-10 demonstrates that a power system only fed by diesel generator (Dz) is only cost competitive when the wind conditions are below 3.4 m/s, or with an insolation under 1,500 kWh/m²/y (4.1 kWh/m²/day). These two values are in accordance with the ones given by manufacturers and project developers around the world about the minimum natural conditions for their technologies to be feasible. In the case of small wind energy, the explanation is that the cut-in speed is normally around 3.5 m/s. This is a minimum value for specific wind speed at specific time (wind must blow at a minimum speed of 3.5 m/s for the

⁷⁴⁹ Adelmann P., Wireless Power, 2009

⁷⁵⁰ Borges Neto M.R. et al., Biogas/photovoltaic hybrid power system for decentralized energy supply of rural areas, 2010

⁷⁵¹ Rana S. et al., Optimal Mix of Renewable Energy Resources to Meet the Electrical Energy Demand in Villages of Madhya Pradesh, 1998

⁷⁵² Fiedler F. et al., PV-Wind hybrid Systems for Swedish Locations, 2008

⁷⁵³ Nandi S.K. and Ghosh H.R., A wind-PV-battery hybrid power system at Sitakunda in Bangladesh, 2009

⁷⁵⁴ Lilienthal P., The HOMER® Micropower Optimization Model, 2004

⁷⁵⁵ Chen H.H. et al., Strategic selection of suitable projects for hybrid solar-wind power generation systems, 2010

⁷⁵⁶ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

turbine to produce electricity). The graph in the right has been calculated to factor in higher diesel prices. The depicted situation of a diesel price of 1.0 €/l is valid for several developing countries, in particular for higher priced rural areas (Fig. 3.4-5). The diesel price in Figure 3.4-10 in the right is assumed to be about 1.0 €/l. At this price a diesel mini-grid is never the least cost option. From 0.75 €/l onwards, a power system that runs only on diesel is never cost competitive. This graph raises another significant point. If the wind conditions and insolation are high enough, as shown in the light blue area, the system does not require the use of a diesel generator to be the least cost option. However, at really high wind speeds, it is more economical not to use PV and to rely on diesel for the periods when wind is not available. This has been the result due to the higher capital cost of PV in the underlying assumptions, which might not be the case anymore (Table 3.2-1).

Access to fresh water is even more important than to electricity, due to being one of life's basic needs. In many off-grid villages no improved water supply is available or daily ways to fresh water sources are long. Solar-powered water pumps save hours of labour daily in rural off-grid areas, where water hauling is traditionally done by hand by women and children. These pumps are durable and immune to fuel shortages.⁷⁵⁷ In most regions, these solar-powered water pumps cost less than diesel-powered generators. Aforementioned local conditions led to the coupling of water pumping and desalination systems to PV-only but typically hybrid PV systems (Fig. 3.4-11).^{758,759,760,761,762} An excellent overview on PV powered reverse osmosis (RO) desalination systems in operation (Fig. 3.4-12) and used technology components is given by Ghermandi and Messalem⁷⁶³ and a good overview on solar desalination systems is given by Kalogirou⁷⁶⁴.

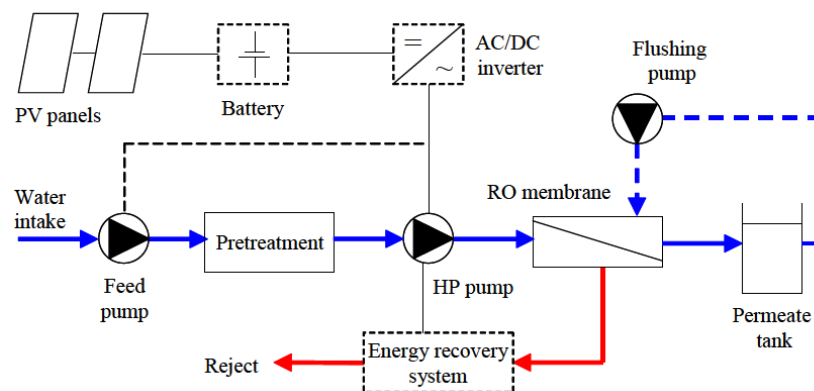


Figure 3.4-11: General design scheme of a PV-reverse osmosis (RO) desalination plant.⁷⁶⁵ Dashed lines identify components and connections that may be absent.

Typical PV-RO desalination systems are in the range of 5 - 20 m³ desalinated potable water for cost of about 7 - 9 USD/m³ and PV system sizes of about 5 - 50 kWp. The specific energy

⁷⁵⁷ IEA, World Energy Outlook 2010, 2010, p. 255

⁷⁵⁸ Papadakis G. et al., Hybrid Renewable Energy Systems for the Supply of Services in Rural Settlements of Mediterranean Partner Countries – The Case Study of the Hybrid System – Microgrid in Egypt, 2010

⁷⁵⁹ Kershman S.A. et al., Hybrid wind/PV and conventional power for desalination in Libya – GECOL's facility for medium and small scale research at Ras Ejder, 2005

⁷⁶⁰ Narvarte L. and Lorenzo E., Sustainability of PV water pipping programmes: 12-years of successful experience, 2010

⁷⁶¹ Fraidenraich N. and Vilela O.C., Dynamic Behaviour of Water Wells Coupled to PV Pumping Systems, 2007

⁷⁶² Mayer O. et al., Photovoltaic Powered Water Purification – Bringing Water to Remote Areas, 2008

⁷⁶³ Ghermandi A. and Messalem R., Solar-driven desalination with reverse osmosis: the state of the art, 2009

⁷⁶⁴ Kalogirou S.A., Solar Energy Engineering – Processes and Systems, 2009, pp. 421-468

⁷⁶⁵ Ghermandi A. and Messalem R., Solar-driven desalination with reverse osmosis: the state of the art, 2009

consumption in PV-RO desalination is comparable to that of conventional RO desalination, which ranges from roughly less than 1 - 7 kWh/m³ for salinities between 1,000 and 45,000 mg/l.

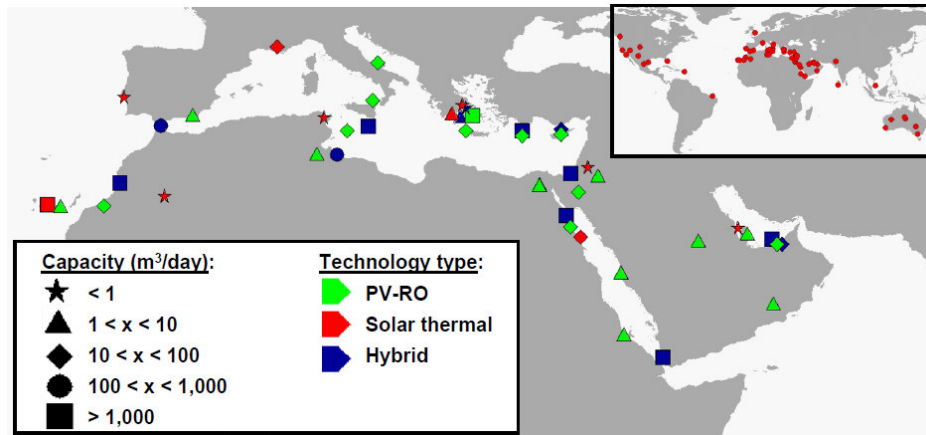
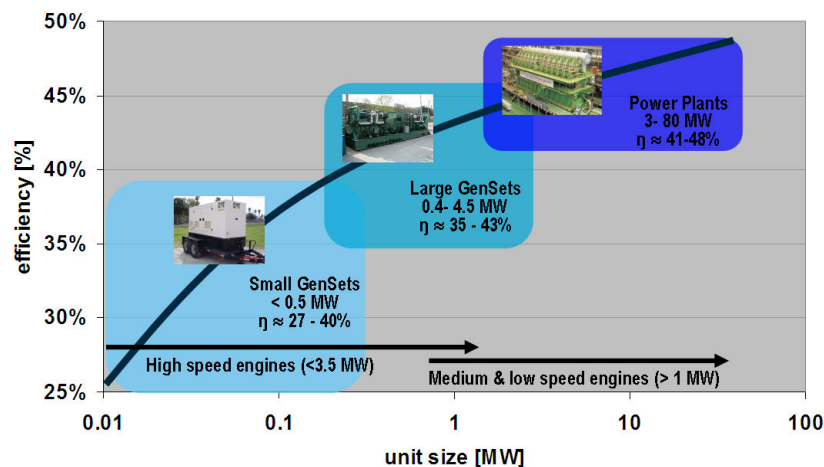


Figure 3.4-12: Solar-driven reverse osmosis (RO) desalination systems: geographical distribution and type in Mediterranean and MENA countries but also worldwide.⁷⁶⁶

3.4.2.2 Hybrid PV-Diesel and PV-Storage Systems

Fossil fuel based electricity generation ranges from small diesel gensets, larger heavy fuel oil fired generators, natural gas power plants (Fig. 3.4-13 and 3.4-14) to coal power plants, all of them can be operated in combination with PV systems of respective size. In this section the smaller hybrid PV systems are focussed, whereas the larger hybrid PV power plants are discussed in much detail in chapters 6 and 7. In the year 2008, the global annual new ordered diesel generator and natural gas power plant capacity was about 45 GW and 70 GW, respectively (Fig. 3.4-14). These generators and plants are sized between some kW and more than 100 MW and are used for stand-by, peaking and continuous operation (Fig. 3.4-14). Their efficiencies range between 30% - 50% (Fig. 3.4-13).



⁷⁶⁶ Ghermandi A. and Messalem R., Solar-driven desalination with reverse osmosis: the state of the art, 2009

Type	typical Size	Fuel Type	Efficiency Rate	Applications
Small Gensets (mobile)	< 500 kW	diesel	≈ 27-40%	backup, mini-grid
Large Gensets (container size)	400kW – 4.5 MW	diesel, heat oil heavy fuel oil	≈ 35-43%	island grid, backup, peak load
Power Plants	3.0 - 85 MW	heavy fuel oil (crude oil, waste)	≈ 41-47%	peak load, base load

Figure 3.4-13: Efficiency dependence of diesel and heavy fuel oil (HFO) generators and power plants on unit size. Data are taken from Wärtsilä⁷⁶⁷ and Hyundai Heavy Industries⁷⁶⁸.

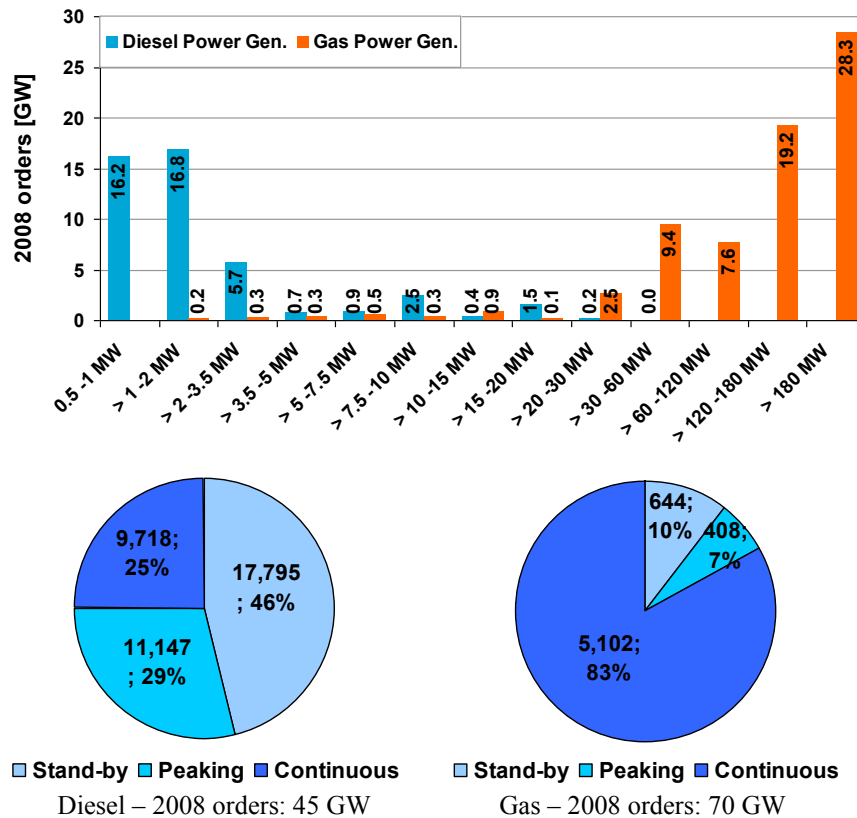


Figure 3.4-14: Global market distribution of diesel and natural gas power generation in unit size (top) and operation modus (bottom). Diesel generators are typically used up to 3.5 MW plant size, natural gas power plants are typically sized 30 MW and larger, whereas unit sizes in between do not show special fuel preferences. Natural gas power plants are used mainly for continuous operation. Diesel generators are used for continuous, peaking and stand-by operation. Data are taken from Diesel & Gas Turbine Worldwide⁷⁶⁹.

Price trends of fossil fuels are driven by increasing global demand and diminishing resources (sub-chapter 1.3), which create pressure for steadily escalating prices. Contrary trend for PV power plants is generated by constantly decreasing LCOE driven by high PV industry growth rates (Fig. 3.1-1). Intersection of these fundamental trends is defined as total plant fuel-parity and fuel-only fuel-parity. Total plant cost comprises all cost components, i.e. capital cost, operational expenditures (Opex), fuel cost and emission cost in case of charge. Fuel-only fuel-parity is defined as cost parity of PV LCOE and the fuel-only fraction of power plant LCOE, i.e. fuel-parity is the strictest measure for PV power plant economics.

⁷⁶⁷ Wärtsilä, Oil Power Plants, 2009

⁷⁶⁸ Hyundai Heavy Industries, Engine & Machinery Division, 2009

⁷⁶⁹ Diesel & Gas Turbine Worldwide, 2008 32nd Power Generation Order Survey, 2008

The main result of fuel-parity analysis is already achieved competitiveness of PV systems to diesel generators in many regions of the world for fuel and cost saving (Fig. 3.4-16 and 3.4-17) as well as in some regions for full substitution (Fig. 3.4-18). Based on crude oil prices of about 80 USD/barrel respective diesel prices are dependent on taxation between 0.72 - 1.70 USD/l (Fig. 3.4-15). These diesel prices equal LCOE of diesel generator of about 0.16 - 0.34 €/kWh_{el}.

Fossil fuels based on crude oil, e.g. heavy fuel oil and diesel, are closely coupled on the crude oil price (Fig. 3.4-15) and are common fuels for electricity generation by diesel generators and oil power plants (Fig. 3.4-13 and 3.4-14). These oil based prices are typically used for taxation or subsidization to either finance national budget or guarantee low and stable energy prices. Energy subsidies might be very harmful for respective countries, as sustainable and low cost renewable energy technologies are artificial hindered from fast market diffusion and national budget might be stressed by fast increasing fossil fuel prices.

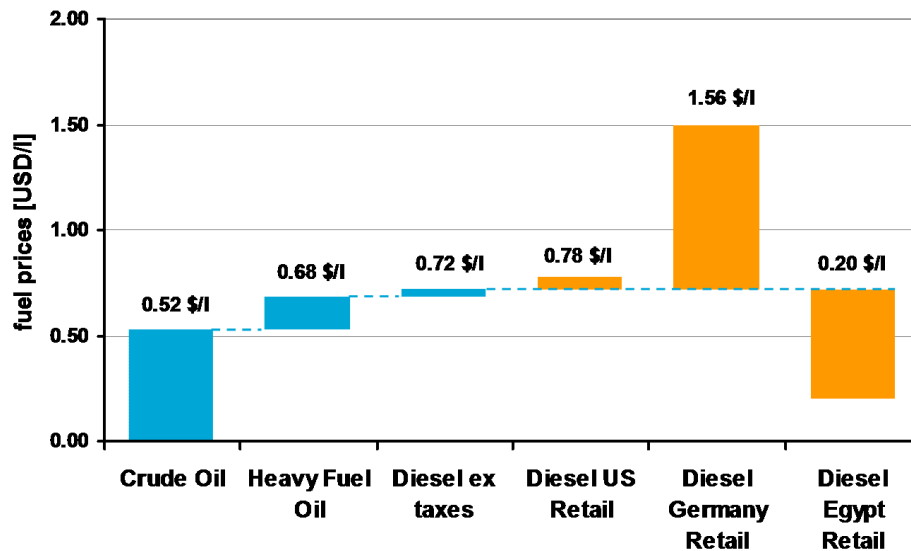


Figure 3.4-15: Cost structure of oil fuels. Prices for oil fuels are mainly driven by crude oil price, assumed to be approximately 80 USD/barrel, plus taxation minus subsidization. Maximum diesel prices of up to 1.70 USD/l have to be paid in some regions in the world.^{770,771,772} Note, in April 2011 the diesel price in Germany had been about 2.10 USD/l and the respective crude oil price had been about 120 USD/barrel.

LCOE of today's PV systems range for annual irradiation on fixed optimally tilted module surface of 1,400 and 2,400 kWh/m²/y (Fig. 2.2-3) between 0.29 and 0.09 €/kWh, respectively (Fig. 3.4-16). LCOE of PV systems in the year 2020 might range between 0.05 and 0.14 €/kWh for comparable irradiation. This translates to an equivalent LCOE range of diesel generators for crude oil prices of 30 to 100 USD/barrel.

⁷⁷⁰ Ebert S. et al., International Fuel Prices 2009 6th Edition, 2009

⁷⁷¹ EIA, Gasoline and Diesel Fuel Update, 2009

⁷⁷² <http://navigatemarket.ru/bunker/0>

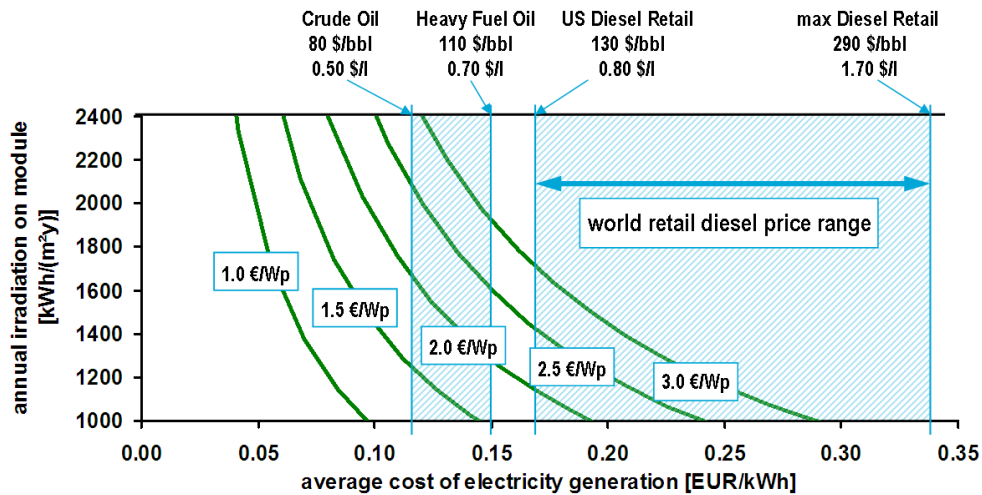


Figure 3.4-16: Levelized cost of electricity (LCOE) for diesel generators and PV systems dependent on irradiation. Prices for oil fuels are mainly driven by crude oil price, assumed to be about 80 USD/barrel, plus taxation (Fig. 3.4-15). PV systems of today's and near future cost structure are competitive to LCOE of oil gensets. Assumptions for PV LCOE are capital expenditures (Capex) as indicated, weighted average cost of capital (WACC) of 6.4%, lifetime of 25 years, operation and maintenance cost (Opex) of 1.5% of PV Capex and performance ratio of 75%. Assumptions for diesel generator LCOE are Capex of 786 €/kW, WACC of 6.4%, lifetime of 25 years, fixed Opex of 40 €/kW, full load hours comparable to PV systems, efficiency of 35%, energy density of diesel of 10 kWh_{th}/l and USD/€ exchange rate of 1.4 is applied.^{773,774}

PV can already serve as a fuel and cost saving energy technology in many regions in the world in respective off- and on-grid hybrid PV-Diesel systems (Fig. 3.4-17). Hybrid PV-Diesel based mini-grids (section 3.4.2.1) would benefit by lower total LCOE, as diesel would be only needed for backup purposes. Hybrid PV-Diesel stand alone systems would be operated as many hours during sunshine hours and use might be restricted in the other time due to high fuel-only LCOE of the diesel component.

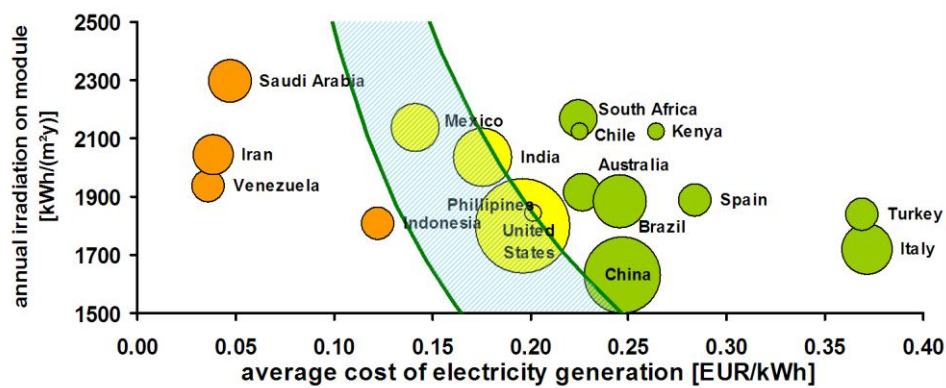


Figure 3.4-17: Competitiveness of PV systems for fuel saving of diesel generators excluding storage in the year 2010. Countries are rated by their population weighted solar irradiation (section 2.3.1) and electricity cost by diesel generators based on local diesel prices (Fig. 3.4-5). The entire electricity market volume is indicated by the size of the respective circle. Levelized cost of electricity (LCOE) of today's PV systems is very competitive for fuel saving in many regions in the world. Assumptions for PV LCOE are capital expenditures (Capex) between 2 - 3 €/Wp as indicated, weighted average cost of capital (WACC) of 6.4%, lifetime of 25 years, operation and maintenance cost (Opex) of 1.5% of PV Capex and performance ratio of 75%. Assumptions for

⁷⁷³ EC, Second Strategic Energy Review: Energy Sources, Production Costs and Performance of Technologies, for Power Generation, Heating and Transport, 2008

⁷⁷⁴ Breyer Ch. et al., Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, 2010e

diesel generator LCOE are Capex of 786 €/kW, WACC of 6.4%, lifetime of 25 years, fixed Opex of 40 €/kW, full load hours comparable to PV systems, efficiency of 35%, energy density of diesel of 10 kWh_{th}/l and USD/€ exchange rate of 1.4 is applied.^{775,776}

In several countries a PV-storage solution can replace existing diesel generators for economic reasons (Fig. 3.4-18). In the world 1.4 billion people have no access to electricity (Fig. 1.4-1 and 3.4-1). Most of them live in sunny regions (Fig. 3.4-2), hence off-grid PV-storage solutions are very likely to be among the least cost electricity options for them in particular in rural areas in developing countries. In case of additional very good local wind resources, hybrid PV-Wind-storage solutions might be the most optimised system design (Fig. 3.4-10). The global residential off-grid PV-storage market potential for two third of these 1.4 billion people can be estimated on basis of small PV applications like pico and solar home systems to about 8 GW which corresponds to about 80 - 90 bn€ being economically fully accessible today (section 3.4.1.1). Another third might be most economically electrified by mini-grids. The market potential of these mini-grids can be very roughly estimated by assuming an average population weighted irradiation of 1,800 kWh/m²/y, local performance ratio of 0.75, average annual electricity consumption per household of 300 kWh, average storage cycle efficiency of 0.8 and ratio of direct consumption to storage of 1:1. This translates to about 250 Wp per household PV capacity leading to an aggregated total demand of about 16 - 17 GWp assuming an average family size of seven family members per household. Average mini-grid Capex are assumed to be about 8 €/Wp, composed by the PV system, other renewable, the grid, an optional diesel genset and storage. Thus, the residential mini-grid market potential can be derived to about 130 bn€. The rough estimated total residential off-grid market potential might be about 25 GW in power and 220 bn€ in sales. The entire off-grid market might be three times this numbers due to the typical ratio of residential to total final electricity consumption of on third. These numbers do not include market potential of hybrid PV-diesel generators or PV-storage solutions in emerging countries currently often relying on diesel gensets in rural regions. On basis of fundamental cost trends and already achieved competitiveness of such new PV applications (Fig. 3.4-18) a sustainable market potential can be estimated to be in the range of several hundred bn€. This economic driven market potential will significantly grow in the years to come.

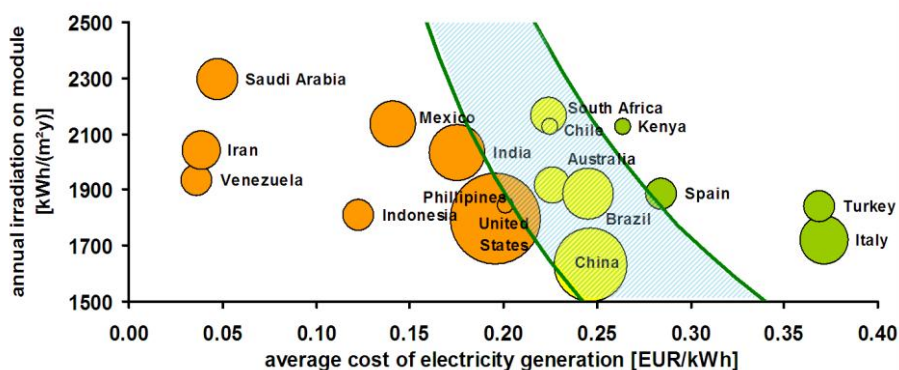


Figure 3.4-18: Competitiveness of PV-Storage systems for fuel saving of diesel generators for complete replacement of diesel generators including storage in the year 2010. Countries are rated by their population weighted solar irradiation (section 2.3.1) and electricity cost by diesel generators based on local diesel prices (Fig. 3.4-5). The entire electricity market volume is indicated by the size of the respective circle. LCOE of today's PV systems is very competitive for fuel saving in many regions in the world. Full competitiveness of PV systems including electric storage solutions, e.g. redox-flow battery storage, is achieved in first markets in the

⁷⁷⁵ EC, Second Strategic Energy Review: Energy Sources, Production Costs and Performance of Technologies, for Power Generation, Heating and Transport, 2008

⁷⁷⁶ Breyer Ch. et al., Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, 2010e

world. Assumptions for PV LCOE are Capex between 2 - 3 €/Wp as indicated, WACC of 6.4%, lifetime of 25 years, Opex of 1.5% of PV Capex and performance ratio of 75%. Assumptions for diesel generator LCOE are Capex of 786 €/kW, WACC of 6.4%, lifetime of 25 years, fixed Opex of 40 €/kW, full load hours comparable to PV systems, efficiency of 35%, energy density of diesel of 10 kWh_{th}/l and USD/€ exchange rate of 1.4 is applied.^{777,778} Assumptions for redox-flow storage systems are Capex for power unit of 150 USD/kW, Capex for energy unit of 150 USD/kWh, WACC of 6.4%, lifetime of 10 years, Opex of 10% of Capex, full cycle storage efficiency of 73%, direct electricity supply by PV unit of 50%, electricity supply by storage unit of 50% and storage size of 150% of annual solar mean day conditions.^{779, 780}

Summing up, the results of the section 3.4.2 for the less poor fraction of the 1.4 billion people without access to electricity the various forms of PV based hybrid power systems represent a fast growing economic alternative to stand-alone diesel systems. This includes all different electricity based energy services, like end-user electricity consumption, water pumping, desalination, telecommunication and other public services. For both good local solar and wind resource availability hybrid PV-Wind systems are a good choice, whereas for high diesel prices a full renewable hybrid system based on balancing storage capacities might be the least cost electricity solution, at all.

⁷⁷⁷ EC, Second Strategic Energy Review: Energy Sources, Production Costs and Performance of Technologies, for Power Generation, Heating and Transport, 2008

⁷⁷⁸ Breyer Ch. et al., Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, 2010e

⁷⁷⁹ Schoenung S.M. and Hassenzahl W.V., Long- vs short-term energy storage: Technologies analysis - A life-cycle cost study, 2003

⁷⁸⁰ Vetter M. et al., Redox flow batteries – Already an alternative storage solution for hybrid PV mini-grids?, 2010

Chapter 4

Solar Thermal and Wind Power Plant Economics

Economics of PV systems discussed in chapter 3 need to be assessed by relative economics in comparison to other renewable power technologies. In this thesis PV is focussed but for evaluating relative significance both **solar thermal electricity generation** (STEG) (sub-chapter 4.1) and **wind power** (sub-chapter 4.2) are analysed in more detail. These two renewable power technologies could be very competitive to PV but also complementary, as a consequence of respective economics, technological characteristics and resource availability. Furthermore, PV, STEG and wind power show by far the highest supply potentials of all renewable energy technologies. An **integrated economic assessment of PV, STEG and wind power plants** concludes this chapter (sub-chapter 4.3).

The other renewable power technologies are discussed briefly in chapters 5 and 7 in the context of this thesis.

4.1 Solar Thermal Electricity Generation

Special perspective is given in this sub-chapter to the direct normal solar resource (section 4.1.1), how this resource is used for power conversion in plants for solar thermal electricity generation (STEG) (section 4.1.2) and the resulting STEG economics (section 4.1.3). A general overview on the broad field of STEG technology is given by Pitz-Paal ^{1,2}, Trieb ^{3,4}, Duffie and Beckmann ⁵, Kalogirou ⁶, Quaschnig ⁷, Kaltschmitt et al. ⁸, Schölkopf ⁹, Konstantin ¹⁰ and IEA ¹¹.

4.1.1 STEG Resource

STEG plants concentrate incident irradiation in a focal line or focal point by a concentration factor of 25 - 3,000 depending on specific technology.¹² Therefore solar resource for STEG plants is direct normal irradiation (DNI) identical to that of 2-axes concentrating continuous tracking PV systems (section 2.2.9). All relevant data on DNI have been discussed in section 2.2.9 and global DNI resource map is depicted in Figure 2.2-27. Due to economic considerations, acceptable DNI quality is typically assumed to be about 2,000 kWh/m²/y ¹³ and should be not lower than 1,700 kWh/m²/y. Figure 4.1-1 illustrates the regions in the world

¹ Pitz-Paal R., Solarthermische Kraftwerke: Wie die Sonne ins Kraftwerk kommt, 2007

² Pitz-Paal R. et al., Ecostar – European Concentrated Solar Thermal Road-Mapping, 2004

³ Trieb F. et al., SOKRATES – Solarthermische Kraftwerkstechnologie für den Schutz des Erdklimas, 2004

⁴ Müller-Steinhagen H. and Trieb F., Concentrating solar power: A review of the technology, 2004

⁵ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

⁶ Kalogirou S.A., Solar Energy Engineering – Processes and Systems, 2009

⁷ Quaschnig V., Regenerative Energiesysteme: Technologie – Berechnung – Simulation, 2007, p. 119-148

⁸ Kaltschmitt M. et al., Erneuerbare Energien, 2006, p. 607-643

⁹ Schölkopf W., Solarthermie, 2002, p. 290-316

¹⁰ Konstantin P., Praxisbuch Energiewirtschaft, 2009, p. 303-312

¹¹ IEA, Technology Roadmap: Concentrating Solar Power, 2010

¹² Müller-Steinhagen H. and Trieb F., Concentrating solar power: A review of the technology, 2004

¹³ Trieb F. et al., Concentrating Solar Power for the Mediterranean Region, 2005, p. 61

of at least 1,700 kWh/m²/y DNI. Best regions in the world for STEG plants are in or next to deserts.

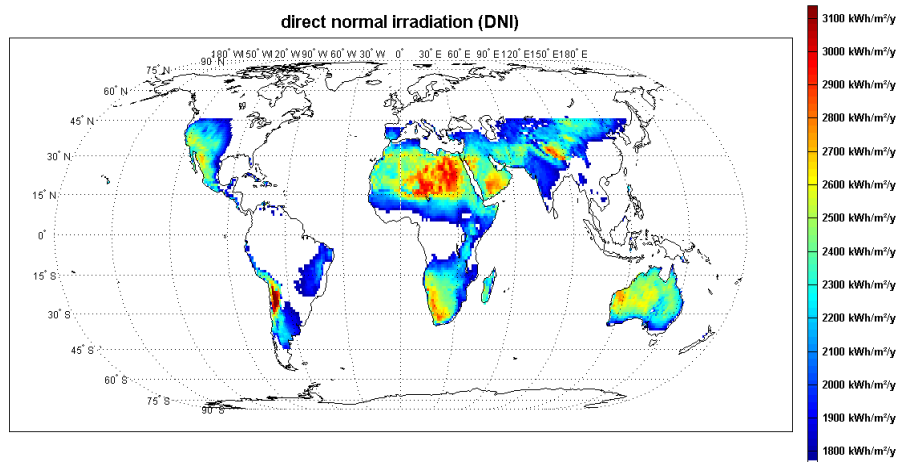


Figure 4.1-1: Annual utilisable irradiation on aperture area of solar thermal electricity generation plants for regions of at least 1,700 kWh/m²/y. Every coordinate of a 1°x1° mesh of latitude and longitude within 65°S and 65°N is separately optimised for maximum annual irradiation on aperture area (section 2.2.9). This solar resource is identical to direct normal irradiation (DNI). HDKR model is performed by calculating each month of the year for maximum annual irradiation (section 2.2.2).

4.1.2 STEG Plants

Overview on STEG market development is handled very briefly here in contrast to other power technologies (chapter 5). This is caused simply, as there have been nearly no markets for STEG plants so far. By early 2009, about 500 MW STEG plants have been installed (Table 5.1-1) – in the entire history of STEG plants. There had been less than 400 MW STEG plants commissioned in the US in 1980s and early 1990s. After a break of almost two decades new plants have been built in Spain and the US. Currently, about 22 GW STEG plants are in planning, construction and commissioning phase.¹⁴

A detailed description of converting solar resource to electric power would exceed the focus of this thesis. However this has already been summarized by the author elsewhere¹⁵ and is mainly based on Kistner¹⁶, Trieb et al.¹⁷, Duffie and Beckmann¹⁸, Pitz-Paal¹⁹, Kleemann and Meliß²⁰, Quaschnig et al.²¹, Cohen et al.²² and Price et al.²³.

¹⁴ Bullard N., Global STEG market overview 2011 – charging the steam lines, 2010

¹⁵ Breyer Ch., Concentrating Solar Power – Global Potential and Application in the UAE, 2007, p. 41-77

¹⁶ Kistner R., Simulation of solar thermal power plants and their evaluation emphasising on energy economic issues and financing issues, 2003

¹⁷ Trieb F. et al., Sokrates-Projekt – Solarthermische Kraftwerkstechnologie für den Schutz des Erdklimas – AP 2.1 Modellbildung und -implementierung, 2004

¹⁸ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

¹⁹ Pitz-Paal R. et al., Ecostar – European Concentrated Solar Thermal Road-Mapping, 2004

²⁰ Kleemann M. and Meliß M., Regenerative Energiequellen, 1993

²¹ Quaschnig V. et al., Influence of Direct Normal Irradiance Variation on the Optimal Parabolic Trough Field Size: A Problem Solved with Technical and Economical Simulations, 2002

²² Cohen G. et al., Final Report on the Operation and Maintenance Improvement Program for CSP Plants, 1999

²³ Price H. et al., Advances in Parabolic Trough Solar Power Technology, 2002

Solar thermal power plants are fully dispatchable as thermal energy storage is an integral component. STEGs including thermal energy storage can be designed even for baseload operation depending on the size of the thermal storage. Structural design of a modular STEG plant is depicted in Figure 4.1-2. During daytime the solar field can directly power the electricity generating power block and further solar fields can be installed for charging thermal energy storage units. In periods of less irradiation and in particular in early morning, late afternoon and evening the storage units can be discharged hence feeding the power block for electricity generation. Multiples of the solar field for daytime operation are called solar multiples (SM) and consist of a solar field and a thermal energy storage unit. Standard daytime operation would be about six hours, therefore solar multiples are reasonable from one to four. Solar multiples enable power operation modes from fluctuation (SM1) to balancing (SM2) up to baseload (SM4). Solar multiples increase capital expenditures (Capex) of a STEG plant but decrease levelized cost of electricity (LCOE) and improve the value of power. In Spain, the largest STEG market in the world besides the US, the standard is a solar multiple of two.

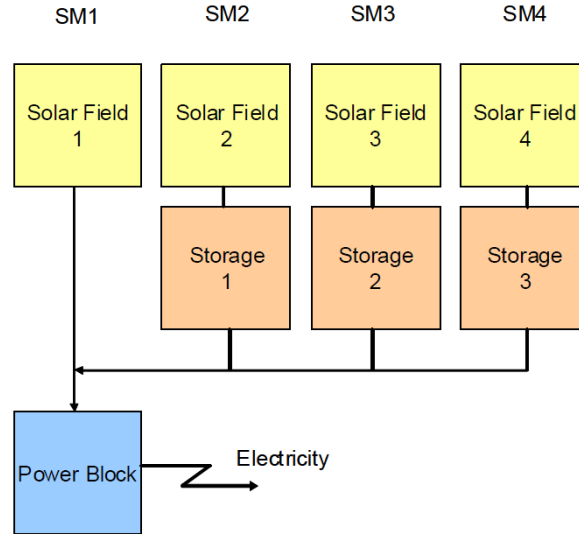


Figure 4.1-2: Definition of STEG plant configuration with different solar multiples (SM).²⁴

In the following a standardized empirical model for STEGs is used to derive full load hours (FLh) based on local DNI conditions.²⁵ The model is described by Trieb et al.²⁶ and assumes current most applied STEG technology, i.e. current parabolic trough technology with molten salt storage, steam cycle power block and dry cooling tower with an annual net solar electric efficiency of about 12%. Dependence on latitude has been neglected. Comparison with detailed data shows a good approximation for sites between 25° and 35° latitude and typical differences of $\pm 10\%$ for 0° latitude (underestimation) and for 40° latitude (overestimation), respectively. The simplified model does not consider possible differences of climate or latitude between sites with similar annual DNI, or performance differences between different CSP technologies and configurations. The accuracy is good enough for the purpose of comparing economics of technologies in this thesis. The model is summarized in Equation 4.1-1:

$$FLh_{STEG} = (2.5717 \cdot DNI + 694) \cdot (-0.0371 \cdot SM^2 + 0.4171 \cdot SM - 0.0744) \quad (\text{Eq. 4.1-1})$$

²⁴ Trieb F. et al., Global Potential of Concentrating Solar Power, 2009

²⁵ Trieb F. et al., Global Potential of Concentrating Solar Power, 2009

²⁶ Trieb F. et al., Global Potential of Concentrating Solar Power, 2009

Equation 4.1-1: STEG performance model.²⁷ Abbreviations stand for: full load hours (*FLh*), solar thermal electricity generation (*STEG*), direct normal irradiation (*DNI*) and solar multiple (*SM*).

Full load hours of STEG plants are derived on basis of DNI resource (Fig. 2.2-27) and the STEG performance model (Eq. 4.1-1) and are illustrated in Figures 4.1-3 and 4.1-4 for the case of solar multiples one to four and efficiency standards assumed for the year 2010 and 2020, respectively. The increase in efficiency is very likely to improve in an evolutionary manner. However, there might be deviations in FLh between the modelled results shown here and the reality, but these deviations should be near to zero over the decade, in particular for the aggressive scenario setting introduced in Table 4.1-1 and for SM2 and SM3. The deviations should be typically within a range of $\pm 10\%$ and only under special circumstances within a range of $\pm 20\%$.

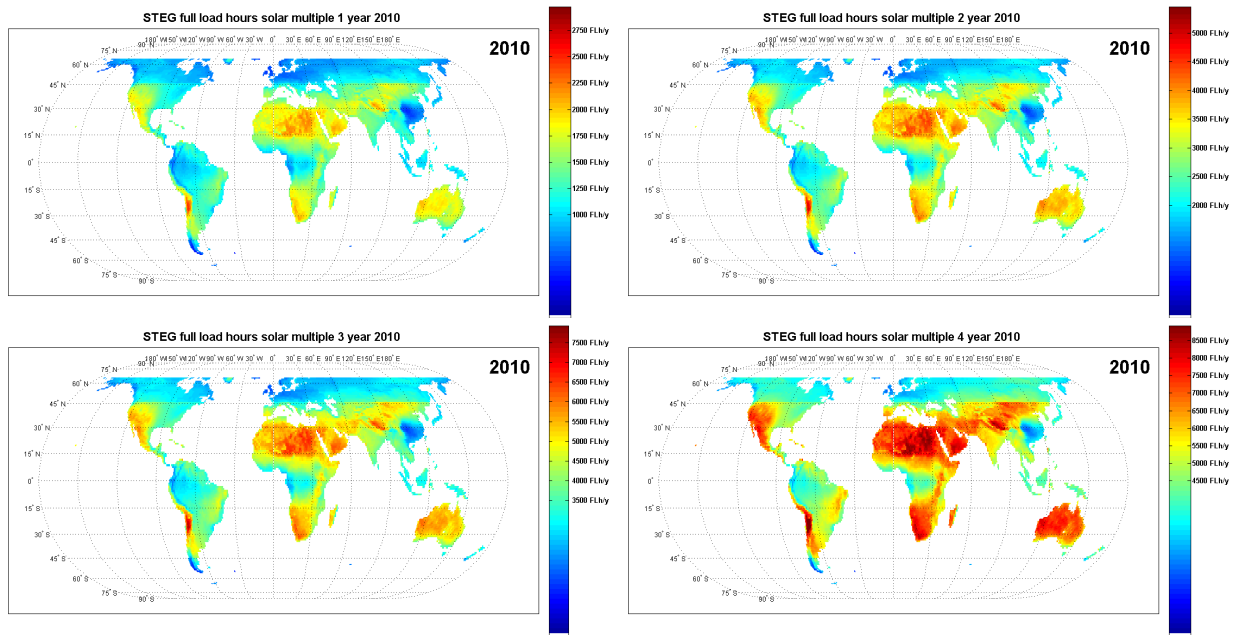
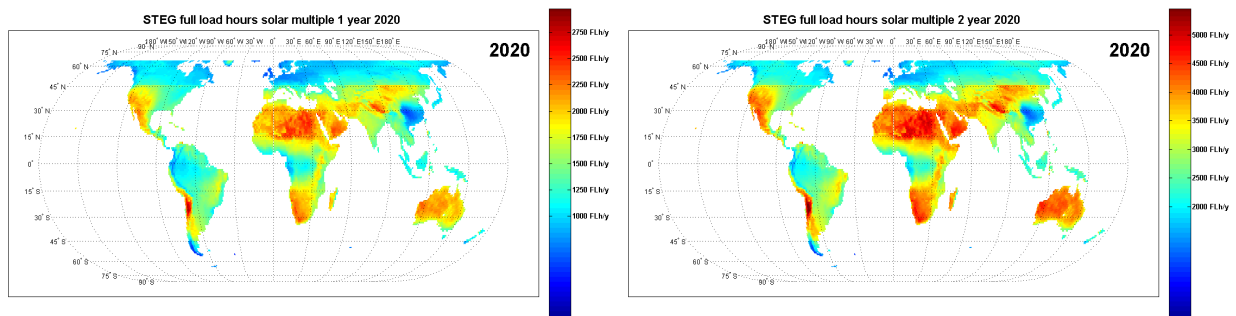


Figure 4.1-3: STEG full load hours for solar multiples of one to four for the efficiency standards of the year 2010. The efficiency standards are defined in Table 4.1-1.



²⁷ Trieb F. et al., Global Potential of Concentrating Solar Power, 2009

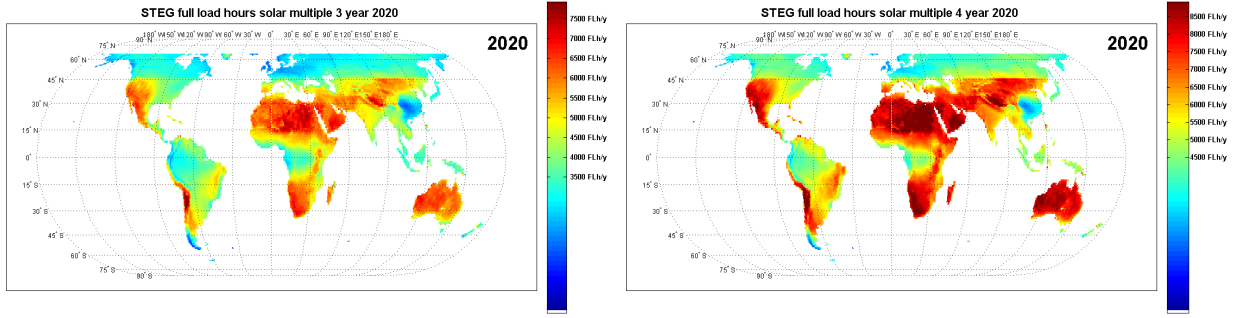


Figure 4.1-4: STEG full load hours for solar multiples of one to four for the efficiency standards of the year 2020. The efficiency standards are defined in Table 4.1-1.

Figures 4.1-3 and 4.1-4 visualise the power supply potential of STEGs being best suited in desert regions showing relative high full load hours. All major regions in the world are at least next to large areas of very good conditions for STEGs. Sahara desert is the by far largest region of excellent conditions for STEGs. Economics of STEG plants are analysed in the next section on basis of full load hours shown in this section.

4.1.3 STEG Economics

A cost model for STEG plants enables the calculation of solar thermal power levelized cost of electricity (LCOE) for all coordinates by applying local resource availability on basis of respective average annual full load hours (FLh) of STEG plants. These STEG FLh contain all relevant data of local DNI resource quality and are already adapted to typical commercially available STEG plants. Such derived STEG LCOE make it possible to compare STEG LCOE to LCOE of other renewable and conventional power plant technologies.

Methodology of calculating STEG LCOE is nearly identical to that of PV (sub-chapter 3.2 and Eqs. 3.2-1). Adjustments are needed for specific differences of STEG and PV, summarized in Equations 4.1-2:

$$LCOE = \frac{Capex \cdot crf + Opex}{FLh_{STEG}} \quad (\text{Eq. 4.1-2a})$$

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (\text{Eq. 4.1-2b})$$

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \quad (\text{Eq. 4.1-2c})$$

Equation 4.1-2: Levelized cost of electricity (LCOE) for STEG plants. Equations 4.1-2 are nearly identical to Equations 3.2-1, except annual full load hours of STEG plant which need to be used instead of final electric PV yield. Abbreviations stand for: capital expenditures (*Capex*), annual operation and maintenance expenditures (*Opex*), annuity factor (*crf*), annual full load hours of STEG plant (FLh_{STEG}), weighted average cost of capital (*WACC*), lifetime of STEG plant (*N*), equity (*E*), debt (*D*), return on equity (k_E) and cost of debt (k_D).

Scenario assumptions for calculating LCOE of STEG plants are summarized in Table 4.1-1. Three different scenario settings have been developed, which mainly differ in *Capex*, but also partly in financing conditions, assumptions of STEG industry growth rates and stability of learning rates. Main difference of the scenarios is a business-as-usual approach (realistic), tough competition, fast cost reduction and excellent bankable products (aggressive) and a scenario with very high competition and fast diffusion of new technologies but still bankable

products (breakthrough). Reality might be somewhere between realistic and aggressive scenario, maybe closer to the aggressive one.

		scenario realistic	scenario aggressive	scenario breakthrough
Capex_STEG_SM1	[€/kW]	3800	3400	3400
Capex_STEG_SMx	[€/kW]	2200	2000	2000
fin_RoE	[%]	12.0%	10.0%	10.0%
fin_interest	[%]	7.0%	6.0%	6.0%
fin_WACC	[%]	8.25%	6.80%	6.80%
fin_equityRatio	[%]	25%	20%	20%
plant_lifetime	[y]	30	30	30
plant_Opex_SM1	[€/kW/y]	160	160	140
plant_Opex_SMx	[€/kW/y]	140	140	120
plant_overall_efficiency	[%]	12%	12%	12%
ratio_FLh2DNI_2010	[%]	74%	74%	74%
ratio_FLh2DNI_2020	[%]	80%	84%	90%
capacity_cumulated_2009	[GW]	0.8	0.8	0.8
capacity_added_2009	[GW]	0.3	0.3	0.3
PR_STEG_2010-2015	[%]	90%	90%	85%
PR_STEG_2015-2020	[%]	90%	90%	90%
growth_rate_2010-2015	[%]	25%	30%	30%
growth_rate_2015-2020	[%]	25%	30%	30%

Table 4.1-1: Scenario assumptions for STEG plant economics. The three scenarios cover a business-as-usual approach (realistic), highly optimised value chain composition (aggressive) and very high competition and very fast technological evolution (breakthrough). Economic parameters are more cost than price oriented due to cost driven prices in competitive markets, which is the case for the STEG industry. Numbers mentioned are for STEG plants of multi-50 MW. Efficiency evolution is triggered by the change of the relative ratio of FLh to DNI. Methodology is identical to PV LCOE calculation (section 3.2.2.2 and Table 3.2-1). General parameters are set identical as far as possible or at least comparable to those of PV. Abbreviations stand for: capital expenditures (Capex), solar multiple (SM), operational expenditures (Opex), return on equity (RoE), weighted average cost of capital (WACC), full load hours (FLh), direct normal irradiation (DNI) and progress ratio (PR). Data are taken from various sources like European Climate Foundation ²⁸, Trieb et al. ²⁹, Pitz-Paal et al. ³⁰, Greenpeace ³¹, Greenpeace and ESTELA ³², Krewitt et al. ^{33,34}, Viebahn et al. ³⁵, Kost and Schlegl ³⁶, Prometheus ³⁷, Zweibel ³⁸, Delucchi and Jacobson ³⁹ and IEA ^{40,41}.

²⁸ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

²⁹ Trieb F. et al., Global Potential of Concentrating Solar Power, 2009

³⁰ Pitz-Paal R. et al., Ecostar – European Concentrated Solar Thermal Road-Mapping, 2004

³¹ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

³² Richter C. et al., Concentrating Solar Power: Global Outlook 09, 2009

³³ Krewitt W. et al., The 2°C scenario – A sustainable world energy perspective, 2007

³⁴ Krewitt W. et al., Energy [R]evolution 2008 – a sustainable world energy perspective, 2009

³⁵ Viebahn P. et al., The potential role of concentrated solar power (CSP) in Africa and Europe – A dynamic assessment of technology development cost development and life cycle inventories until 2050, 2010

³⁶ Kost C. and Schlegl T., Stromgestehungskosten Erneuerbare Energien, 2010

³⁷ Grama S. et al., Concentrating Solar Power -Technology, Cost, and Markets, 2008

³⁸ Zweibel K., Should solar photovoltaics be deployed sooner because of long operating life at low, predictable cost?, 2010

³⁹ Delucchi M.A. and Jacobson M.Z., Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies, 2011

⁴⁰ IEA, Technology Roadmap: Concentrating Solar Power, 2010

⁴¹ IEA, Energy Technology Perspectives 2010 – Scenarios and Strategies to 2050, 2010

Experience curve approach (section 3.1.2) is applied for Capex projection in the 2010s in the same way as for PV. However, learning rates for STEGs are significantly lower than those for PV. Fundamental reason might be the lower degree of modularity and scalability of STEG technology in comparison to PV, in particular for the conventional power block. Growth rates of STEG industry are high and comparable to PV, but slightly lower. These growth rates might be too high due to much longer project cycles and much higher hurdles of bankability. Outcome for the development of Capex is depicted in Figure 4.1-5 for the years 2010 – 2020. In case of STEG the relative industry dynamic is high but not on such an outstanding high level than PV mentioned before. Scenario assumptions for the realistic and aggressive case seem to be likely to a high degree, whereas the aggressive scenario should be used as the standard reference.

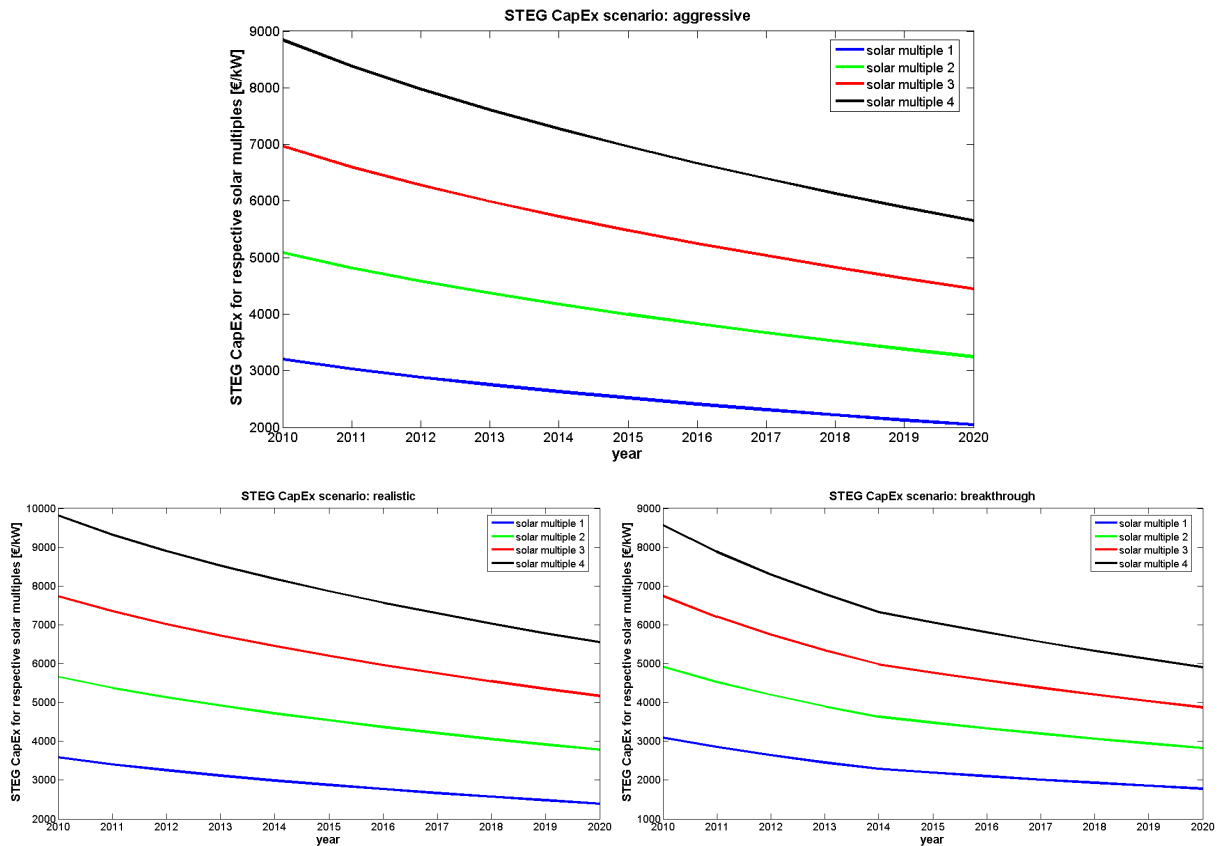


Figure 4.1-5: STEG plant Capex estimates in 2010s for the scenarios aggressive (top), realistic (bottom, left) and breakthrough (bottom, right) in dependence on solar multiples. The scenarios are defined in Table 4.1-1.

Full scenario assumptions defined in Table 4.1-1 lead to STEG LCOE illustrated in Figures 4.1-6 (SM2) and 4.1-7 (SM3) for the aggressive scenario and in Figures 4.1-8 (SM2) and 4.1-9 (SM3) for the breakthrough scenario. LCOE calculations based on Equations 4.1-2 are mainly driven by STEG Capex (Fig. 4.1-5) and local DNI resource availability (Fig. 4.1-1), which can be converted by STEG plants in electricity described by annual full load hours of a STEG plant (Fig. 4.1-3 and 4.1-4). In this thesis economic analyses including STEG plants are based on STEG LCOE depicted in Figures 4.1-6 to 4.1-9 based on assumptions in Table 4.1-1.

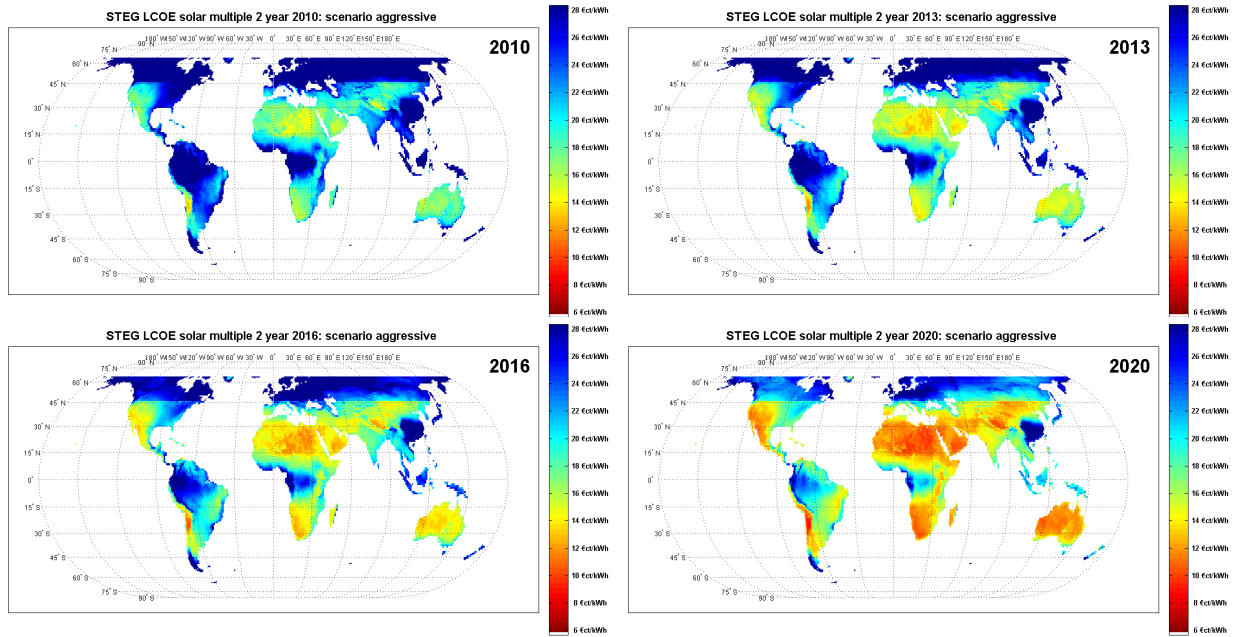


Figure 4.1-6: Global LCOE of STEG plants and a solar multiple of 2 in the 2010s for the aggressive scenario. DNI resource (Fig. 4.1-1) is applied for respective full load hours (Fig. 4.1-3 and 4.1-4). The aggressive scenario is defined in Table 4.1-1.

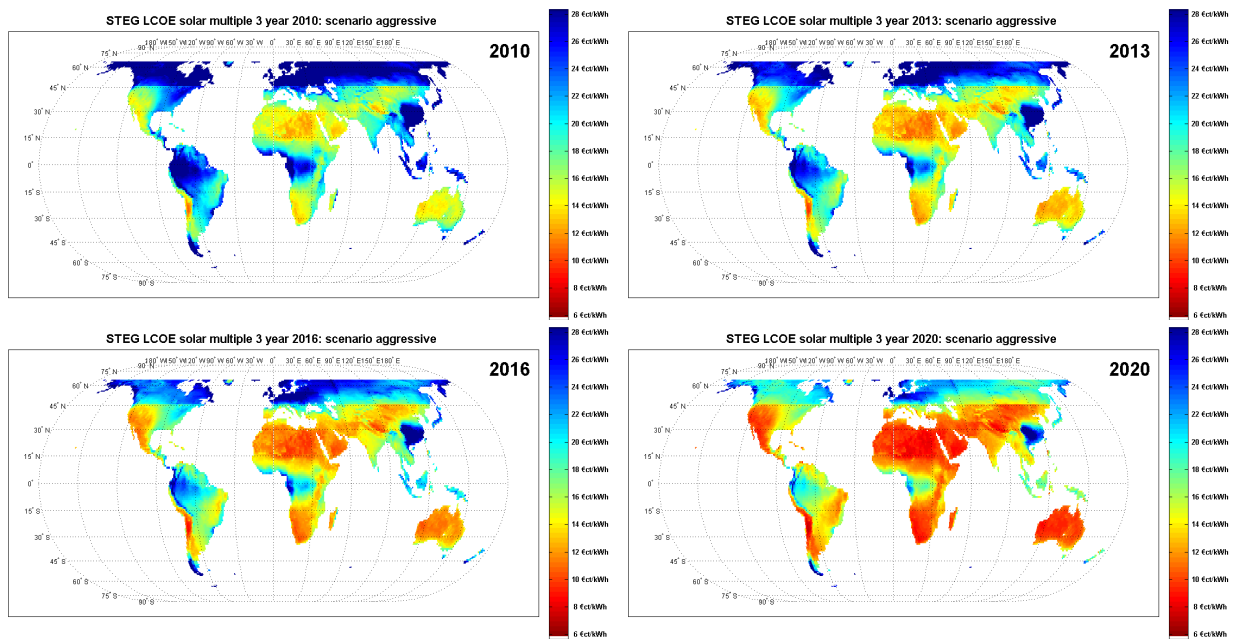


Figure 4.1-7: Global LCOE of STEG plants and a solar multiple of 3 in the 2010s for the aggressive scenario. DNI resource (Fig. 4.1-1) is applied for respective full load hours (Fig. 4.1-3 and 4.1-4). The aggressive scenario is defined in Table 4.1-1.

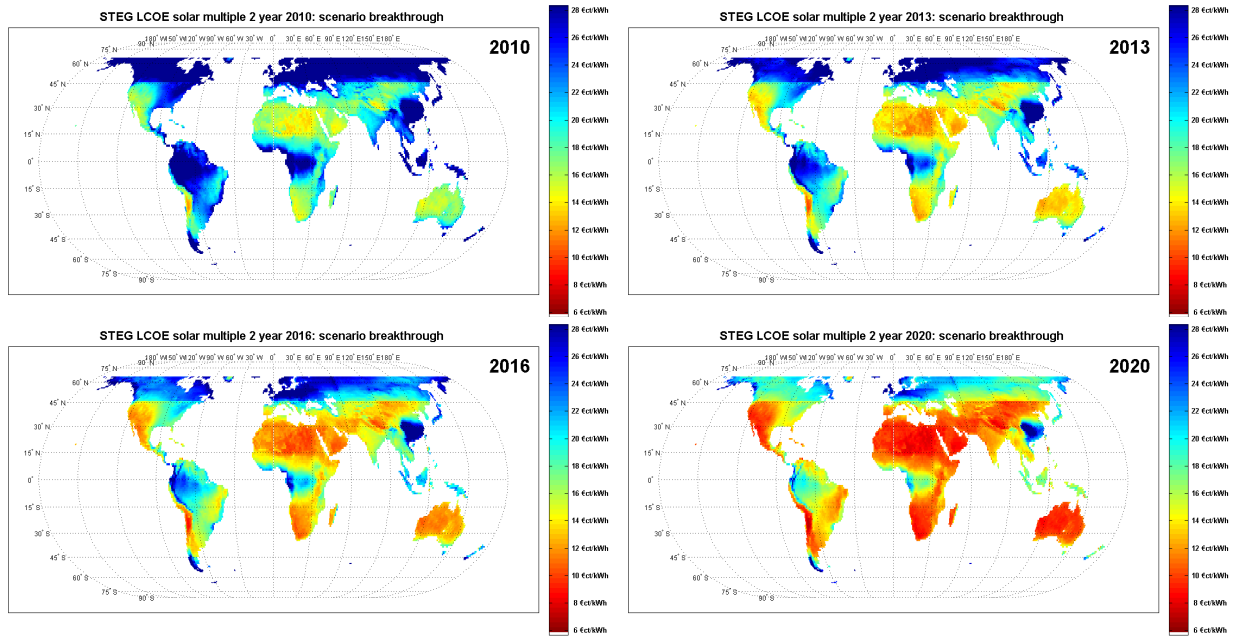


Figure 4.1-8: Global LCOE of STEG plants and a solar multiple of 2 in the 2010s for the breakthrough scenario. DNI resource (Fig. 4.1-1) is applied for respective full load hours (Fig. 4.1-3 and 4.1-4). The breakthrough scenario is defined in Table 4.1-1.

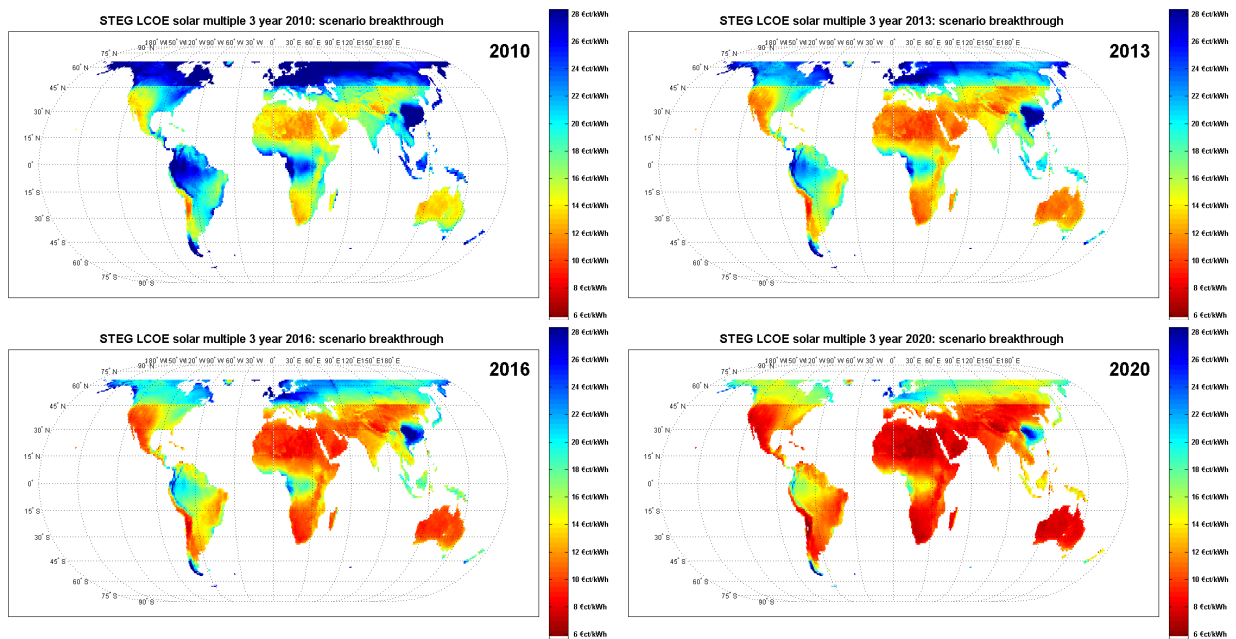


Figure 4.1-9: Global LCOE of STEG plants and a solar multiple of 3 in the 2010s for the breakthrough scenario. DNI resource (Fig. 4.1-1) is applied for respective full load hours (Fig. 4.1-3 and 4.1-4). The breakthrough scenario is defined in Table 4.1-1.

STEG LCOE is strongly dependent on DNI resource, solar multiple, applied scenario and respective year due to early position of STEG technology on the experience curve. For better understanding and respective discussion some further diagrams are needed. An exemplarily site in Egypt is depicted for the three scenarios and the four solar multiples in dependence of the years in the 2010s (Fig. 4.1-10). Impact of DNI resource is illustrated in Figure 4.1-11 for the scenarios and the two years 2010 and 2020. For the special case of the aggressive scenario the dependence on DNI resource and the years of the 2010s is shown for the solar multiples one to four in Figure 4.1-12.

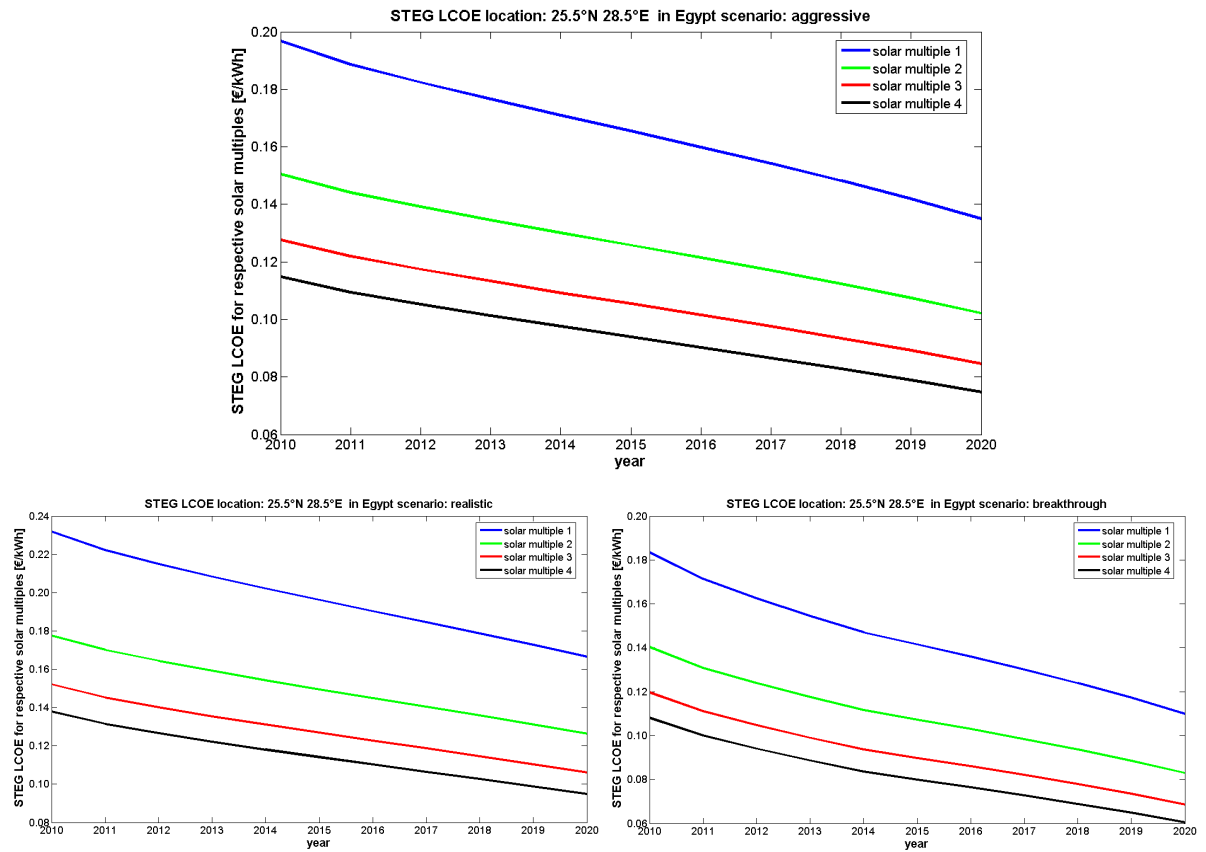
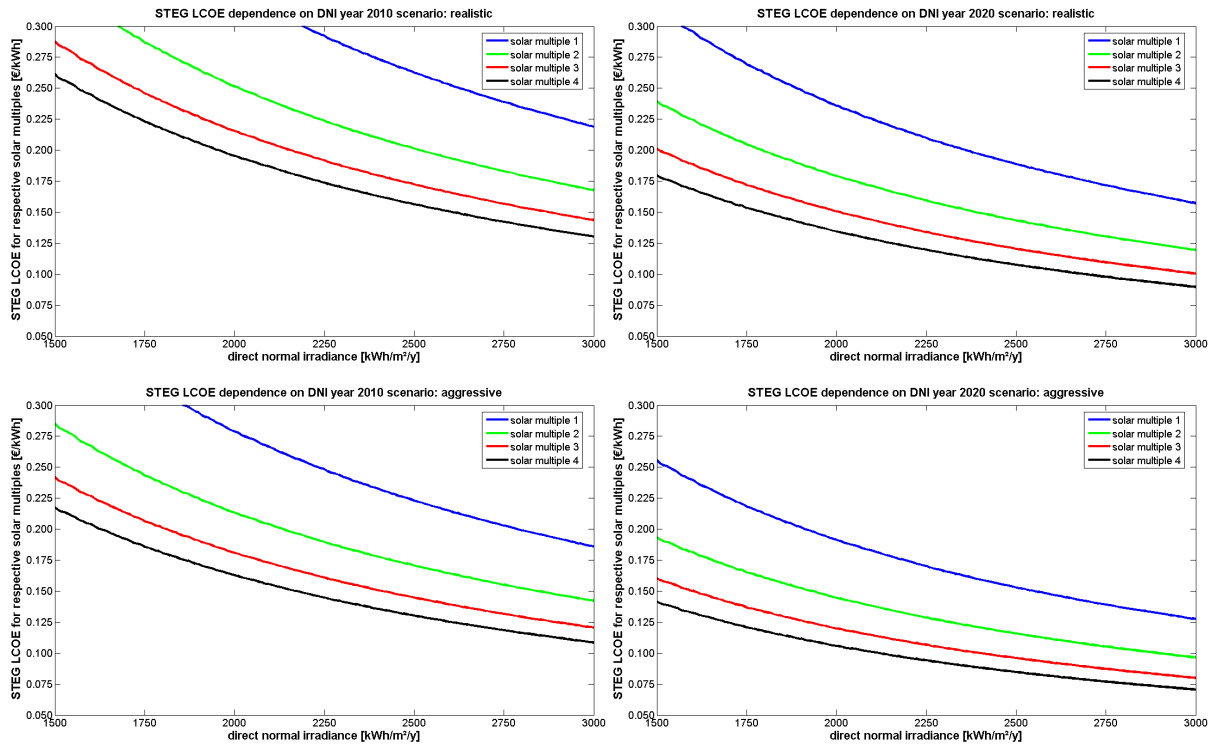


Figure 4.1-10: STEG LCOE for a site in Egypt for solar multiples one to four in aggressive (top), realistic (bottom, left) and breakthrough (bottom, right) scenario. The site is located in 25.5°N / 28.5°E and receives a DNI of about 2,800 kWh/m²/y. The scenarios are defined in Table 4.1-1.



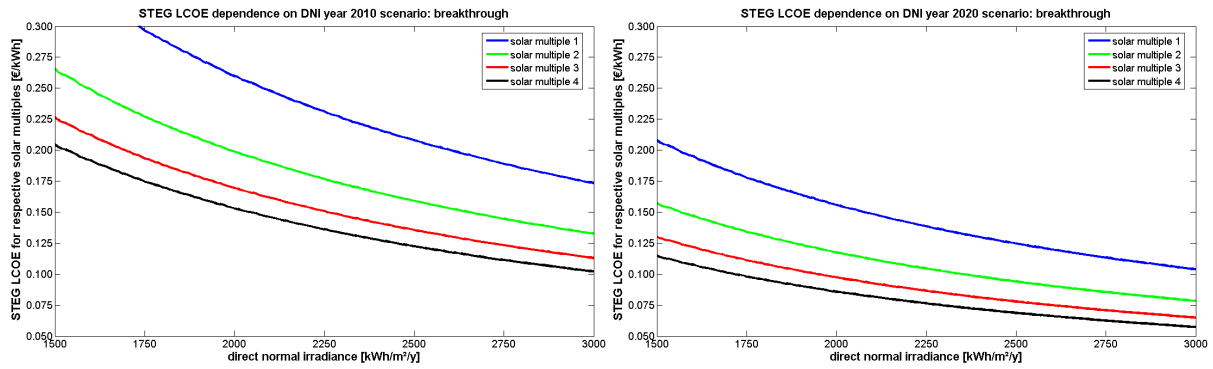


Figure 4.1-11: Impact of DNI resource and solar multiples on STEG LCOE is shown for the years 2010 and 2020 for the scenarios realistic (top, left and right), aggressive (centre, left and right) and breakthrough (bottom, left and right), respectively. The scenarios are defined in Table 4.1-1.

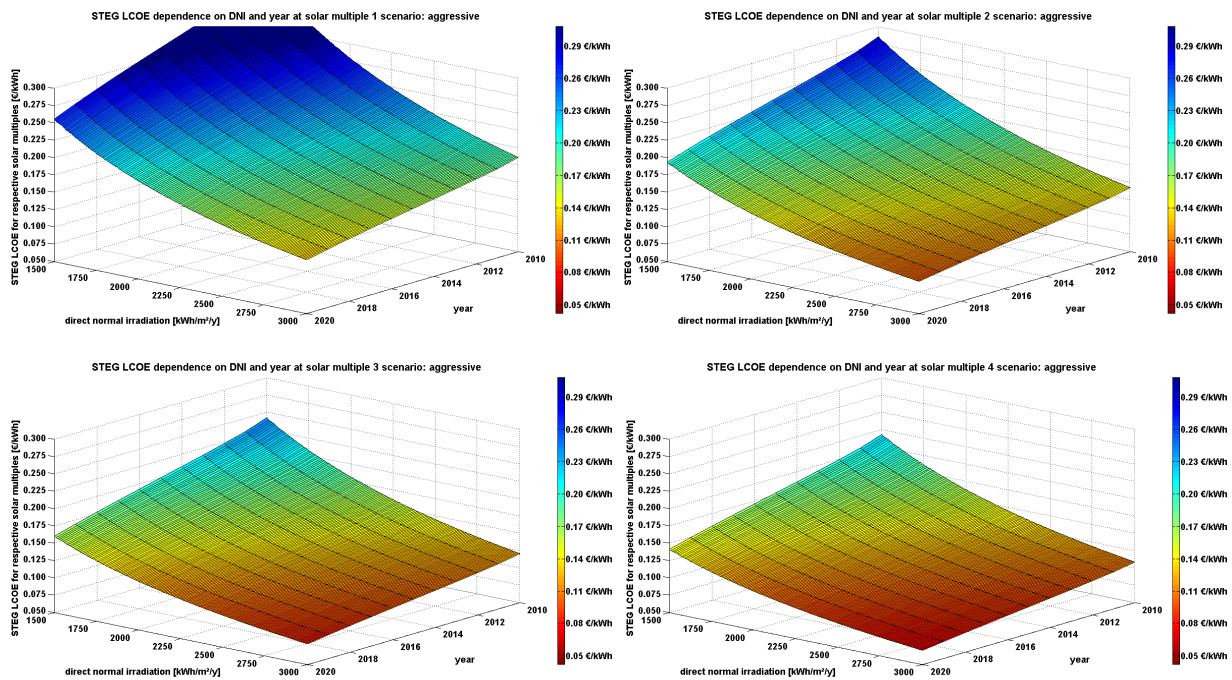


Figure 4.1-12: STEG LCOE in dependence on DNI resource and the year in the 2010s for the solar multiple one to four in the aggressive scenario. The aggressive scenario is defined in Table 4.1-1.

STEG LCOE are strongly dependent on possible full load hours documented by dependence on solar multiples (Fig. 4.1-10 and 4.1-12) but also by dependence on DNI resource (Fig. 4.1-11 and 4.1-12). STEG plants without thermal energy storage (SM1) are not dispatchable and high in cost, as LCOE stay above 0.10 €/kWh even in 2020 for DNI of 3,000 kWh/m²/y and the breakthrough scenario (Fig. 4.1-11). Therefore SM1 STEG plants might find no markets as qualitatively comparable PV power plants are significantly lower in LCOE (section 3.2.3). SM2 STEG plants are much more valuable due to their dispatchability and significantly decreased LCOE (Fig. 4.1-10 to 4.1-12). However, competitiveness might be reduced due to relatively high LCOE, as progress until 2020 and very high DNI resource of 3,000 kWh/m²/y is needed in the aggressive scenario to reach a LCOE level of 0.10 €/kWh (Fig. 4.1-11). Nevertheless, SM2 STEG plants might become the most likely plant design to be built as they equal roughly 4,000 – 5,000 full load hours (Fig. 4.1-3 and 4.1-4), which represents the average global power demand (sub-chapter 5.1). For being competitive STEG plants need technological and economic evolution according to the breakthrough scenario, i.e. LCOE of

about 0.07 – 0.10 €/kWh for SM3 in the year 2020 for DNI resource of 3,000 – 2,000 kWh/m²/y, respectively (Fig. 4.1-9). Both SM2 STEG LCOE in the breakthrough scenario (Fig. 4.1-8) and SM3 STEG LCOE in the aggressive scenario (Fig. 4.1-7) might be still too high.

Summing up, STEG LCOE shows considerably unfavourable values in comparison to wind power (sub-chapter 4.2) and to PV (sub-chapter 3.2). However, being dispatchable is a significant value for its own due to enormous improved grid integration. High growth rates, high learning rates and high competition among STEG players might be very relevant for the entire STEG industry to reach a LCOE level for SM2 and SM3 below 0.10 €/kWh in the 2010s. Otherwise, STEG technology might be at risk to become a niche application.

4.2 Wind Power

Special perspective is given in this sub-chapter to the wind resource (section 4.2.1), how this resource is used for power conversion in wind power plants (section 4.2.2) and the resulting wind power economics (section 4.2.3). A general overview on the broad field of wind power technology is given by EWEA ⁴², Gipe ⁴³, Heier ⁴⁴, Gasch and Twele ⁴⁵, Hau ⁴⁶, IEA ⁴⁷ and a small but excellent chapter in Duffie and Beckmann ⁴⁸.

4.2.1 Wind Resource

Renewable resource for wind power is the wind speed and its distribution over a specific period of time. Excellent wind resources are high and stable wind speeds, like in Patagonia, the North American Mid West or the North Sea in Europe. In this sub-chapter the wind resource consideration is based on NASA SSE 6.0 dataset.^{49,50} A brief description of the dataset is summarized in sub-chapter 2.1. Data are provided for a 1°x1° mesh of latitude and longitude. For all coordinates data are provided in the following structure: average wind speed 50 m above ground per year and for all months of the year and fraction of prevailing wind speed for all hours of the respective month and the year within wind speed classes of 0 - 2 m/s, 2 - 6 m/s, 6 - 10 m/s, 10 - 14 m/s, 14 - 18 m/s, 18 - 25 m/s, higher than 25 m/s. Data are averaged for the 10 years period from July 1983 to June 1993. The average wind speed 50 m above ground for the world is depicted in Figure 4.2-1.

⁴² EWEA, Wind Energy – The Facts: A guide to the technology, economics and future of wind power, 2009

⁴³ Gipe P., Wind Energy Basics – A Guide to Small and Micro Wind Systems, 1999

⁴⁴ Heier S., Windkraftanlagen – Systemauslegung, Netzintegration und Regelung, 2009

⁴⁵ Gasch R. and Twele J., (eds.), Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb, 2010

⁴⁶ Hau E., Windkraftanlagen – Grundlagen, Technik, Einsatz, Wirtschaftlichkeit, 2008

⁴⁷ IEA, Technology Roadmap: Wind energy, 2009

⁴⁸ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006

⁴⁹ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

⁵⁰ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

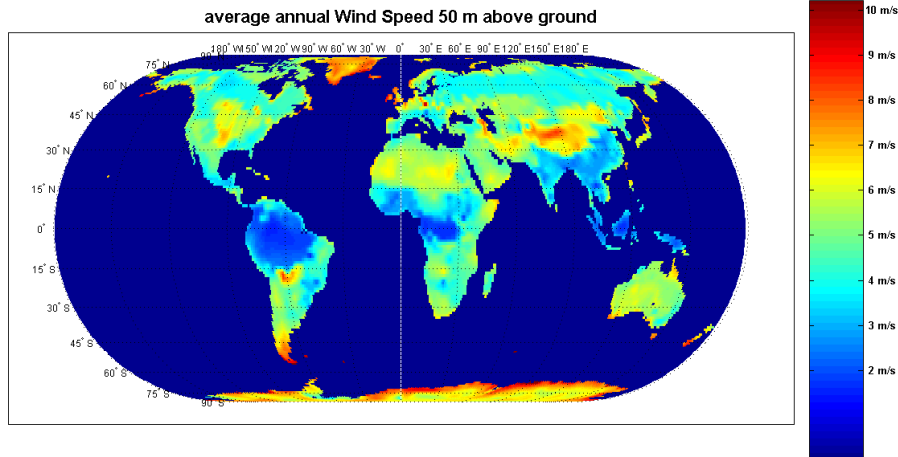


Figure 4.2-1: Average annual wind speed 50 m above ground. Data are taken from NASA ⁵¹.

Modern wind turbines harvest the wind energy at a hub height of 100 m to 150 m for gaining access to improved wind resource, i.e. mainly a higher wind speed and less turbulences hence more stable wind flow conditions. Gain of wind speed as a function of height is dependent on the topography of the site of interest. Obstacles on the ground disturb the laminar flow of the wind, hence the higher the wind turbine is erected the more laminar will become the wind speed. Every site is characterized by its ground roughness. This specific property of each site is the local roughness length. The average roughness length over an entire year for a $1^\circ \times 1^\circ$ mesh of latitude and longitude is shown in Figure 4.2-2. Regions of a very flat surface show low roughness lengths, e.g. all the oceans and Sahara desert, and regions of diverse forests are characterized by respective long roughness lengths, like the Tundra or the rain forests in the world.

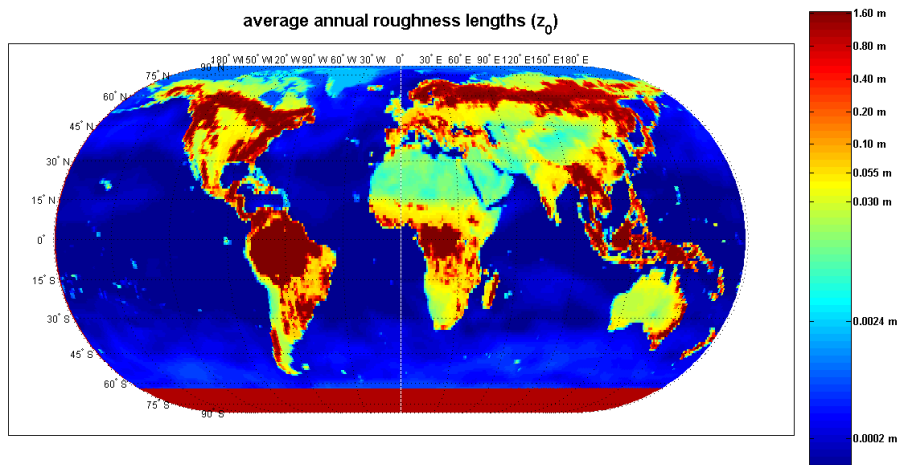


Figure 4.2-2: Average annual roughness lengths. The roughness length is available in a $1^\circ \times 1^\circ$ mesh of latitude and longitude. There is no data for latitudes lower than 65°S . Data are provided by DLR ⁵².

The wind speed of a specific height can be transformed to the wind speed of a different height by applying the roughness lengths described in Equation 4.2-1:⁵³

⁵¹ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

⁵² Scholz Y. et al., High Resolution Inventory of Renewable Electricity Generation Potentials in Europe, 2009

⁵³ Langreder W. and Bade P., Der Wind, 2010

$$v_2(h_2) = v_1(h_1) \cdot \frac{\ln \frac{h_2}{z_0}}{\ln \frac{h_1}{z_0}} \quad (\text{Eq. 4.2-1})$$

Equation 4.2-1: Transformation of wind speed to different heights. Abbreviations stand for: wind speed ($v_{l,2}$), height ($h_{l,2}$) and roughness length (z_0).

Most modern wind turbines have their hub height at 100 m to 150 m, therefore the average annual wind speed 50 m above ground (Fig. 4.2-1) is transformed to 100 m and 150 m above ground (Fig. 4.2-3) by applying Equation 4.2-1 and using respective local roughness length (Fig. 4.2-2).

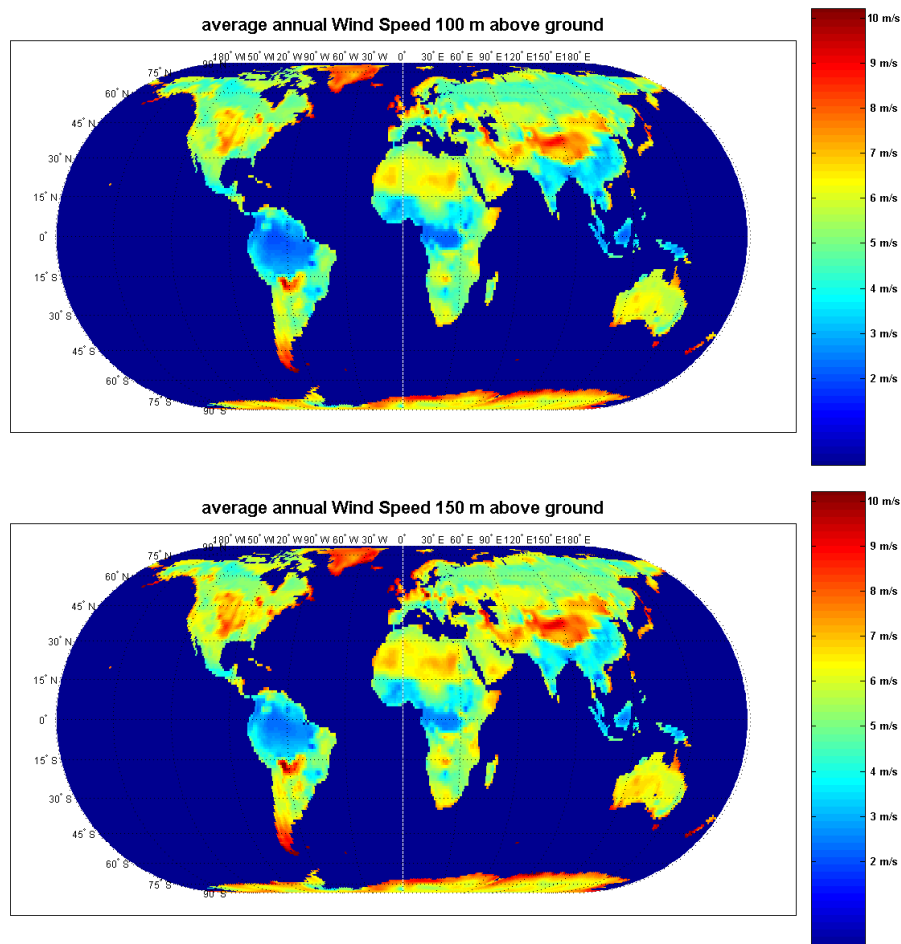


Figure 4.2-3: Average annual wind speed 100 m (top) and 150 m (bottom) above ground.

The wind resource is not fully described by the average annual wind speed of a specific height. Power generated by a wind turbine is very sensitive to the actual wind speed, hence the wind speed distribution of a period of time is of utmost relevance for calculating power output. Typically, the distribution of wind speed is best described by the Weibull distribution (Equation 4.2-2a). The clou of the Weibull distribution is that only two parameters fully describe the entire distribution. Required input data are the distribution of wind speed of a period of time. Equations 4.2-2 summarize the Weibull distribution and the routine for extracting the two Weibull parameters:⁵⁴

⁵⁴ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006, p. 776-799

$$p(U) = \frac{k}{c} \cdot \left(\frac{U}{c}\right)^{k-1} \cdot \exp\left[-\left(\frac{U}{c}\right)^k\right] \quad (\text{Eq. 4.2-2a})$$

$$\bar{U} = \frac{1}{N} \cdot \sum_{i=1}^N U_i \quad (\text{Eq. 4.2-2b})$$

$$\sigma = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^N (U_i - \bar{U})^2} \quad (\text{Eq. 4.2-2c})$$

$$\sigma^2 = \bar{U}^2 \cdot \left[\frac{\Gamma(1+2/k)}{\Gamma^2(1+1/k)} - 1 \right] \quad (\text{Eq. 4.2-2d})$$

$$\bar{U} = c \cdot \Gamma(1+1/k) \quad (\text{Eq. 4.2-2e})$$

Equation 4.2-2: Weibull distribution and the routine for extracting the Weibull parameters. Abbreviations stand for: Weibull distribution ($p(U)$), Weibull shape factor (k), Weibull scaling factor (c), wind speed (U), average wind speed ($\bar{U}$), number of wind speed events (N), standard deviation (σ) and gamma function (Γ).

Input data for wind speed classes and its Weibull function are depicted in Figure 4.2-4 for average annual data of an exemplarily site in Central Germany. Data of wind resource for each coordinate depicted in Figures 4.2-1 and 4.2-3 can be described by the two Weibull parameters and used for transforming the wind resource data into electric power output of a specific wind turbine.

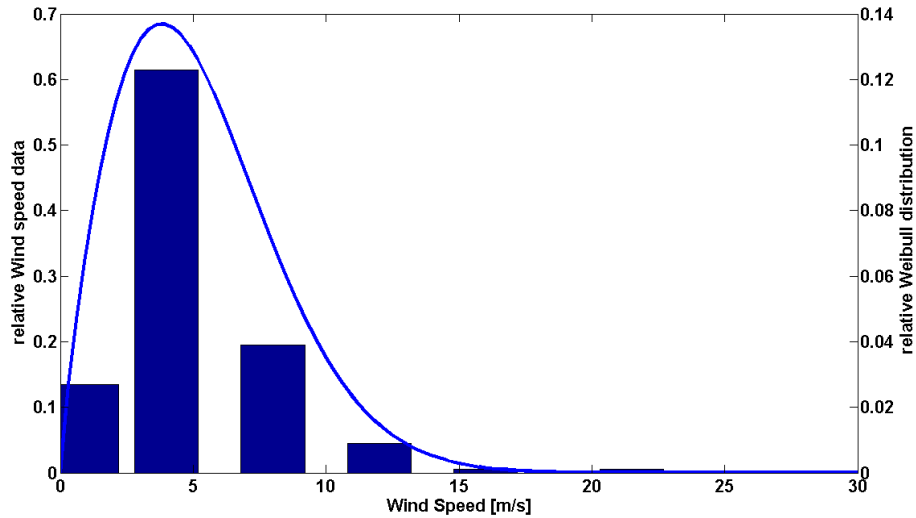


Figure 4.2-4: Histogram for wind speed classes of average annual conditions and the corresponding Weibull function.

4.2.2 Wind Power Plants

In this section a rough overview is given on global installed wind power capacity (section 4.2.2.1) and a simple electrical wind power model (section 4.2.2.2) is applied for deriving wind power full load hours based on wind resources (section 4.2.1).

4.2.2.1 Global Overview on Wind Power Capacity

Total global installed wind power capacity was 120.3 GW by end of 2008 and 158.5 GW by end of 2009.⁵⁵ Generated electricity was 219 TWh in the year 2008⁵⁶, translating to 2,050 full load hours assuming that 50% of 27.1 GW of new installed capacity in 2008 was grid-connected in average. Average annual growth rate of wind power installations is 30% for the years 1996 – 2009.⁵⁷

It is necessary to have the coordinates of the wind power plants for further analysis. Due to that the UDI World Electric Power Plants database⁵⁸ has been enhanced by coordinates of all 145,000 power plants in the world.⁵⁹ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. However, a crosscheck reveals a missing capacity of 35.5 GW of wind power plants (84.8 GW in the database versus 120.3 GW real capacity⁶⁰).

It is not clear why the database is of such low quality in wind power, in particular due to many included very small diesel generators of only some kW, which is much lower than most of all wind power plants in the world. In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration have been taken in these cases. The result of the georeferenced global power plant capacity being in operation is depicted in Figure 4.2-5.

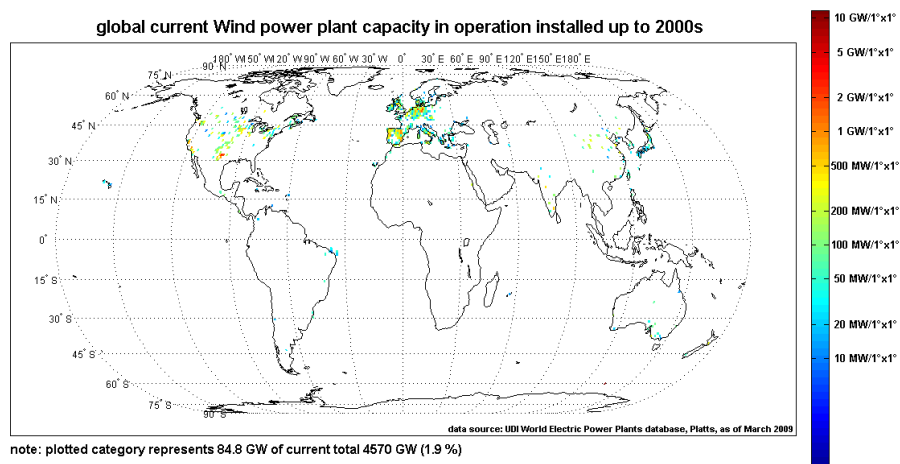


Figure 4.2-5: Global wind power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. However, only 84.8 GW of total installed 120.3 GW are recorded in the database leaving capacity of 35.5 GW dislocated. Data are plotted in a 1°x1° mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database⁶¹ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced wind power plant data (Fig. 4.2-5) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current wind power plant capacity (Fig. 4.2-6). More than 30 GW out of 84.8 GW included in the database are located in areas of more than 1,800

⁵⁵ GWEC, Global Wind 2009 Report, 2010

⁵⁶ IEA, World Energy Outlook 2010, 2010

⁵⁷ GWEC, Global Wind 2009 Report, 2010

⁵⁸ Platts, UDI World Electric Power Plants data base, 2009

⁵⁹ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

⁶⁰ GWEC, Global Wind 2009 Report, 2010

⁶¹ Platts, UDI World Electric Power Plants data base, 2009

kWh/m²/y irradiation on fixed optimally tilted module surfaces, i.e. 35% of global wind power installed base is already installed in regions of very good solar resource quality.

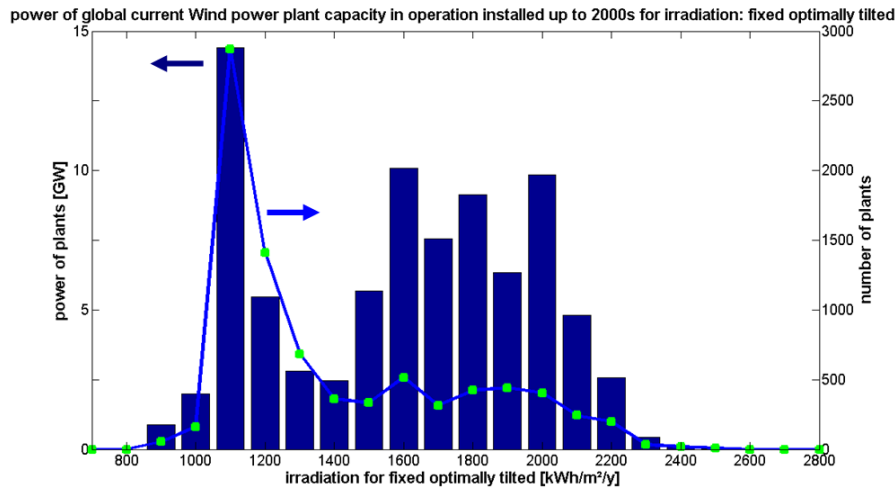


Figure 4.2-6: Global wind power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 4.2-5) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 4.2-7 and shows that most power plants are in the power class of 1 - 10 MW or even smaller in size. However, their contribution to global power capacity is negligible. Almost 63% of global power plant capacity consists of power plants of 10 – 100 MW in size and 22% in the power class of 100 - 1000 MW. In this consideration, the definition of a wind power plant is an electrical integrated ensemble of single wind turbine, i.e. typically wind farms.

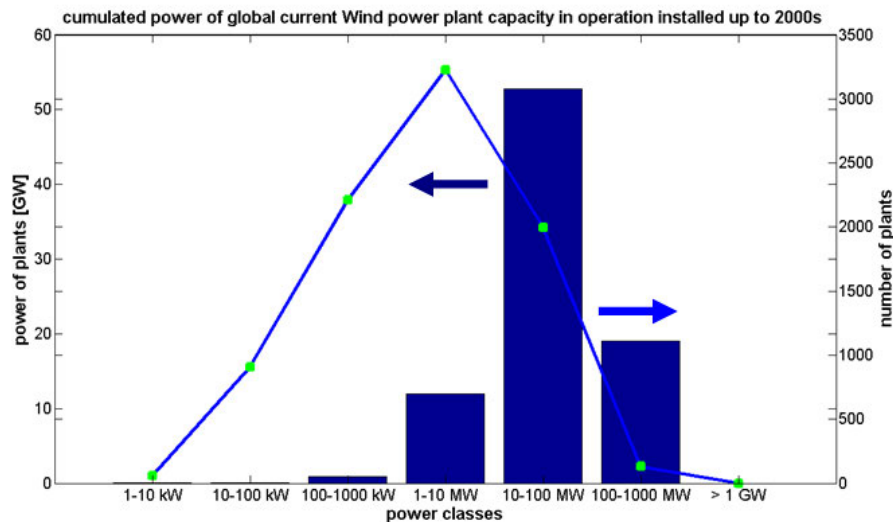


Figure 4.2-7: Global wind power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are

referred to the left axis and represent the power plant capacity. Data are taken from UDI World Electric Power Plants database⁶².

Contribution of wind power to global electricity supply is still low. Global average total electricity generation per capita is about 3.0 MWh but 5 – 10 MWh in industrialised countries (sub-chapter 5.1). Leading wind electricity per capita country in the world is Denmark achieving 1.1 MWh per capita (Fig. 4.2-8). Most other countries are far below. Comparison of global wind power generation (Fig. 4.2-8) to global wind resource (Fig. 4.2-3) reveals a nearly untapped source of power all over the world. Obviously, there is enormous room for further growth.

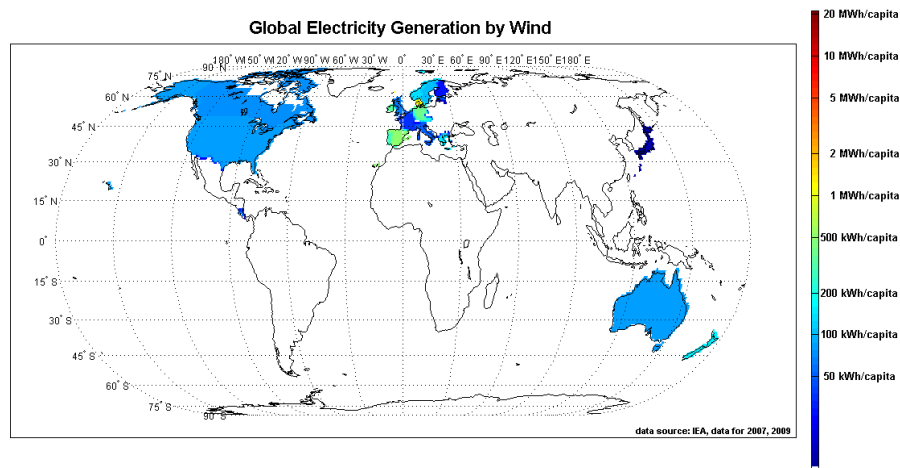
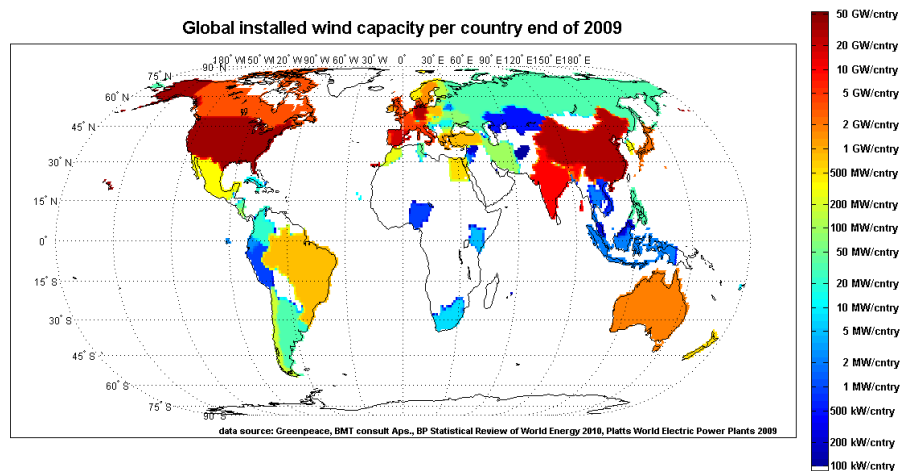


Figure 4.2-8: Global electricity generation by wind per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency⁶³ and United Nations⁶⁴.

Global installed wind power plant capacity per country is illustrated in Figure 4.2-9. Leading countries by cumulated wind power capacity are the US, Germany, Spain, China and India by end of 2008. However, wind resource (Fig. 4.2-3) is also excellent in Argentina, North Africa, Central Asia and Australia, hence significant wind power installations in these regions can be expected in future.



⁶² Platts, UDI World Electric Power Plants data base, 2009

⁶³ IEA, Key World Energy Statistics 2009, 2009

⁶⁴ UN, World Population Prospects: The 2008 Revision Highlights, 2009

Figure 4.2-9: Global wind power plant capacity per country by end of 2009. Only power plants in operation are regarded. However, only 84.8 GW of total installed 120.3 GW are recorded in the UDI database leaving capacity of 35.5 GW dislocated. Further data sources completed the country data. Data are taken from UDI World Electric Power Plants database ⁶⁵ and Greenpeace ⁶⁶.

Structure of wind power plant capacity can be illustrated on a per country basis for relevance of respective domestic overall electricity generation (Fig. 4.2-10). This view clearly discloses that wind power is still an emerging power technology, as only five countries in the world use wind power for about 5% or more in relation to the total domestic electricity generation. These countries are Denmark (13%), Spain (8%), Portugal (6%), Ireland (6%) and Germany (5%). Again, there is enormous room for further growth of wind power plants in the world.

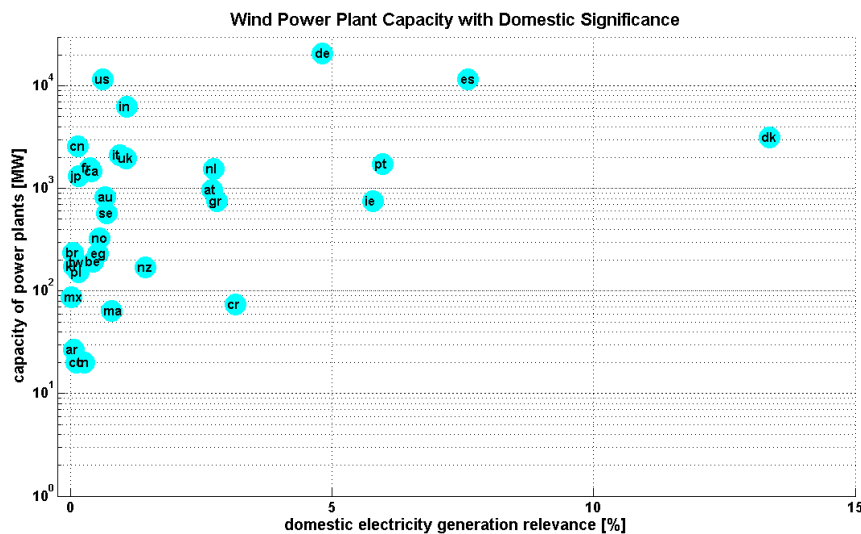


Figure 4.2-10: Wind power plant capacity in dependence on domestic electricity generation relevance per country. Each dot represents the absolute and relative wind power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ⁶⁷ and International Energy Agency ⁶⁸.

Summing up, global wind power plant capacity of about 159 GW is in average 2,050 full load hours in operation and generate annually about 326 TWh of electricity, representing 3.4% of total global installed power capacity and 1.6% of global generated electricity. Available global wind resource is currently used in a nearly negligible manner for global power supply.

4.2.2.2 Simple Electric Wind Power Modelling

Development of wind turbines has been very dynamic in last three decades and resulted in well engineered and cost effective wind power plants. Wind turbines convert the power of the air flow into electric power. Basic formulas for describing wind power plants are summarized in Equations 4.2-3:⁶⁹

⁶⁵ Platts, UDI World Electric Power Plants data base, 2009

⁶⁶ Teske S., private communications, 2011

⁶⁷ Platts, UDI World Electric Power Plants data base, 2009

⁶⁸ IEA, Key World Energy Statistics 2009, 2009

⁶⁹ Duffie J.A. and Beckmann W.A., Solar Engineering of Thermal Processes, 2006, p. 776-799

$$P_w = \partial_t E_w = \frac{1}{2} \dot{m} U^2 = \frac{1}{2} \rho \dot{V} U^2 = \frac{1}{2} \rho A U^3 \quad \text{with } \rho = \frac{p}{RT} \quad (\text{Eq. 4.2-3a,b})$$

$$P_{W,el} = \eta_T \cdot P_T = \eta_T \cdot c_p \cdot P_w \quad (\text{Eq. 4.2-3c})$$

$$\bar{U} = \frac{1}{N} \sum_{i=1}^N U_i = \int_0^\infty U \cdot p(U) dU \quad (\text{Eq. 4.2-3d})$$

$$\bar{P}_{W,el} = \eta_T \cdot \frac{1}{N} \sum_{i=1}^N P_{T,i} = \frac{A \bar{\rho} \eta_T}{2} \int_0^\infty c_p U^3 p(U) dU \quad (\text{Eq. 4.2-3e})$$

$$\bar{P}_{W,el} = \frac{A \bar{\rho} \eta_T}{2} \int_0^\infty c_p U^3 \cdot \frac{k}{c} \cdot \left(\frac{U}{c} \right)^{k-1} \cdot \exp \left[- \left(\frac{U}{c} \right)^k \right] dU \quad (\text{Eq. 4.2-3f})$$

$$\bar{E}_{W,el} = \bar{P}_{W,el} \cdot 8760 = FLh_{W,el} \cdot P_N \quad (\text{Eq. 4.2-3g})$$

Equation 4.2-3: Power output of wind power plants. Abbreviations stand for: power of wind (P_w), energy of wind (E_w), mass flow ($\partial_t m$), wind speed (U), air density (ρ), air volume flow ($\partial_t V$), swept area (A), air pressure (p), gas constant (R), temperature (T), electric power of wind power plant ($P_{W,el}$), turbine efficiency (η_T), power of wind turbine (P_T), power coefficient (c_p), average wind speed ($\bar{U}$), number of wind speed events (N), Weibull distribution ($p(U)$), Weibull shape factor (k), Weibull scaling factor (c), annual electricity generation of wind power plant ($E_{W,el}$), annual full load hours of wind power plant ($FLh_{W,el}$) and rated power of wind turbine (P_N).

The annual electricity generation of a wind power plant (Eq. 4.2-3g) is based on the power conversion of the wind turbine mainly depending on the wind speed and its distribution over the year. The power output of a wind turbine is very sensitive to the wind speed, due to a dependence on the third power of the wind speed (Eqs. 4.2-3e and 4.2-3f). However, air density is a linear factor for the power of wind turbines. Figure 4.2-11 illustrates the distribution of air density on earth. Air density is a function of temperature and air pressure (Eq. 4.2-3b), hence it is also dependent on the altitude. Impact of altitude on air density for mountain regions and plateaus is significant for example for the Himalayas and the Andes (Fig. 4.2-11) and respective consequence for the wind power potential of these regions.

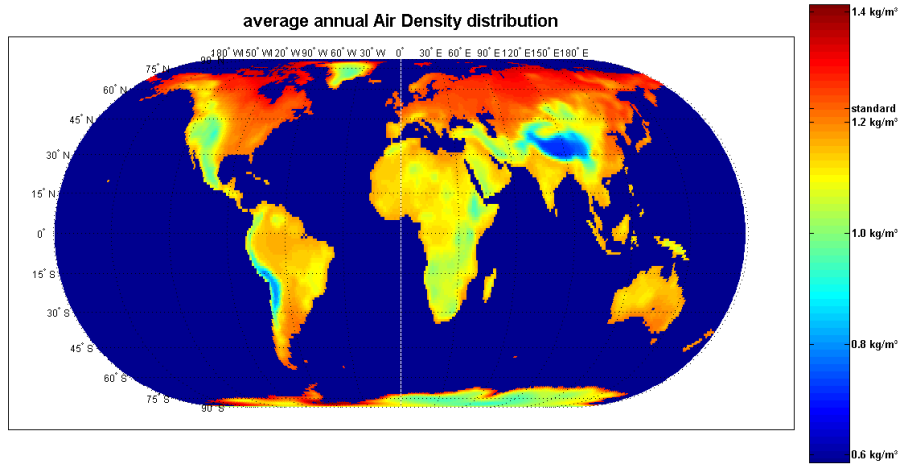


Figure 4.2-11: Average annual air density distribution. Air density calculation is performed according to Equation 4.2-3b. Data for air pressure and temperature are taken from NASA ⁷⁰.

A specific wind turbine is characterized by its power coefficient (c_p) and the turbine efficiency (η_T). For the wind power calculations of this chapter one of the best designed most

⁷⁰ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

widely spread wind turbines is used. A picture and power coefficient data of the gearless E-82 wind turbine from Enercon are shown in Figure 4.2-12.

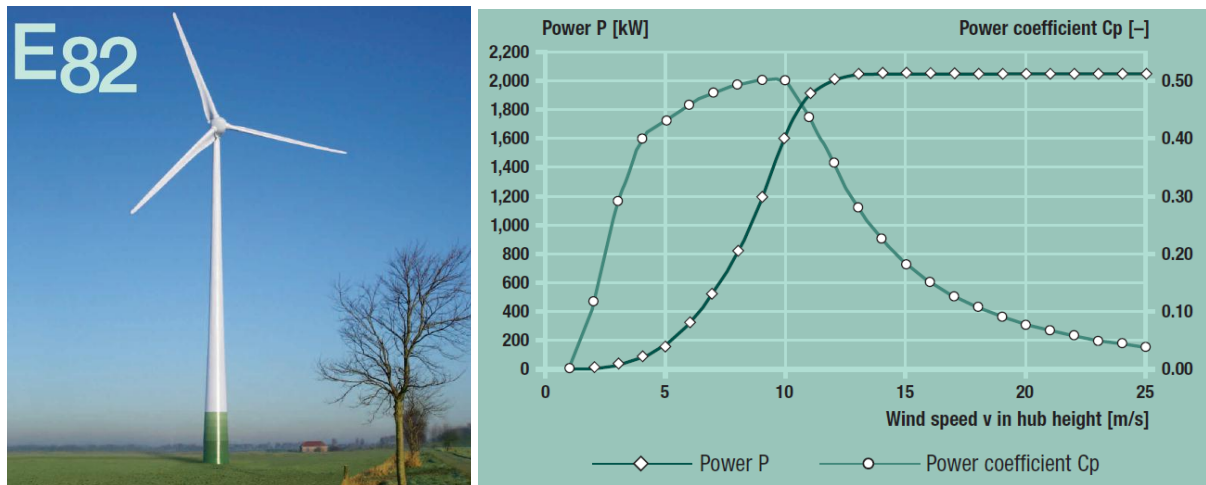
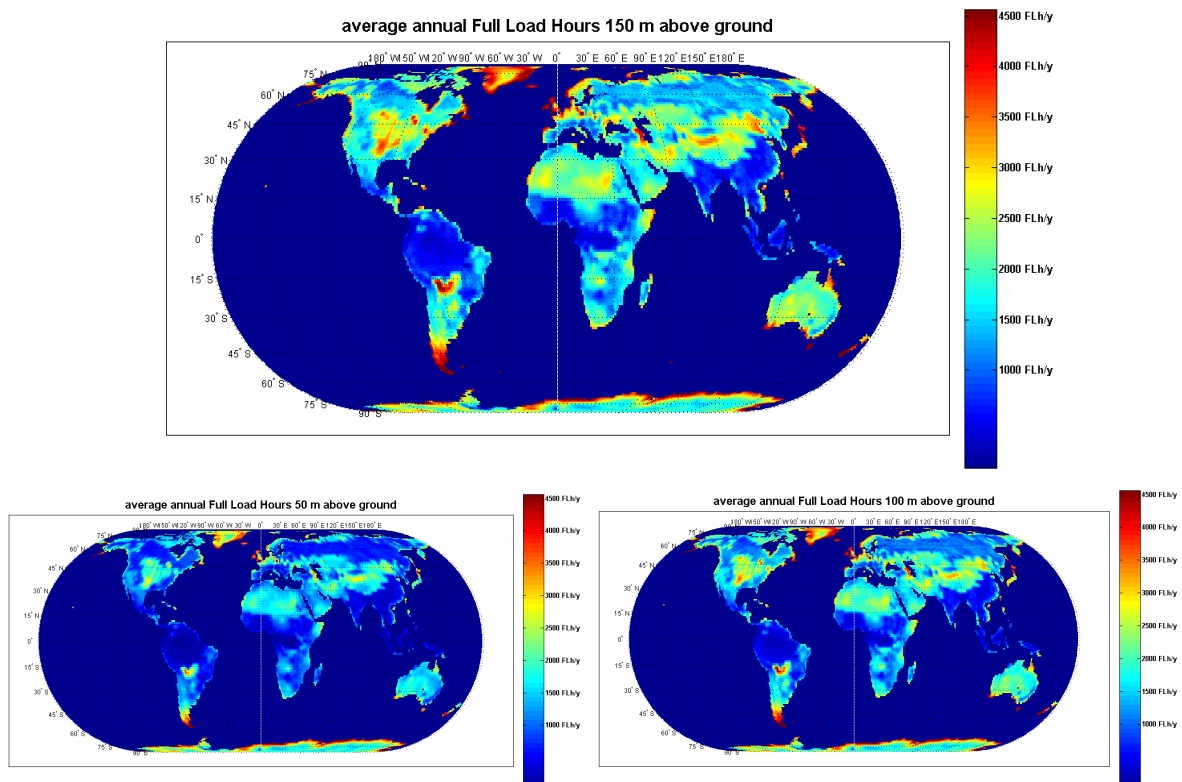


Figure 4.2-12: Wind turbine E-82 from Enercon (left) and its power curve and power coefficient (right). Further technical data of the turbine are: rated power of 2 MW, rotor diameter of 82 m, hub height between 78 m – 138 m, swept area of 5,281 m², cut-out wind speed of 28 m/s – 34 m/s in its storm control feature by turning the rotor blades slightly out of the wind. Data are taken from Enercon ⁷¹.

A good measure for availability of wind power are the average annual full load hours defined in Equation 4.2-3g. This key performance indicator comprises the wind resource quality, i.e. the average annual wind speed (Fig. 4.2-1 and 4.2-3), its Weibull distribution (Fig. 4.2-4) and the local air density (Fig. 4.2-11), and specific wind turbine characteristics (Fig. 4.2-12). The data and mathematical description of wind power are summarized in Figure 4.2-13 for the hub heights of 50 m, 100m and 150m.



⁷¹ Enercon, Wind Turbines – Product Overview, 2009

Figure 4.2-13: Average annual full load hours of wind power plants. Data of wind resource are according to Figure 4.2-1, 4.2-3 and 4.2-11 applied for wind turbines based on E-82 from Enercon (Fig. 4.2-12) ⁷². Efficiency of wind turbine (η_T) was set to 90%, including power plant availability.

Wind power is not limited to onshore electricity generation. Off-shore wind power shows high growth rates, in particular in the North Sea. The wind resource is excellent due to stable and high wind speed. Furthermore, there are less landscape related conflicts compared to onshore wind power. All commercially available off-shore wind power plants are based on fixed foundations. Research and development efforts aim also buoyant wind power plants, but they might need some further time to market. Regions in the world of sea depths down to 100 m as an assumed limitation for the foundation are depicted in Figure 4.2-14 and indicated by potential full load hours for a hub height 100 m above ground. The relative large area of the $1^\circ \times 1^\circ$ mesh of latitude and longitude may distort considerably the available site potential.

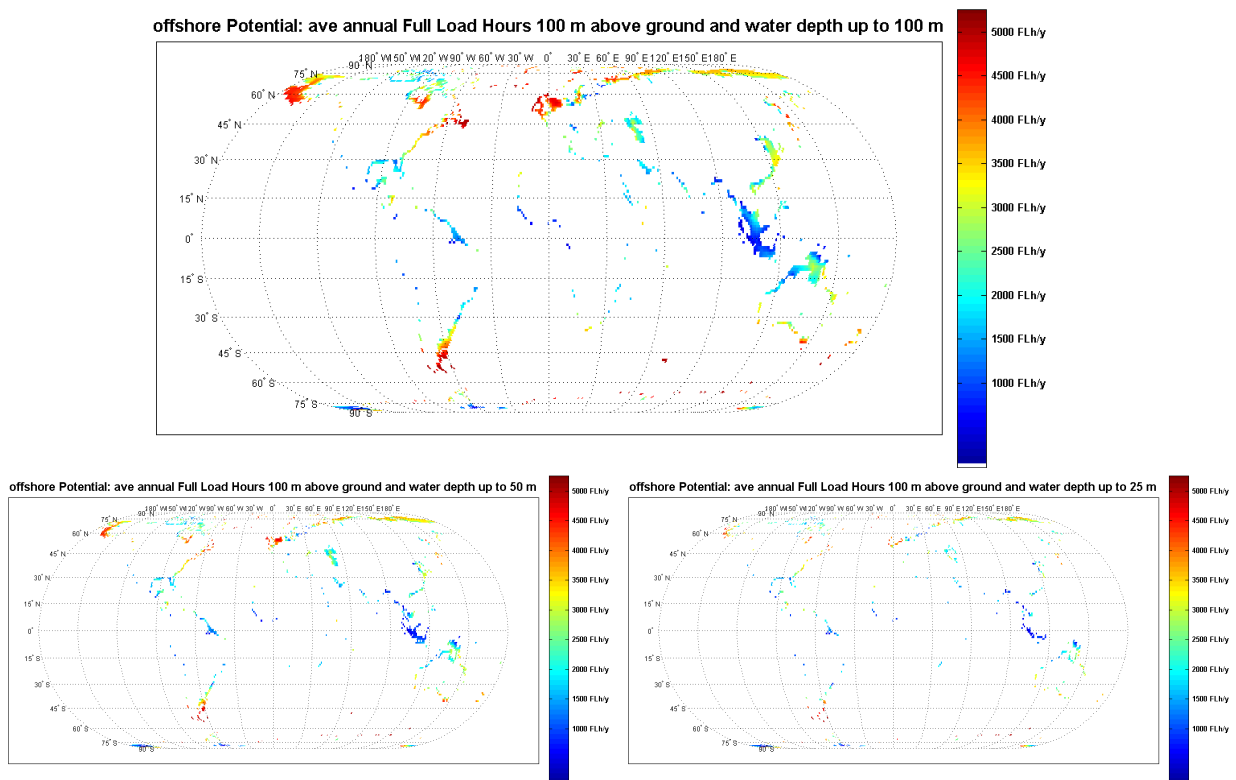


Figure 4.2-14: Offshore wind power potential of depths down to 100 m (top), 50 m (bottom, left) and 25 m (bottom right). Data for wind resource are taken from NASA ⁷³.

Offshore wind resource in North Sea seems to be one of the best in the world, due to low sea depths and high average wind speed typical for $40^\circ - 60^\circ$ N/S latitudes. In South East Asia large offshore areas would be available but average wind speeds are rather low, typical for $0^\circ - 10^\circ$ N/S latitudes. Offshore wind power potential might be very interesting in the North Sea, at the east coast of China, north coast of Australia, coast of Argentina, east coast of Canada and the US and at the Bering Sea between Russia and the US.

⁷² Enercon, Wind Turbines – Product Overview, 2009

⁷³ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

4.2.3 Wind Power Economics

A cost model for wind power plants enables the calculation of wind power levelized cost of electricity (LCOE) for all coordinates by applying local resource availability on basis of respective average annual full load hours (FLh) of wind power plants. These wind FLh contain all relevant data of local wind resource quality and are already adapted to typical commercially available wind power plants. Such derived wind LCOE make it possible to compare wind LCOE to LCOE of other renewable and conventional power plant technologies.

Methodology of calculating wind power LCOE is nearly identical to that of PV (section 3.2.1 and Eqs. 3.2-1). Adjustments are needed for specific differences of wind power and PV, summarized in Equations 4.2-4:

$$LCOE = \frac{Capex \cdot crf + Opex}{FLh_{w,el}} \quad (\text{Eq. 4.2-4a})$$

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (\text{Eq. 4.2-4b})$$

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \quad (\text{Eq. 4.2-4c})$$

Equation 4.2-4: Levelized cost of electricity (LCOE) for wind power plants. Equations 4.2-4 are nearly identical to Equations 3.2-1, except annual full load hours of wind power plant which need to be used instead of final electric PV yield. Abbreviations stand for: capital expenditures (*Capex*), annual operation and maintenance expenditures (*Opex*), annuity factor (*crf*), annual full load hours of wind power plant ($FLh_{w,el}$), weighted average cost of capital (*WACC*), lifetime of wind power plant (*N*), equity (*E*), debt (*D*), return on equity (k_E) and cost of debt (k_D).

Scenario assumptions for calculating LCOE of wind power plants are summarized in Table 4.2-1. Three different scenario settings have been developed, which mainly differ in Capex, but also partly in financing conditions, assumptions of wind industry growth rates and stability of learning rates. Main difference of the scenarios is a business-as-usual approach (realistic), tough competition, fast cost reduction and excellent bankable products (aggressive) and a crucial scenario with very high imbalanced and fierce competition but still bankable products (bloody). Reality might be somewhere between realistic and aggressive scenario.

		scenario realistic	scenario aggressive	scenario bloody
Capex_Wind_onshore	[€/kW]	1150	1000	850
Capex_Wind_offshore	[€/kW]	3300	2100	1800
fin_RoE_onshore	[%]	10.0%	8.0%	9.0%
fin_RoE_offshore	[%]	12.0%	10.0%	11.0%
fin_interest_onshore	[%]	6.0%	5.0%	5.5%
fin_interest_offshore	[%]	7.0%	6.0%	6.5%
fin_WACC_onshore	[%]	7.00%	5.60%	6.20%
fin_WACC_offshore	[%]	8.25%	6.80%	7.40%
fin_equityRatio	[%]	25%	20%	20%
plant_lifetime	[y]	20	25	20
plant_Opex_onshore	[€/kW/y]	20	20	30

plant_Opex_offshore	[€/kW/y]	90	80	100
plant_turbine_efficiency	[%]	95%	95%	95%
plant_others_availability	[%]	95%	95%	95%
capacity_cumulated_2009	[GW]	157.9	157.9	157.9
capacity_added_2009	[GW]	37.5	37.5	37.5
PR_Wind_2009-15	[%]	95%	90%	90%
PR_Wind_2015-20	[%]	95%	95%	95%
growth_rate_2009-15	[%]	30%	30%	30%
growth_rate_2015-20	[%]	25%	30%	30%

Table 4.2-1: Scenario assumptions for wind power plant economics. The three scenarios cover a business-as-usual approach (realistic), highly optimised value chain composition (aggressive) and very high competition (bloody). Economic parameters are more cost than price oriented due to cost driven prices in competitive markets, which is the case for the wind power industry. Numbers mentioned are for wind power plants of multi-10 MW. Methodology is identical to PV LCOE calculation (section 3.2.2.2 and Table 3.2-1). General parameters are set identical as far as possible or at least comparable to those of PV. Abbreviations stand for: capital expenditures (Capex), operational expenditures (Opex), return on equity (RoE), weighted averaged cost of capital (WACC) and progress ratio (PR). Data are taken from various sources like European Climate Foundation ⁷⁴, Greenpeace ⁷⁵, European Wind Energy Association ⁷⁶, Global Wind Energy Council ⁷⁷, Kost and Schlegl ⁷⁸, Zweibel ⁷⁹, PricewaterhouseCoopers ⁸⁰, BMU ⁸¹, European Commission ⁸², IEA ^{83,84}, Nemet ⁸⁵, Delucchi and Jacobson ⁸⁶, Shah and Greenblatt ⁸⁷ and neue energie ⁸⁸.

Experience curve approach (section 3.1.2) is applied for Capex projection in the 2010s in the same way as for PV. However, learning rates for wind power are significantly lower than those for PV. Fundamental reason might be the lower degree of modularity and scalability of wind power technology in comparison to PV. Growth rates of wind power industry are high and comparable to PV, but slightly lower. Outcome for the development of Capex is depicted in Figure 4.2-15 for the years 2010 – 2020. In case of wind power the relative industry dynamic is high but not on such an outstanding high level than PV, hence uncertainty on future development should be lower. Scenario assumptions for the realistic and aggressive case seem to be likely to a high degree, whereas the realistic scenario should be used as the standard reference.

⁷⁴ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

⁷⁵ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

⁷⁶ EWEA, Wind Energy – The Facts: A guide to the technology, economics and future of wind power, 2009

⁷⁷ GWEC, Global Wind 2009 Report, 2010

⁷⁸ Kost C. and Schlegl T., Stromgestehungskosten Erneuerbare Energien, 2010

⁷⁹ Zweibel K., Should solar photovoltaics be deployed sooner because of long operating life at low, predictable cost?, 2010

⁸⁰ PwC, 100% renewable electricity: A roadmap to 2050 for Europe and North Africa, 2010

⁸¹ BMU, Leitstudie 2010 – Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global, 2010

⁸² EC, Second Strategic Energy Review, 2008

⁸³ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008

⁸⁴ IEA, Projected Costs of Generating Electricity 2010 Edition, 2010

⁸⁵ Nemet G.F., Interim monitoring of cost dynamics for publicly supported energy technologies, 2009

⁸⁶ Delucchi M.A. and Jacobson M.Z., Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies, 2011

⁸⁷ Shah V. and Greenblatt J., Solar Energy Handbook: The Third Growth Phase of the Solar Era, 2010

⁸⁸ May H., Windindustrie in China – Faktor 10, 2009

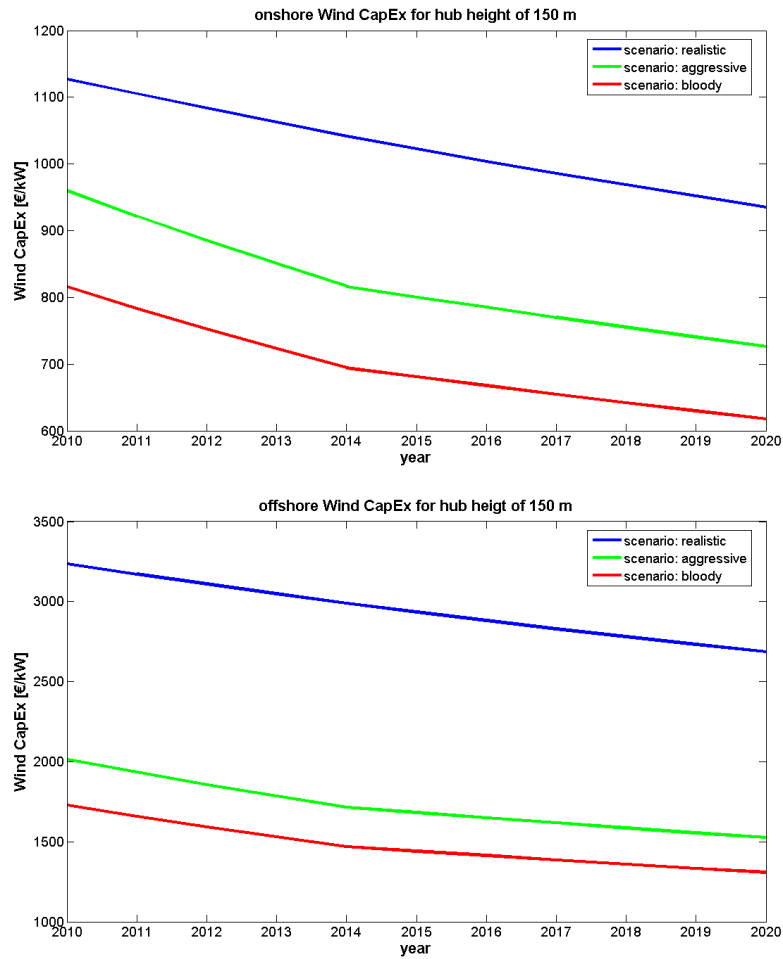
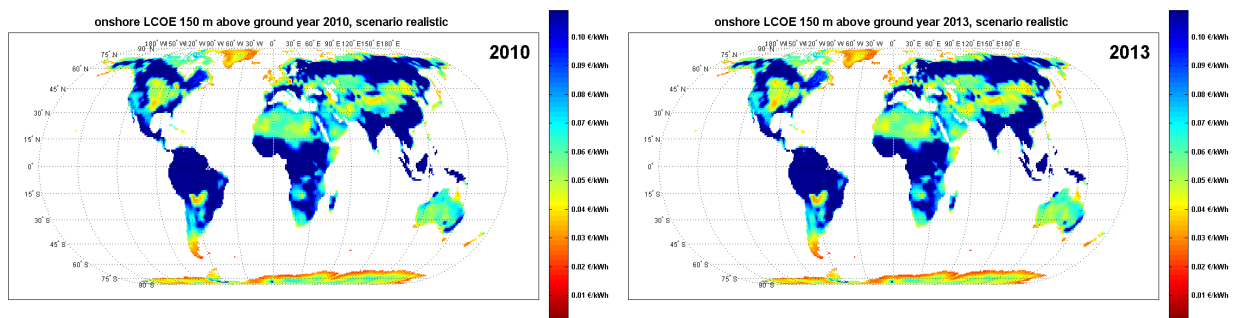


Figure 4.2-15: Wind power Capex estimates for onshore (top) and offshore (bottom) plants. Scenarios are defined in Table 4.2-1.

Full scenario assumptions defined in Table 4.2-1 lead to onshore wind power LCOE illustrated in Figure 4.2-16 for the realistic scenario and in Figure 4.2-17 for the aggressive scenario. LCOE calculations based on Equations 4.2-4 are mainly driven by wind power Capex (Fig. 4.2-15) and local wind resource availability (Fig. 4.2-3), which can be converted by wind turbines in electricity described by annual full load hours of a wind power plant. In this thesis economic analyses including wind power are based on wind power LCOE depicted in Figures 4.2-16 and 4.2-17.



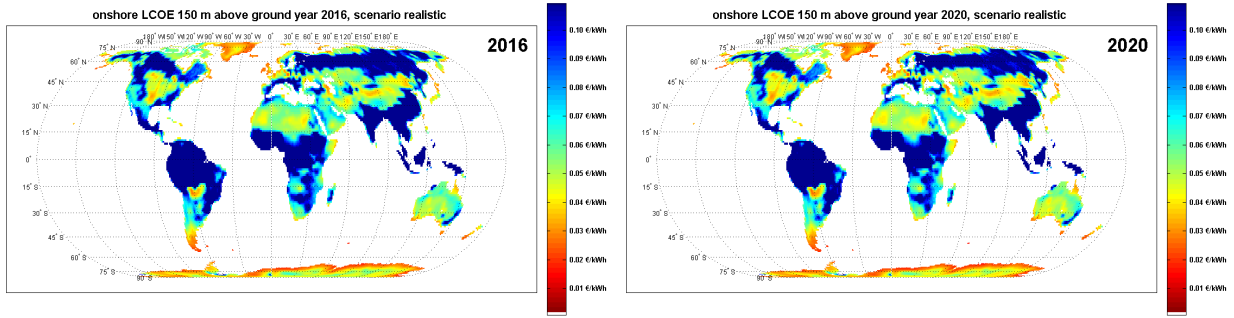


Figure 4.2-16: Global LCOE of onshore wind power plants in the 2010s for the realistic scenario. Wind resource is applied for a hub height of 150 m (Fig. 4.2-3 and 4.2-13). The realistic scenario is defined in Table 4.2-1.

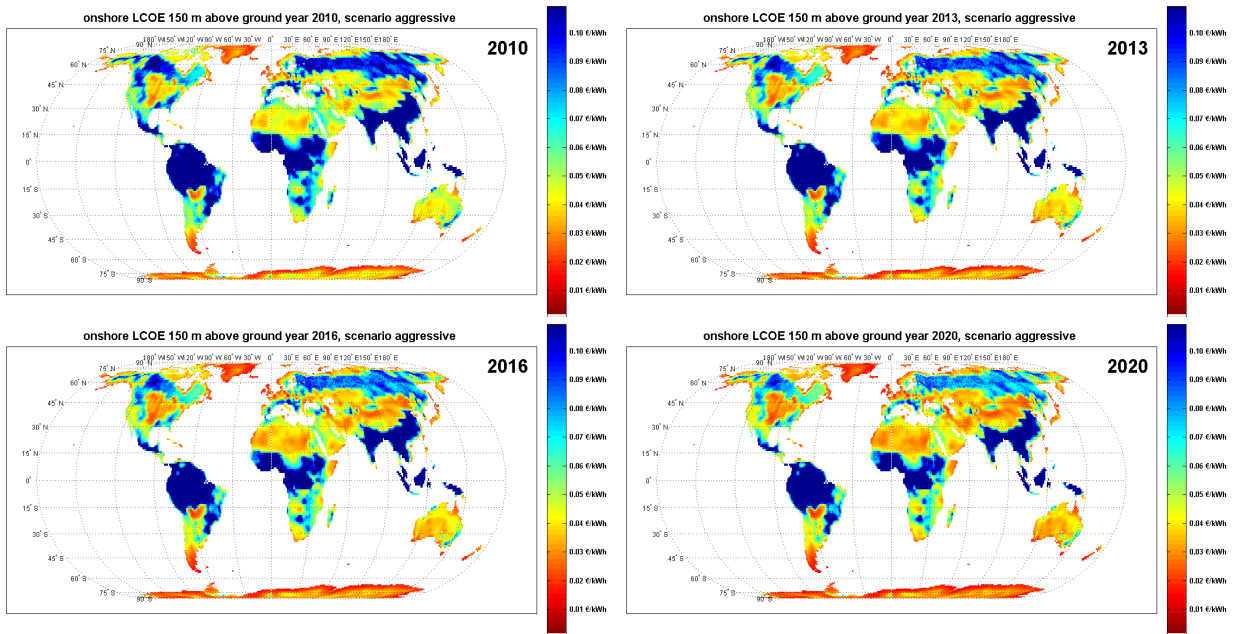


Figure 4.2-17: Global LCOE of onshore wind power plants in the 2010s for the aggressive scenario. Wind resource is applied for a hub height of 150 m (Fig. 4.2-3 and 4.2-13). The aggressive scenario is defined in Table 4.2-1.

The absolute and relative dynamic of wind power LCOE is less than that of PV, as a consequence of lower learning rates and slower growth of historic cumulated installations being a more mature energy technology. However, absolute LCOE for regions of good and excellent wind resources is at a level of 4 €/kWh to 6 €/kWh for the realistic case and at a level of 3 €/kWh to 4 €/kWh for the aggressive scenario. These LCOE are already fully competitive to LCOE of oil and natural gas power plants in most regions in the world (sections 6.2.2 and 6.3.2). Nevertheless, there are several large regions in the world of very low average annual wind speeds and therefore resulting high LCOE. These regions are the tropical rain forests, tundra regions in northern hemisphere and large parts of South and South-East Asia, in particular in India and China. There are many regions in the world having access to low cost wind power (Fig. 4.2-16 and 4.2-17) but also very soon low cost PV (Fig. 3.2-17 and 3.2-18). This is the case for some regions in Southern North America, in the Southern part of South America, in most parts of Sahara desert, parts of Middle East, some Southern parts of Africa, most regions in Australia and regions in Central Asia including regions in China. The question will be raised whether wind power and PV will become very competitive or rather complementary technologies. Discussion on that topic can be found in sub-chapters 4.3 and 7.3.

Offshore wind power LCOE are depicted in Figure 4.2-18 for the realistic scenario and in Figure 4.2-19 for the aggressive scenario. Due to comparably high Capex and Opex the LCOE are significantly higher than those for onshore wind power. Wind resource is excellent for some offshore regions like the North Sea, but this is largely compensated by drastic higher cost. Market share of cumulated installed offshore wind power capacity in relation to total wind power capacity is about 1.3% as of end 2009.⁸⁹

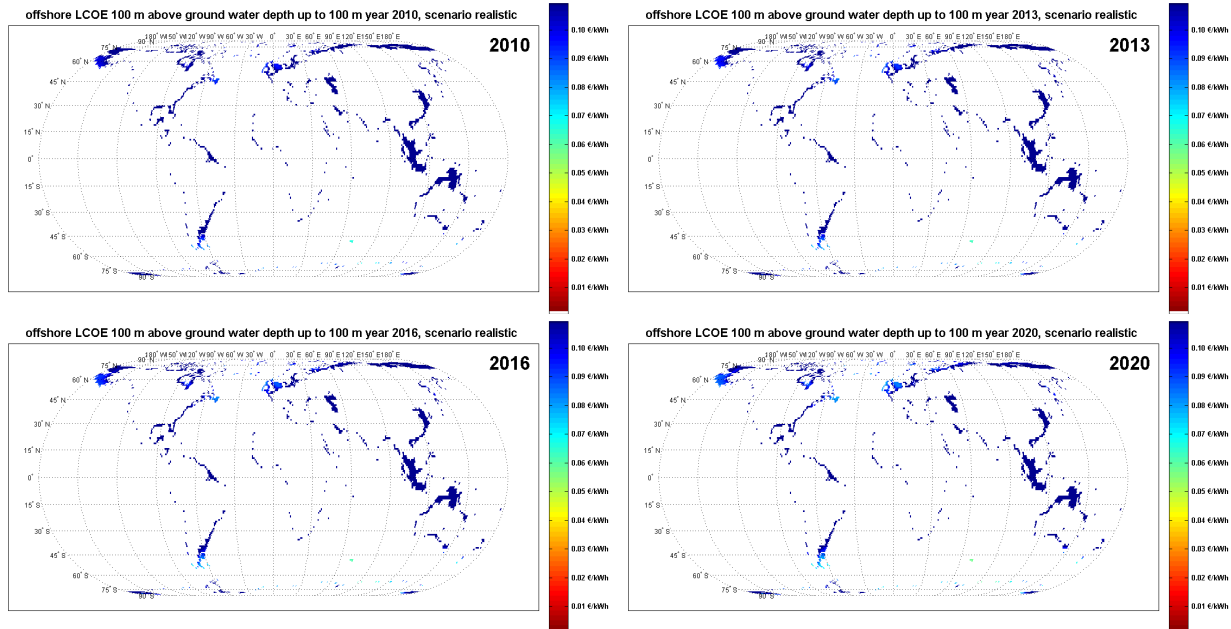


Figure 4.2-18: Global LCOE of offshore wind power plants in the 2010s for the realistic scenario. Wind resource is applied for a hub height of 100 m (Fig. 4.2-14). The realistic scenario is defined in Table 4.2-1.

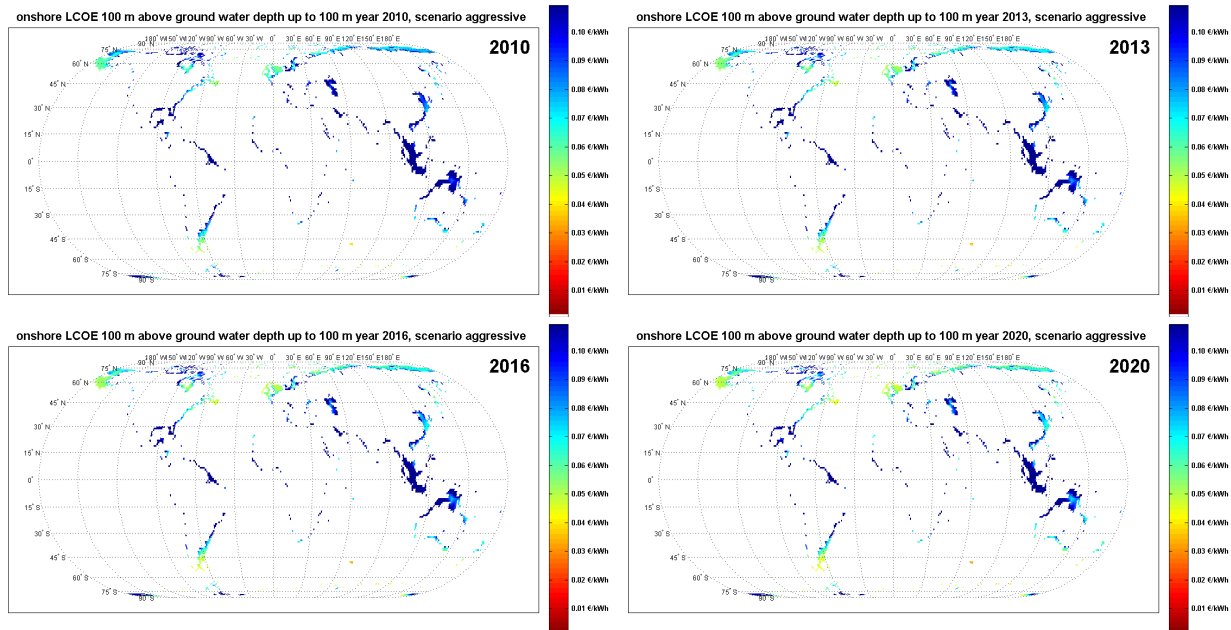


Figure 4.2-19: Global LCOE of offshore wind power plants in the 2010s for the aggressive scenario. Wind resource is applied for a hub height of 100 m (Fig. 4.2-14). The aggressive scenario is defined in Table 4.2-1.

⁸⁹ GWEC, Global Wind 2009 Report, 2010

Offshore wind power shows an economic potential, in particular in regions of limited onshore installation potential. The realistic scenario seems to be considerably more likely than the aggressive one, however LCOE are rather high and range on a 10 €/kWh level for most regions in the world, or even higher. Despite of offshore wind power potential, this variation of wind power technology is not considered in the following. The reasons are mainly the competing onshore wind power potential in adjacent regions and a reduction in complexity for further analyses, in particular due to the focus in this thesis on PV power plants.

Summing up, results for wind power give plenty of insights for an excellent competitiveness of wind power technology. Many regions in the world have good and excellent wind resources (Fig. 4.2-3) which lead to high full load hours of wind power (Fig. 4.2-13), compared to PV power plants. Wind power LCOE are very good (Fig. 4.2-16), but show a lower dynamic compared to PV. Nevertheless, at the end of the 2010s several regions in the world might show quite similar LCOE for wind power and PV. This raises a quite interesting question: Will wind power plants and PV power plants become rather competitive or complementary technologies?

4.3 Integrated Assessment of PV, STEG and Wind Power Economics

Major global renewable power technologies are PV (chapters 2 and 3), STEG (sub-chapter 4.1) and wind power (sub-chapter 4.2) by amount of sustainable utilizable power resource (sub-chapters 7.3 and 7.4).^{90,91,92,93,94} A rough overview on some key criteria is summarized in Table 4.3-1. The evaluation of the technologies by the tabled criteria shows that relative status of the technologies is different at the begin of the 2010s, but the general trend is excellent in this decade. However, further development of PV and wind power is assumed to be more stable and sustainable compared to STEG being faced to some obstacles like lower growth rate, learning rate, scalability and maturity. Nevertheless, all this could be overcome, at least in case of a possible technological and economical breakthrough evolutionary path.

Criteria	PV	STEG	Wind
relative development	fast market diffusion	market entry	nearly mature
energy resource availability	excellent	good	good
raw material limitation	no	no	no
energy return on energy investment	high	high	high
accessible to not electrified people	yes	no	limited
relative cost	moderate/ improving	improving	very good
cost dynamics	very fast	moderate	moderate
learning rate	very high	moderate/ high	moderate/ high
growth rate	outstanding high	high	high
dispatchability - alone	no	yes	no
dispatchability - hybrid	yes	yes	yes
scalability in power size	excellent	good for >50MW	good

Table 4.3-1: Qualitative comparison of PV, STEG and wind power.

⁹⁰ Jacobson M.Z. and Delucchi M.A., Providing all global energy with wind, water, and solar power, 2011

⁹¹ Kohn W., A world powered predominantly by solar and wind energy, 2010

⁹² Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

⁹³ WBGU, World in Transition: Towards Sustainable Energy Systems, 2003

⁹⁴ Weingart J.M., The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, 1978

This sub-chapter is focussed on the relative economics of the major new renewable power technologies, i.e. PV, STEG and wind power. The economic evaluation of these technologies is based on scenario assumptions and resource data for PV (Table 3.2-1 and sub-chapter 2.2), STEG (Table 4.1-1 and sections 2.2.9 and 4.1.1) and wind power (Table 4.2-1 and section 4.2.1). Highly significant for the absolute and relative economic competitiveness is the status and further development of Capex. Overview is given in Figure 4.3-1 on Capex dynamics of the three technologies in its variations and for all applied scenarios for an exemplarily site in Northern Africa.

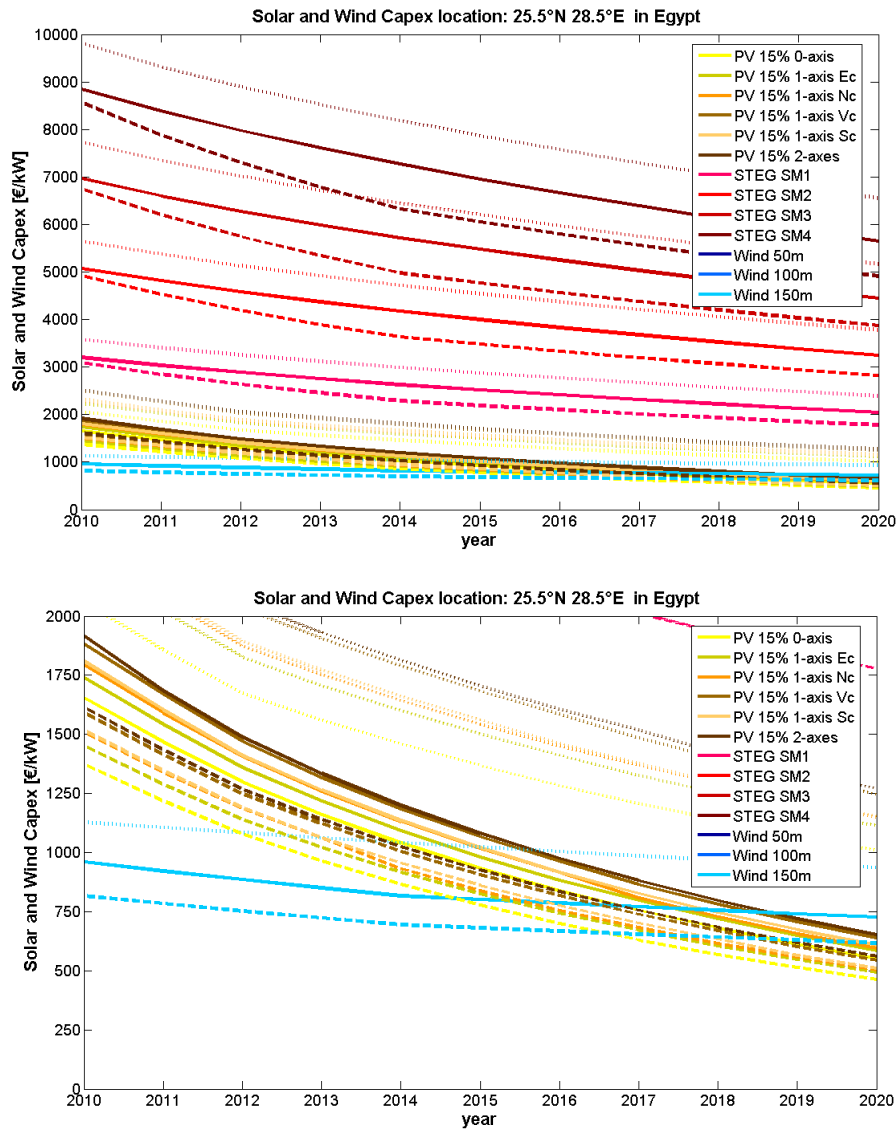


Figure 4.3-1: Status and development of Capex for PV, STEG and wind power plants. Curves are based on scenario assumptions for PV (Table 3.2-1), STEG (Table 4.1-1) and wind power (Table 4.2-1). Scenarios are indicated by dotted (realistic), solid (aggressive) and dashed (bloody/ breakthrough) lines, respectively. Major characteristics are indirectly depicted in low Capex intensive scenario options (bottom) and all options (top). Exemplarily site is 25.5°N/ 28.5°E located in Egypt and shows a GHI of about 2,090 kWh/m²/y, irradiation on 1-axis horizontal north-south tracking of about 2,930 kWh/m²/y, a DNI of about 2,520 kWh/m²/y and average annual wind speed of 6.1 m/s at 150 m hub height. Abbreviations stand for: 15% efficient modules fixed optimally tilted (15% 0-axis), 15% efficient modules 1-axis horizontal east-west tracking (15% 1-axis Ec), 15% efficient modules 1-axis horizontal north-south tracking (15% 1-axis Nc), 15% efficient modules 1-axis vertical optimally tilted tracking (15% 1-axis Vc), 15% efficient modules 1-axis optimally tilted north-south tracking (15% 1-axis Sc) and 15% efficient modules 2-axes non-concentrating tracking (15% 2-axes), solar multiples one to four (SM1 – SM4) and wind power plants on hub heights of 50 m, 100 m and 150 m (Wind 50m, Wind 100m and Wind 150m).

STEG Capex are the highest by far, but STEGs including thermal energy storage of several hours are fully dispatchable and it would be possible to increase annual full load hours into the baseload regime. Therefore value of STEG electricity is the highest, as well. Cost and value of STEG need to be assessed on a LCOE value, at least. Currently, wind power Capex are lower than those of PV, but this is likely to change during the decade due to higher growth and learning rates of PV versus wind power. However, development of LCOE is also dependent on respective full load hours. The value of power is also dependent on its statistical feed-in over the day, i.e. PV power might be more valuable as load is typically higher at daytime when sun is shining.

Comparison of Capex gives a first hint on relative competitiveness but LCOE data generate more precise insights. An overview on absolute and relative status and further scenario expectation for the respective LCOE is illustrated in Figure 4.3-2 for another site in North Africa. LCOE are calculated according to Equations 3.2-1, 4.1-2 and 4.2-4 and respective scenario assumptions defined in Table 3.2-1 (PV), Table 4.1-1 (STEG) and Table 4.2-1 (wind power).

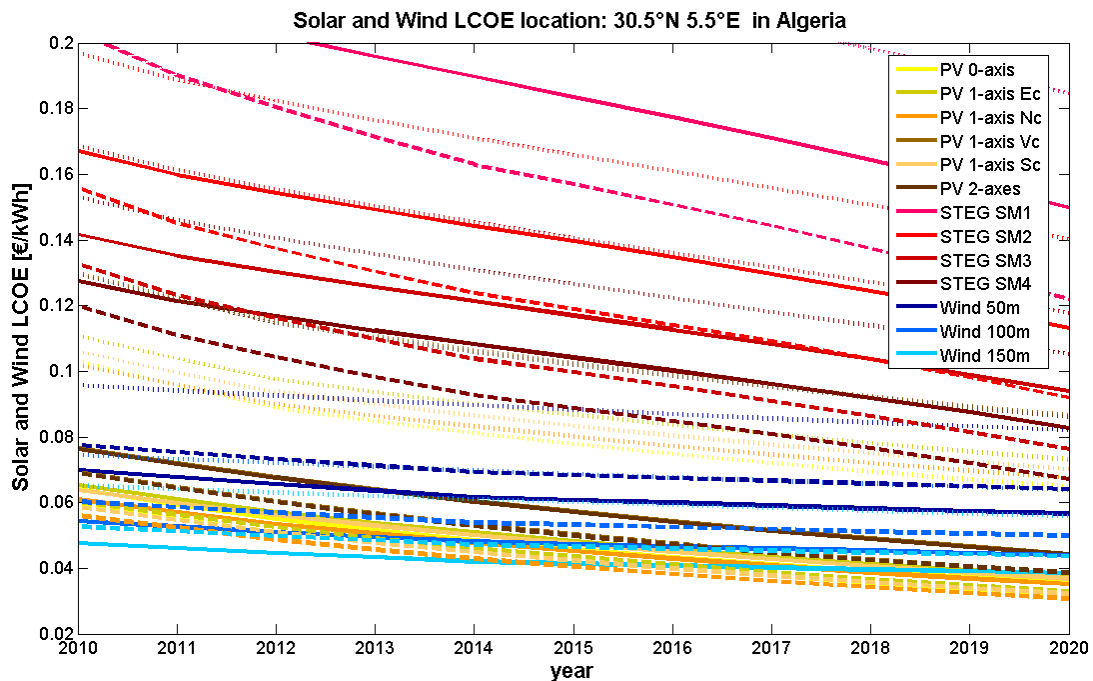


Figure 4.3-2: Status and development of LCOE of PV, STEG and wind power plants. Curves are based on scenario assumptions for PV (Table 3.2-1), STEG (Table 4.1-1) and wind power (Table 4.2-1). Scenarios are indicated by dotted (realistic), solid (aggressive) and dashed (bloody/ breakthrough) lines, respectively. Exemplarily site is 30.5°N/ 5.5°E in Algeria and shows a GHI of about 2,350 kWh/m²/y, irradiation on 1-axis horizontal north-south tracking of about 3,310 kWh/m²/y, a DNI of about 2,940 kWh/m²/y and average annual wind speed of 7.0 m/s at 150 m hub height. Abbreviations stand for: 15% efficient modules fixed optimally tilted (15% 0-axis), 15% efficient modules 1-axis horizontal east-west tracking (15% 1-axis Ec), 15% efficient modules 1-axis horizontal north-south tracking (15% 1-axis Nc), 15% efficient modules 1-axis vertical optimally tilted tracking (15% 1-axis Vc), 15% efficient modules 1-axis optimally tilted north-south tracking (15% 1-axis Sc) and 15% efficient modules 2-axes non-concentrating tracking (15% 2-axes), solar multiples one to four (SM1 – SM4) and wind power plants on hub heights of 50 m, 100 m and 150 m (Wind 50m, Wind 100m and Wind 150m).

STEG LCOE are higher than those of PV and wind power, however STEG plants can be used as a dispatchable power sources in contrary to PV and wind power. Until the mid of the

decade wind power might stay the least cost energy option among the three technologies, but this could change in the second half of the decade, as 1-axis horizontal north-south tracking PV systems catch up. These results are derived for an exemplarily site in North Africa.

The global dynamic of absolute LCOE of the three major renewable power technologies is discussed in the following. Solar and wind resources are the most abundant sources for sustainable power generation on earth (sub-chapter 7.3).^{95,96,97,98,99} Least cost energy options of the variations of PV, STEG and wind power plants are depicted in Figure 4.3-3 for the aggressive scenarios and the 2010s.

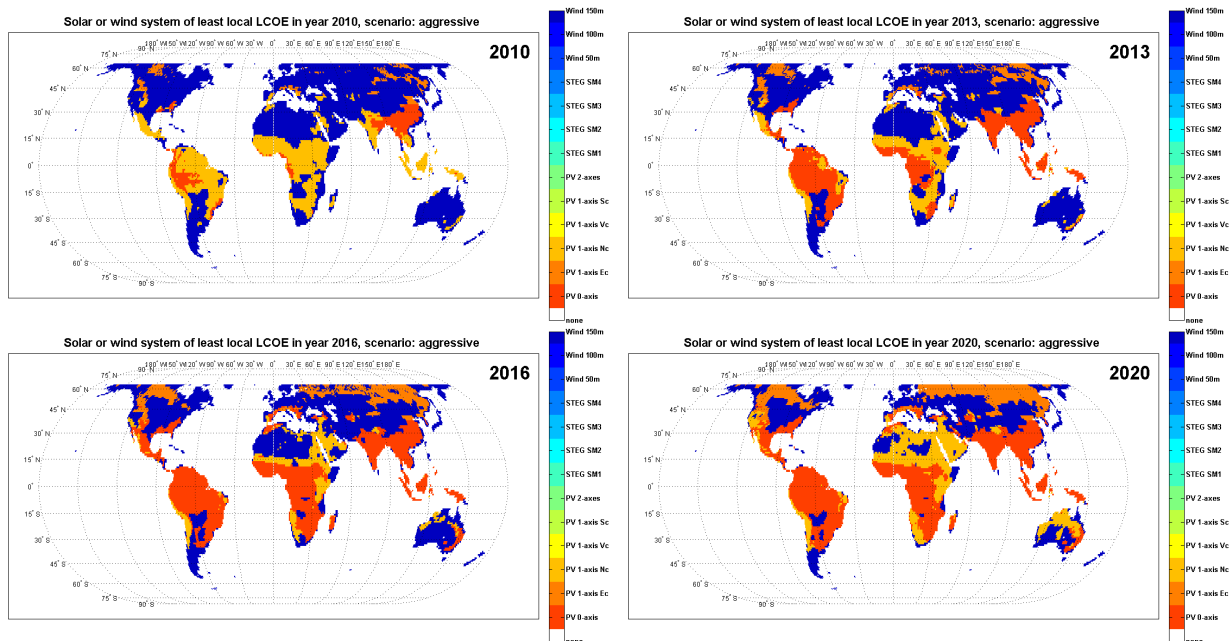


Figure 4.3-3: Least cost PV, STEG and wind power technology in the 2010s for the aggressive scenario. Scenarios are defined in Table 3.2-1 (PV), Table 4.1-1 (STEG) and Table 4.2-1 (wind power). Abbreviations stand for: PV fixed optimally tilted (0-axis), PV 1-axis horizontal east-west tracking (1-axis Ec), PV 1-axis horizontal north-south tracking (1-axis Nc), PV 1-axis vertical optimally tilted tracking (1-axis Vc), PV 1-axis optimally tilted north-south tracking (1-axis Sc) and PV 2-axes non-concentrating tracking (2-axes), solar multiples one to four (SM1 – SM4) and wind power plants on hub heights of 50 m, 100 m and 150 m (Wind 50m, Wind 100m and Wind 150m).

Least cost dynamic reflects absolute quality of renewable resources, in particular at the begin of the 2010s, i.e. good wind resources always result in least cost energy generated by wind power. However, this changes in the decade. At the end of the decade only the excellent wind resource sites are left as least energy cost sites, the entire rest is then covered by PV power plants. But even the least PV energy cost systems change over the years documented by 1-axis horizontal north-south tracking systems, which might be replaced by fixed optimally tilted systems in many regions (section 3.2.4), e.g. in South America, Sub-Sahara Africa and South Asia. However, sites of excellent solar conditions show least LCOE for 1-axis horizontal north-south tracking systems. The results concerning PV only are deeply discussed in section 3.2.4. No single site in the world is found where STEG would be the least cost

⁹⁵ Jacobson M.Z. and Delucchi M.A., Providing all global energy with wind, water, and solar power, 2011

⁹⁶ Kohn W., A world powered predominantly by solar and wind energy, 2010

⁹⁷ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

⁹⁸ WBGU, World in Transition: Towards Sustainable Energy Systems, 2003

⁹⁹ Weingart J.M., The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, 1978

energy option. Consequently, STEG technology needs to offer added value for balancing this disadvantage. Highly valuable characteristic of STEG plants is the thermal energy storage for improved covering of the needs in the grid. Due to that STEG plants are dispatchable and can cover the load requirements, especially in the evenings showing the highest load of a day in many regions in the world.

Absolute least energy cost independent on the specific considered technology is shown in Figure 4.3-4.

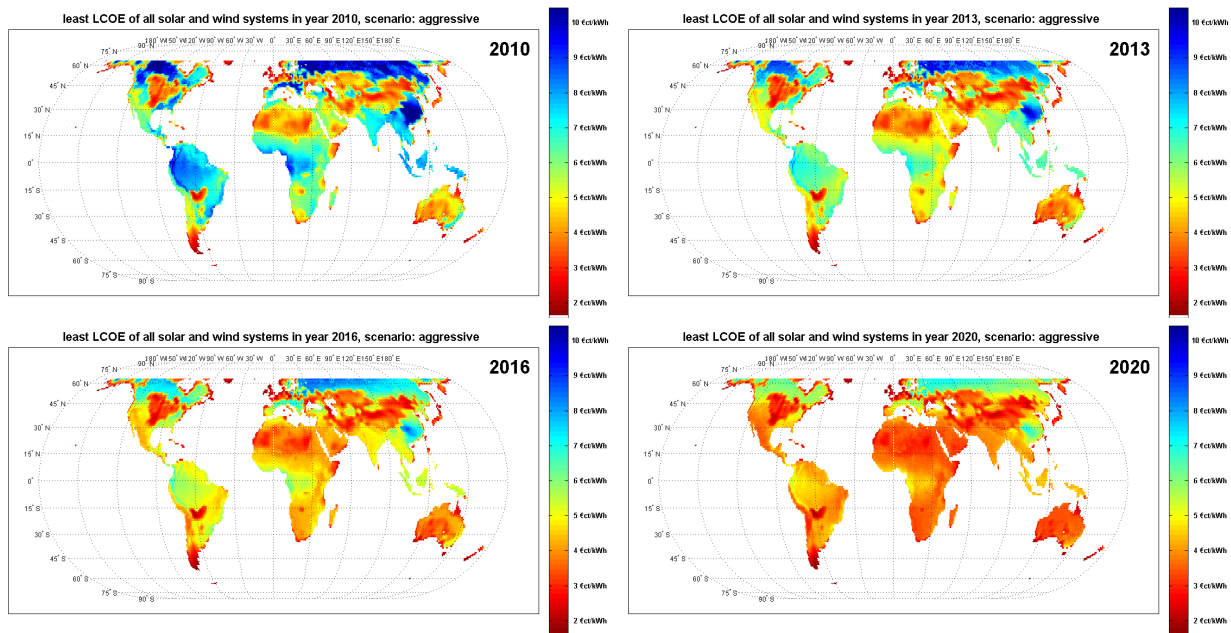


Figure 4.3-4: Least power generation cost of covered PV, STEG and wind power technologies in the 2010s for the aggressive scenario. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately optimised for least LCOE of all considered power technologies of this section. Technology of least LCOE is named in Figure 4.3-3. The scenarios are defined in Table 3.2-1 (PV), Table 4.1-1 (STEG) and Table 4.2-1 (wind power).

Most relevant outcome of least LCOE analysis is the convergence of PV and wind power plants. At the beginning of the 2010s the regions of excellent wind resource conditions (section 4.2.1) already achieve competitive LCOE even compared to fossil fuel fired power plants (sub-chapters 6.2 to 6.4). Regions of unfavourable wind conditions often receive very good solar irradiation, therefore least PV LCOE is below 10 €/kWh. Regions of only moderate wind and solar resource are unable to generate renewable electricity below 10 €/kWh by power technologies investigated in this thesis. However, this changes dramatically during the decade. In the mid of the decade all regions within latitudes of 65°N/S show LCOE below 10 €/kWh and most regions of excellent solar or wind resources might achieve renewable LCOE below 5 €/kWh. At the end of the decade regions of highest renewable LCOE might be at a level of 7 €/kWh and most regions in the world could be below 5 €/kWh and at sites of excellent solar or wind conditions a LCOE level of 4 – 5 €/kWh might be achieved. All these LCOE refer to the aggressive scenarios. The values for the realistic scenarios would be 30% - 40 % higher in average.

For a better understanding of relative PV and wind power cost levels, the absolute difference of the least cost PV system to wind power LCOE is depicted in Figure 4.3-5 for the aggressive scenario in the 2010s.

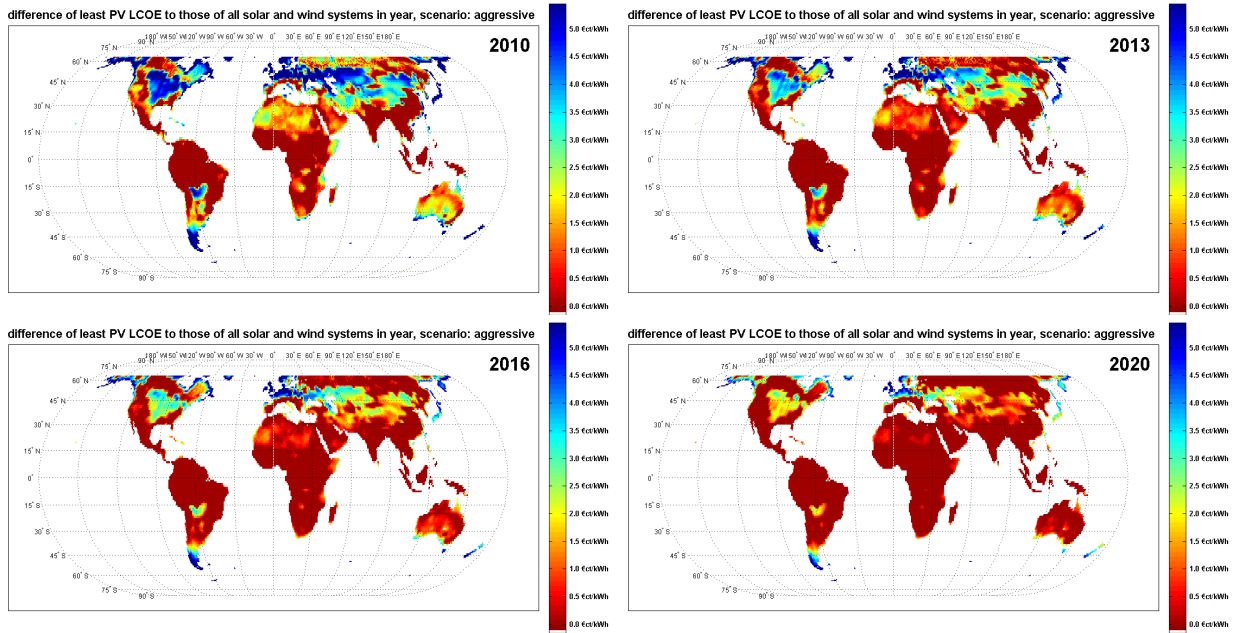


Figure 4.3-5: Difference of least PV LCOE to all solar and wind LCOE in the 2010s for the aggressive scenario. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately considered. The technology of least LCOE is named in Figure 4.3-3 and the absolute LCOE level is depicted in Figure 4.3-4. The scenarios are defined in Table 3.2-1 (PV), Table 4.1-1 (STEG) and Table 4.2-1 (wind power).

The outcome is similar to the results found for the least absolute LCOE. Regions of only moderate wind resource show PV as least cost renewable technology as a consequence at the begin of the 2010s. In all regions of excellent wind resources and only moderate solar resources, PV is more than 5 €/kWh higher in LCOE. Regions receiving excellent solar irradiation, too, show LCOE difference of below 5 €/kWh. By mid of the 2010s, more and more regions can be supplied by least cost PV systems. If excellent solar and wind resources are available, the cost difference of the respective least cost PV system to those of wind power will be lower than 5 €/kWh. By the end of the 2010s, only regions of excellent wind resources might represent lower wind power LCOE than PV LCOE. In most regions PV systems are the least cost energy option at an absolute LCOE level of 5 €/kWh or below (Fig. 4.3-4 and 4.3-5). All the statements of this paragraph are valid for aggressive scenario assumptions.

The calculations in this chapter are derived on average annual resource data. A very relevant question arises now: Are the solar and the wind resources available in a competitive or a complementary manner? Wind power reaches 2,000 – 3,500 full load hours at good sites (Fig. 4.2-13), whereas sites of good fixed optimally tilted PV systems reach 1,600 – 2,000 full load hours for a respective solar resource of 2,000 – 2,500 kWh/m²/y (Fig. 2.2-3) and sites of good 1-axis horizontal north-south continuous tracking PV systems reach 1,900 – 2,700 full load hours for a respective solar resource of 2,500 – 3,500 kWh/m²/y (Fig. 2.2-14). Solar resources and wind resources are the most abundant sustainable energy sources on earth, as shown in this section in particular in its economic dimension. It could be of the utmost relevance to understand the time resolved power supply potential of PV and wind power. A detailed assessment on this coherence is discussed in sub-chapter 7.3, i.e. whether solar and wind resource availability is characterised by a rather competitive or complementary nature in terms of time resolved power supply potential.

Summing up the results of this section, it can be stated that the status at the beginning of the 2010s is best described by very competitive wind power plants, whereas the dynamic is much

higher for PV power plants. At the end of the decade PV and wind power technology are very likely to reach both low absolute levels of LCOE, i.e. about or even below 5 €/kWh in most regions in the world. STEG plants can be expected to range at a level of 9 – 12 €/kWh. Despite of a factor of two in higher LCOE, relative competitiveness could be not too bad, as thermal energy storage enables STEG plants full dispatchability. Nevertheless, seasonal variations in resource availability also affect STEG plants. Answering the question, whether solar and wind resources, i.e. PV and wind power plants, are characterized best by a rather competitive or complementary nature is at utmost relevance for future power supply on earth. Both PV and wind power technology are a fluctuating power generation source, but they are available for rather low LCOE all around the world and are sustainable in all dimensions. If these two technologies were rather complementary than competitive they would have the potential to become the major pillar of sustainable energy supply in the world.

Chapter 5

Power Plants of the World

Renewable power plants need to be integrated into the current power plant structure. However, not the today's electricity supply habits create the most relevant constraints but the criteria for a sustainable energy supply, hence non sustainable traditions have to be overcome in the decades to come. Long-lasting available and cheap energy sources will form the key cornerstones of a power infrastructure in transition. This is true for hydro power, wind power and PV power, at least at the end of the 2010s. STEG plants might complement the aforementioned core power technologies. The other power technologies violate one or more sustainability criteria and need to be substituted (e.g. oil, natural gas, coal, nuclear), will never reach significant amount in global sustainable energy supply (e.g. biomass), or stuck still in basic research (e.g. ocean power).

The fast growing new core technologies need to be integrated into the current power infrastructure and the energy system has to be transformed for a rapid market diffusion of these technologies, in particular solar PV and wind power. For a better understanding of all these circumstances the currently used power technologies are illustrated in some key characteristics and typically from a global perspective, as PV and wind power will diffuse fast in all regions in the world. Therefore a general overview on the global electricity consumption patterns and the **power plants of the world** (sub-chapter 5.1) is given.

All major power plant technologies are discussed in this thesis, however in different chapters representing the special view of this thesis. In this chapter only these power plant technologies are discussed which are not treated elsewhere due to their negligible role for hybrid PV power plants in the next one to two decades, i.e. **biomass power** (sub-chapter 5.2), **geothermal power** (sub-chapter 5.3), **ocean power** (sub-chapter 5.4) and **nuclear power** (sub-chapter 5.5). An overview on the power technologies and in which chapters they can be found is given in Table 5.0-1.

Power Technology	Chapter/ Sub-chapter/ Section
Photovoltaic	2, 3, 4.3, 5.1, 6, 7
STEG	2.2.9, 4.1, 4.3, 5.1, 7.2
Wind	3.4.2, 4.2, 4.3, 5.1, 7.3, 7.4
Hydro	5.1, 7.1
Biomass	5.1, 5.2
Geothermal	5.1, 5.3
Ocean	5.4
Nuclear	1.3.4, 3.1.3.4.3, 5.1, 5.5
Oil	1.3.1, 5.1, 6.2, 6.5
Natural Gas	1.3.2, 5.1, 6.3, 6.5
Coal	1.3.3, 5.1, 6.4, 6.5

Table 5.0-1: Overview on power plant technologies and their treatment in this thesis.

5.1 Overview on General Global Electricity Consumption Patterns and Power Plants

Global electricity generation has been 20,180 TWh in the year 2008 and was provided by a power plant fleet of 4,720 GW which corresponds to an average of about 4,300 full load hours per power plant.¹ Therefore, global average electricity generation per capita is about 3.0 MWh_{el} for the world population of about 6.83 billion people². However, neither the average electricity consumption per capita (Fig. 5.1-1) nor the electricity flow rate per area (Fig. 5.1-4) is equally distributed in the world. Industrialised countries consume annually electricity of about 5 – 10 MWh_{el}/capita, whereas emerging countries range between 0.5 – 3 MWh_{el}/capita and poor developing countries consume typically below 300 kWh_{el}/capita. Countries consuming annually less than 1 MWh_{el}/capita show typical electrification rates of less than 50% (Fig. 1.4-5 and 3.4-1).

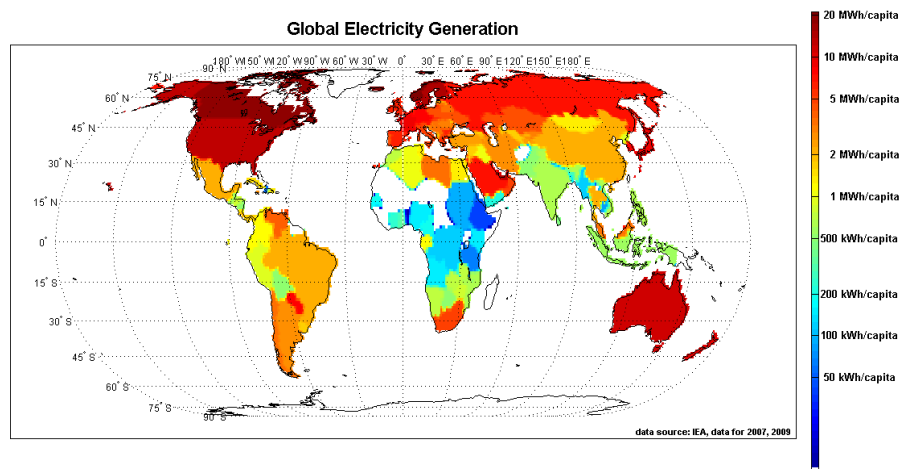


Figure 5.1-1: Global electricity generation per capita for the year 2007. No data have been available for white coloured countries. Data are provided by International Energy Agency³ and United Nations⁴.

However, energy efficiency measured in electricity consumption per GDP is distributed quite inhomogeneously in the world (Fig. 5.1-2 and 5.1-3). Among the industrialised countries, North America seem to be significantly less energy efficient than the European Union and Japan. The transition economies of the former Soviet Union range even higher than North America and hence clearly indicate a highly inefficient use of electricity. However, several emerging and developing countries show even higher electricity consumption per GDP. This is the case for China, Egypt and countries in Southern Africa.

Nevertheless, electricity consumption per capita and GDP per capita are highly interdependent (Fig. 5.1-3). It is not absolutely clear whether electricity consumption is dependent on GDP or vice versa, however there are indications that electricity consumptions rather drives the GDP than the other way round (sub-chapter 1.4). The dependence in a double logarithmic plot is a linear function. There are deviations for developing countries. Electricity consumption per capita is much lower for instance in Angola and Congo than average and much higher than average as an example in Tajikistan, Kyrgyzstan and Uzbekistan. The

¹ IEA, World Energy Outlook 2010, 2010

² UN, World Population Prospects: The 2008 Revision Highlights, 2009

³ IEA, Key World Energy Statistics 2009, 2009

⁴ UN, World Population Prospects: The 2008 Revision Highlights, 2009

former are among the countries of most inhomogeneous income distribution and the latter are among the transition countries characterized by very inefficient energy use.

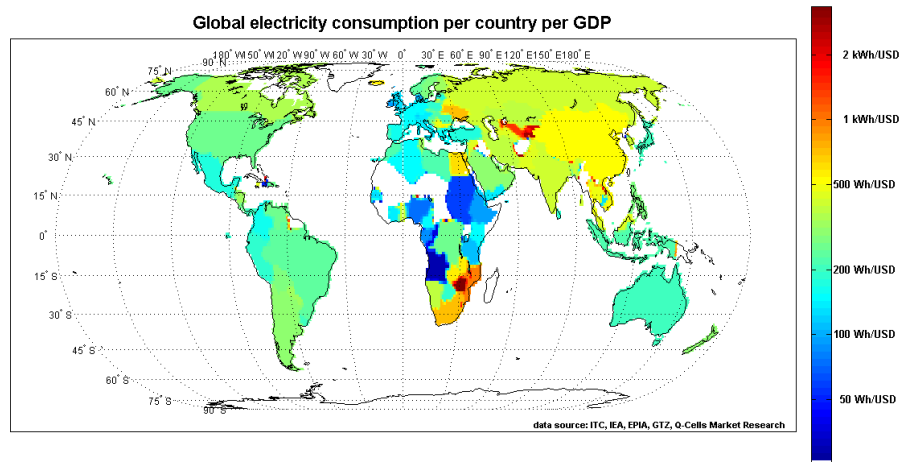


Figure 5.1-2: Global electricity consumption per country and per GDP for the year 2007. No data have been available for white coloured countries. The unit for specific electricity consumption is GWh/mUSD. Data are provided by International Energy Agency ⁵ and World Bank ⁶.

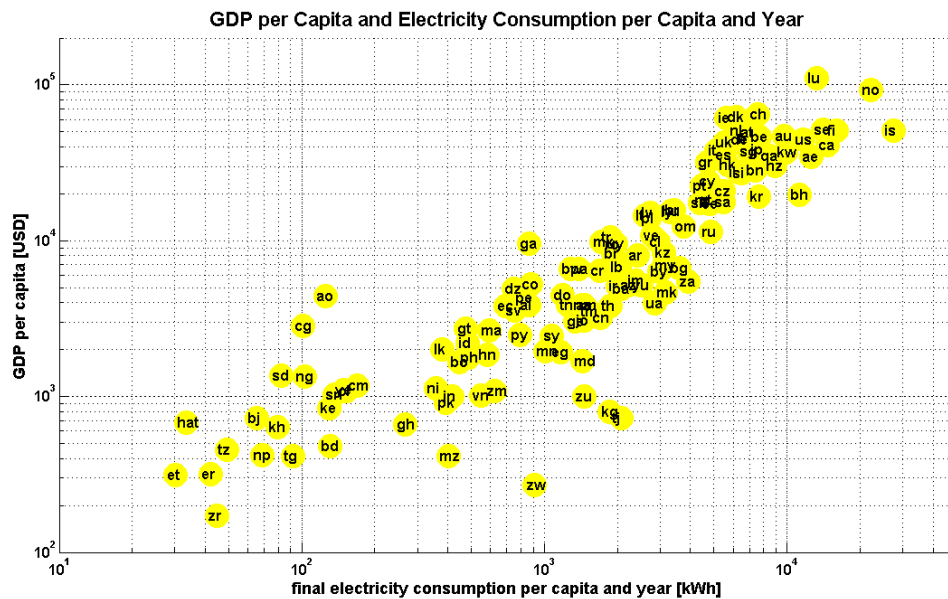


Figure 5.1-3: GDP per capita in dependence on electricity consumption per capita for the year 2007. The dataset comprises all countries in the world being named by respective country codes of top level web domain (Appendix Table 4). Data are provided by International Energy Agency ⁷, United Nations ⁸ and World Bank ⁹.

Since electricity generation and consumption is typically located close to one another it is possible to plot electricity consumption per area (Fig. 5.1-4) which is based on the per capita distribution (Fig. 5.1-1) and the global population density distribution (Fig. 2.3-1). Per capita consumption in Asia is lower than in Europe or North America, but electricity consumption density per area is comparable due to a much higher population density in Asia.

⁵ IEA, Key World Energy Statistics 2009, 2009

⁶ World Bank, Gross domestic product 2008, World Development Indicators database, 2009

⁷ IEA, Key World Energy Statistics 2009, 2009

⁸ UN, World Population Prospects: The 2008 Revision Highlights, 2009

⁹ World Bank, Gross domestic product 2008, World Development Indicators database, 2009

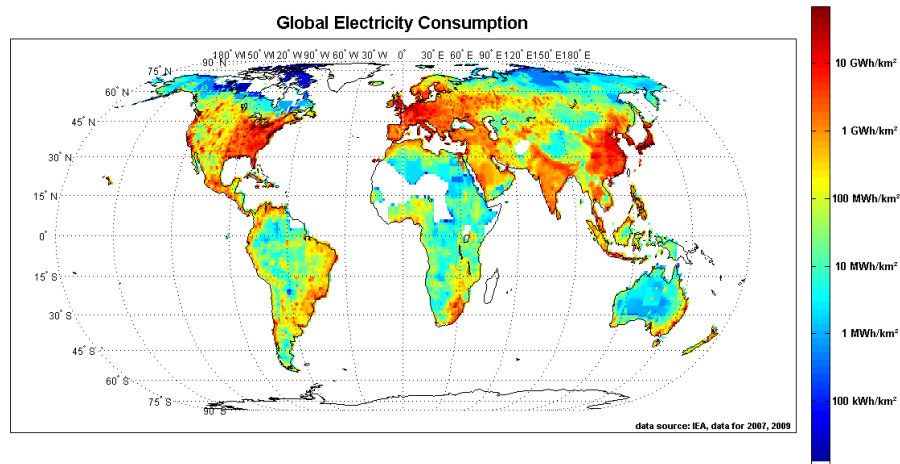


Figure 5.1-4: Global electricity consumption per area for the year 2007. No data have been available for white coloured countries. Electricity consumption per country is weighted by population density (Fig. 2.3-1) according to the assumption of approximately equal per capita consumption per country. Areas coloured red show a high and dark red a very high density of electricity consumption. The unit for electricity consumption density is kWh/km². Data are provided by International Energy Agency ¹⁰ and Center for International Earth Science Information Network ¹¹. Population input data are used in a 1°x1° mesh.

In the following the integrated view is more decoupled from the electricity consumption patterns and more focussed on the power plants based on UDI World Electric Power Plants database provided by Platts ¹² and supplemented by IEA data ¹³.

Global installed power plant capacity per country is illustrated in Figure 5.1-5. Industrialised countries and emerging countries have considerable power plant capacities in operation, whereas least developed countries hold nearly no power plant capacity, which is the case for instance for most countries in Sub-Sahara Africa.

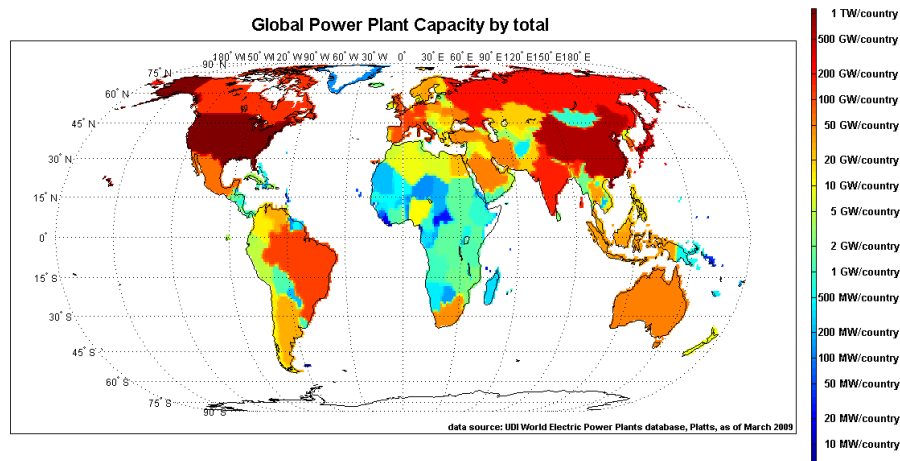


Figure 5.1-5: Global power plant capacity per country by early 2009. Only power plants in operation are regarded. Data are taken from UDI World Electric Power Plants database ¹⁴.

¹⁰ IEA, Key World Energy Statistics 2009, 2009

¹¹ Balk D. and Yetman G., The Global Distribution of Population: Gridded Population of the World, 2005

¹² Platts, UDI World Electric Power Plants data base, 2009

¹³ IEA, Key World Energy Statistics 2009, 2009

¹⁴ Platts, UDI World Electric Power Plants data base, 2009

It is necessary to have the coordinates of the power plants for further analysis. Due to that the UDI World Electric Power Plants database¹⁵ has been enhanced by coordinates of all 145,000 power plants in the world.¹⁶ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. Compared to the cumulated data of IEA¹⁷, capacities of 150 GW are missing. A crosscheck by power technologies reveals a missing capacity of 14 GW PV systems (1.6 GW in the database versus 15.7 GW real capacity¹⁸), 35.5 GW wind power plants (84.8 GW in the database versus 120.3 GW real capacity¹⁹), 55 GW hydro power plants (890 GW in the database versus 945 GW real capacity²⁰) and 20 GW of biomass and waste power plants (31.6 GW in the database versus 52 GW real capacity²¹). The remaining difference of 25 GW of IEA and UDI data concerns different fuel type classification of oil and natural gas power plants and exact date of coal power plant commissioning. It is not clear why the database is of such low quality in PV and wind power, in particular due to many included very small diesel generators of only some kW, which is much lower than most of the large PV systems and most of all wind power plants in the world. In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration have been taken in these cases. The result of the georeferenced global power plant capacity being in operation is depicted in Figure 5.1-6. Power plant capacity in China and India is largely concentrated in state capitals in the dataset, this deviates from reality, but the distortion for the further analysis is very low due to similar local resource conditions.

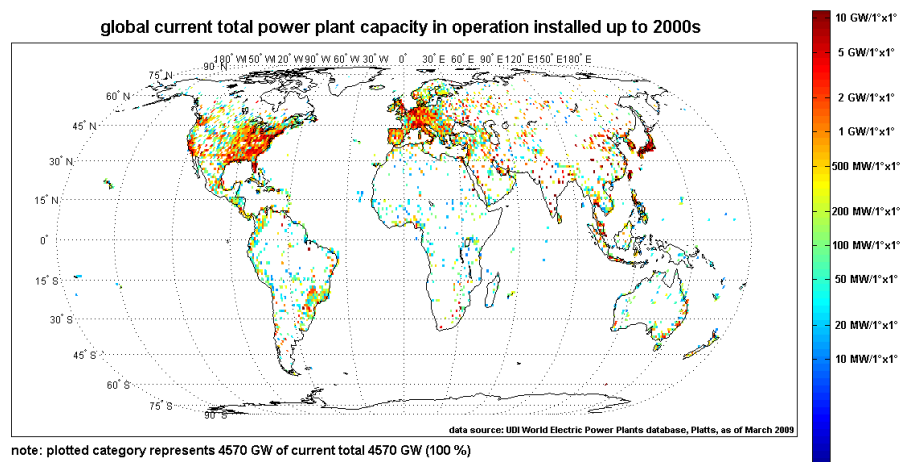


Figure 5.1-6: Global power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. Data are plotted in a 1°x1° mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database²² and enhanced by exact coordinates of all power plants.

Coupling of georeferenced power plant data (Fig. 5.1-6) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current power plant capacity (Fig. 5.1-7). Based on this analysis, current global electricity generation weighted average fixed optimally tilted irradiation is computed to about 1,690 kWh/m²/y (section 2.3.2).

¹⁵ Platts, UDI World Electric Power Plants data base, 2009

¹⁶ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

¹⁷ IEA, World Energy Outlook 2010, 2010

¹⁸ EPIA, Global Market Outlook for Photovoltaics until 2014, 2010

¹⁹ GWEC, Global Wind 2009 Report, 2010

²⁰ IEA, World Energy Outlook 2010, 2010

²¹ IEA, World Energy Outlook 2010, 2010

²² Platts, UDI World Electric Power Plants data base, 2009

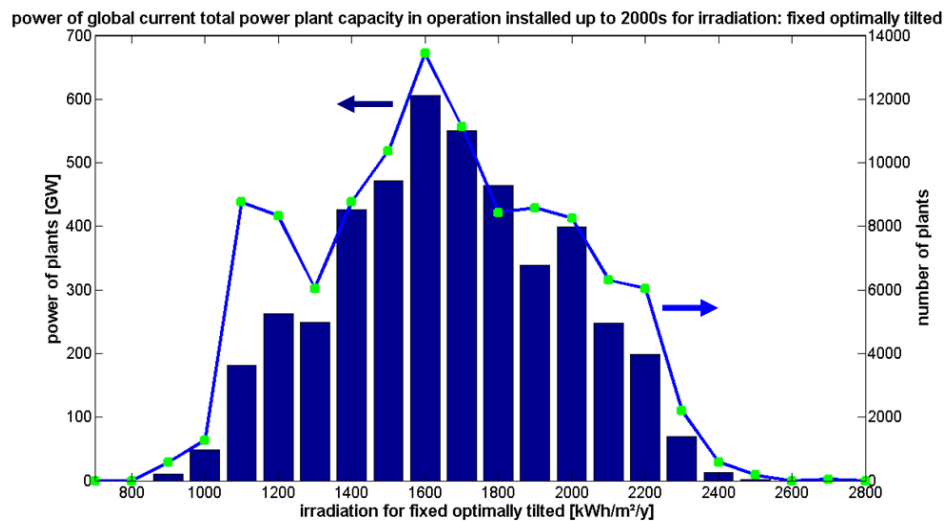


Figure 5.1-7: Global power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 5.1-6) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

Based on the global electricity generation weighted average fixed optimally tilted irradiation of about 1,690 kWh/m²/y (section 2.3.2), it is possible to derive a rough estimate of global PV capacity which can be installed without severe structural impact on current power system structure (section 3.1.1.3). It is assumed that a 10% electricity supply contribution of PV systems would have no dramatic consequences for the electricity system.²³ Hence, 10% of current global 20,000 TWh electricity generation²⁴, i.e. 2,000 TWh, could be provided by PV systems. Average irradiation at sites of global power plant capacity is about 1,690 kWh/m²/y, which translates to a yield of about 1,335 kWh/kWp installed capacity assuming a moderate performance ratio of 79%. Consequently, about 1,500 GW installed PV power capacity would be needed to generate 2,000 TWh per year for an average yield of 1,335 kWh/kWp. Most of this technical easily accessible capacity might be tapped by PV systems which become economic by grid-parity events in the 2010s (sub-chapter 3.3). If an advanced economic storage system for PV electricity was available, the technical potential would dramatically increase by factors.

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 5.1-8 and shows that most power plants are in the power class of 1 - 10 MW or even smaller in size. However, their contribution to global power capacity is negligible. Almost 70% of global power plant capacity consists of power plants of 100 – 1000 MW in size. Only a few power plants are larger in size.

²³ Braun M. et al., Value of PV Energy in Germany - Benefit from the Substitution of Conventional Power Plants and Local Power Generation, 2008

²⁴ IEA, World Energy Outlook 2010, 2010

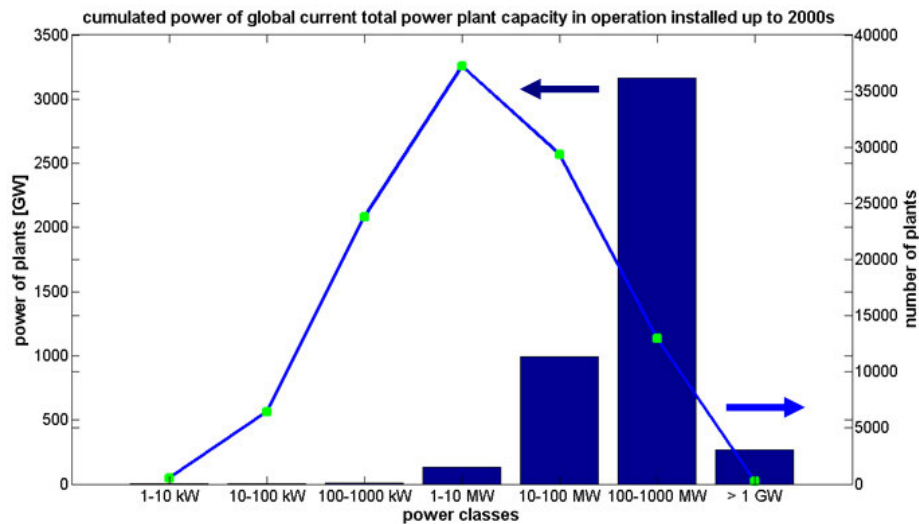


Figure 5.1-8: Global power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent power plant capacity. Data are taken from UDI World Electric Power Plants database ²⁵.

Global power plant capacity shows several significant trends if it is arranged by major power technologies and sorted by year of commissioning for all power plants still in operation (Fig. 5.1-9). From the 1970s to the 1990s average annual new capacity investments had been about 80 GW, whereas the late 1980s and early 1990s had a dip by about 20 GW, which might be caused by the collapse of the Soviet Union and the democratisation in Eastern Europe. The 2000s had been years of enormous new power plant investments of annually 120 – 180 GW. However, nuclear power plants received no significant new capacities, which might be a consequence of Three Miles Island disaster in 1979 and Chernobyl meltdown in 1986, but also of market liberalizations and cut down of subsidies. Hydro power and even oil power plants have been built on an approximately stable rate. Natural gas power plants have gained a major market share in new installations, in particular from the beginning of the early 1990s. Coal power plants seem to be the fastest growing power plant technology in the last years, however a regional split of power plant investments clearly shows, that coal power is on a phasing out path in nearly all countries in the world, except China accounting for about 85% - 90% of global coal power installations (Fig. 5.1-10). About 40% - 50% of global new power plant investments are currently realised in China. However, global trend to large investments in new natural gas power plant investments is not supported in Asia, where only relatively low investments in those plants can be found (Fig. 5.1-10).

²⁵ Platts, UDI World Electric Power Plants data base, 2009

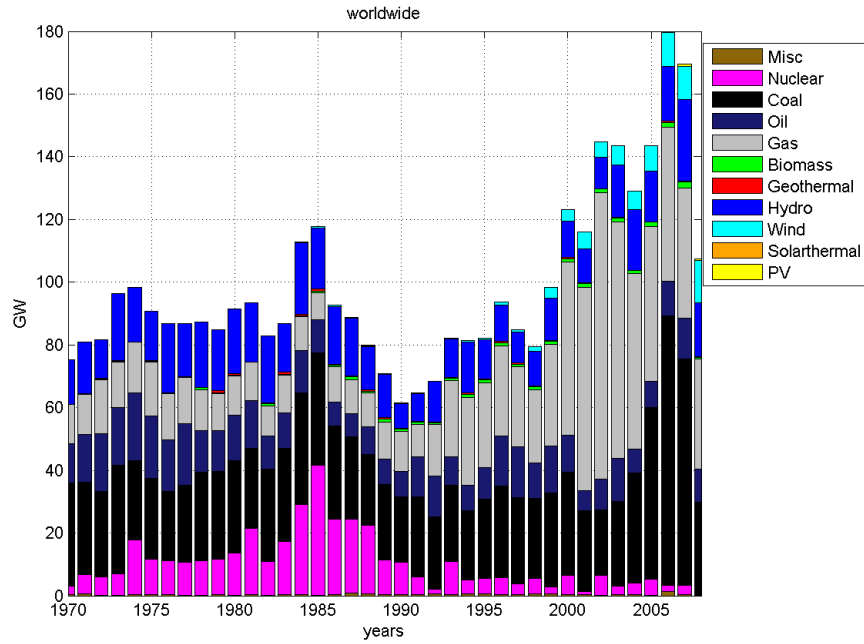


Figure 5.1-9: Global annual power plant capacity investments by power technology for the years 1970 to 2008. Only power plants still in operation are regarded. Data are taken from UDI World Electric Power Plants database ²⁶.

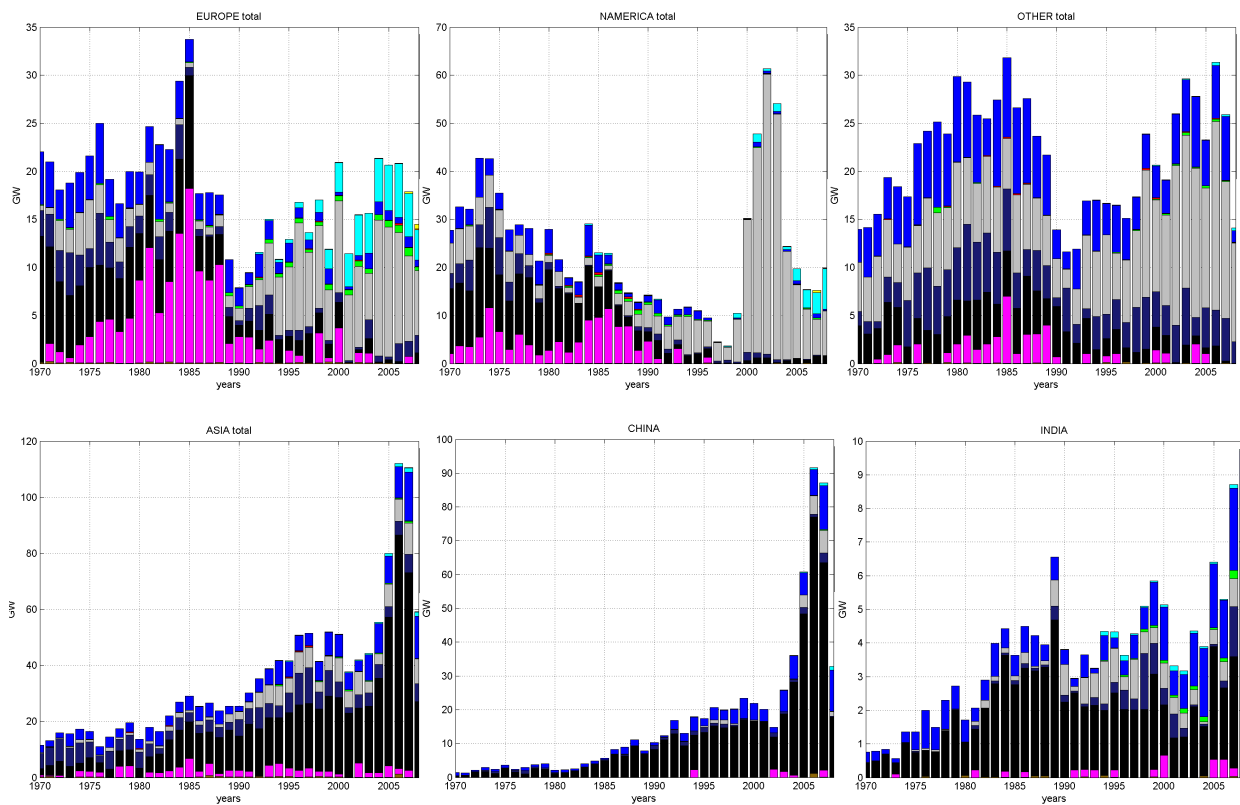


Figure 5.1-10: Regional annual power plant capacity investments in Europe (top, left), North America (top, centre), Asia (bottom, left), China (bottom, centre), India (bottom, right) and other regions (top, right) by power technology for the years 1970 to 2008. Colour coding of power plant capacity is identical to Figure 5.1-9. Only power plants still in operation are regarded. Data are taken from UDI World Electric Power Plants database ²⁷.

²⁶ Platts, UDI World Electric Power Plants data base, 2009

²⁷ Platts, UDI World Electric Power Plants data base, 2009

Global power plant capacity in operation is summarized in absolute (Table 5.1-1) and relative (Table 5.1-2) numbers for all major power plant technologies and the respective decade of commissioning. By end of 2000s global power plant capacity was structured in coal power (1,470 GW, 32%), natural gas power (1,100 GW, 24%), hydro power (890 GW, 20%), oil power (560 GW, 12%), nuclear power (390 GW, 9%), wind power (85 GW, 2%), biomass power (30 GW, 1%), geothermal power (10 GW, 0%) and other technologies (40 GW, 1%) according to the UDI World Electric Power Plants database.²⁸ Nearly 50% of global power plant capacity has been installed in the last two decades. However, more than 150 GW of hydro power capacity is older than 60 years confirming the high lifetime assumptions of that major renewable power technology (section 3.1.6.2).

	up to 1930s [GW]	1940s [GW]	1950s [GW]	1960s [GW]	1970s [GW]	1980s [GW]	1990s [GW]	2000s [GW]	up to 2000s [GW]
PV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	1.6
STEG	0.0	0.0	0.0	0.0	0.0	0.3	0.1	0.1	0.5
Wind	0.1	0.0	0.1	0.1	0.3	2.3	11.2	81.0	84.8
Hydro	33.8	24.0	105.7	187.9	269.8	305.3	211.5	282.3	889.7
Geothermal	0.0	0.0	0.1	0.5	1.8	5.7	5.4	3.1	10.6
Biomass	0.2	0.2	0.7	1.6	4.1	6.4	11.8	16.6	31.6
Gas	1.8	3.3	27.0	106.7	212.8	190.6	330.0	679.5	1101.9
Oil	0.5	1.1	7.8	77.0	263.6	198.3	221.9	167.5	558.4
Coal	0.5	3.0	66.3	198.5	355.7	446.5	502.4	804.9	1465.5
Nuclear	0.0	0.0	0.0	2.9	115.7	267.5	82.0	52.8	392.2
misc/ unknown	0.2	0.4	1.3	5.1	6.2	8.3	12.2	15.8	35.8
total	30.8	25.1	167.1	418.3	876.3	929.2	822.7	1303.1	4572.6

Table 5.1-1: Global power plant capacity by power plant technology and decade of commissioning by early 2009 in absolute capacity. Only power plants still in operation are regarded. Data are taken from UDI World Electric Power Plants database²⁹.

	up to 1930s [%]	1940s [%]	1950s [%]	1960s [%]	1970s [%]	1980s [%]	1990s [%]	2000s [%]	up to 2000s [%]
PV	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
STEG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Wind	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	1.8%	1.9%
Hydro	0.7%	0.5%	2.3%	4.1%	5.9%	6.7%	4.6%	6.2%	19.5%
Geothermal	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.2%
Biomass	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.3%	0.4%	0.7%
Gas	0.0%	0.1%	0.6%	2.3%	4.7%	4.2%	7.2%	14.9%	24.1%
Oil	0.0%	0.0%	0.2%	1.7%	5.8%	4.3%	4.9%	3.7%	12.2%
Coal	0.0%	0.1%	1.4%	4.3%	7.8%	9.8%	11.0%	17.6%	32.0%
Nuclear	0.0%	0.0%	0.0%	0.1%	2.5%	5.8%	1.8%	1.2%	8.6%
misc/ unknown	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.3%	0.3%	0.8%
total	0.7%	0.5%	3.7%	9.1%	19.2%	20.3%	18.0%	28.5%	100.0%

²⁸ Platts, UDI World Electric Power Plants data base, 2009

²⁹ Platts, UDI World Electric Power Plants data base, 2009

Table 5.1-2: Global power plant capacity by power plant technology and decade of commissioning by early 2009 in relative numbers. Only power plants still in operation are regarded. Data are taken from UDI World Electric Power Plants database³⁰.

Structure of power plant capacity can be illustrated on a per country and per major power technology. This is basis for average annual full load hours (Fig. 5.1-11) and relevance of respective domestic overall electricity generation (Fig. 5.1-12). Differences in relative operation modes of the power technologies are indicated, e.g. baseload operation of nuclear power plants, intermediate to baseload operation of coal power plants, intermediate load operation of natural gas power plants and peaking operation of oil power plants in average for most countries.

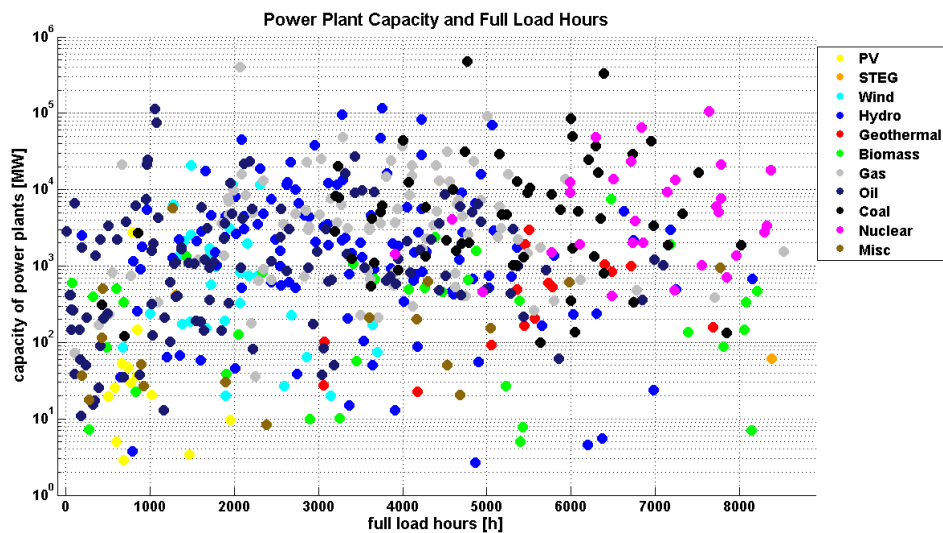


Figure 5.1-11: Power plant capacity in dependence on annual full load hours per country and per major power technology. Each dot represents a power plant category of one country in the world. Data are taken from UDI World Electric Power Plants database³¹ and International Energy Agency³².

Relative dependence of countries on power technologies is depicted in Figure 5.1-12. Several countries are strongly dependent on a single source of electricity, e.g. Algeria on natural gas (97%), Brazil on hydro (83%), China on coal (80%), France on nuclear (78%) and Saudi Arabia on oil (53%). Very high dependence on a single source of electricity might cause a high vulnerability on power supply security, which might be reduced by an upgrade of the respective capacities by PV systems.

³⁰ Platts, UDI World Electric Power Plants data base, 2009

³¹ Platts, UDI World Electric Power Plants data base, 2009

³² IEA, Key World Energy Statistics 2009, 2009

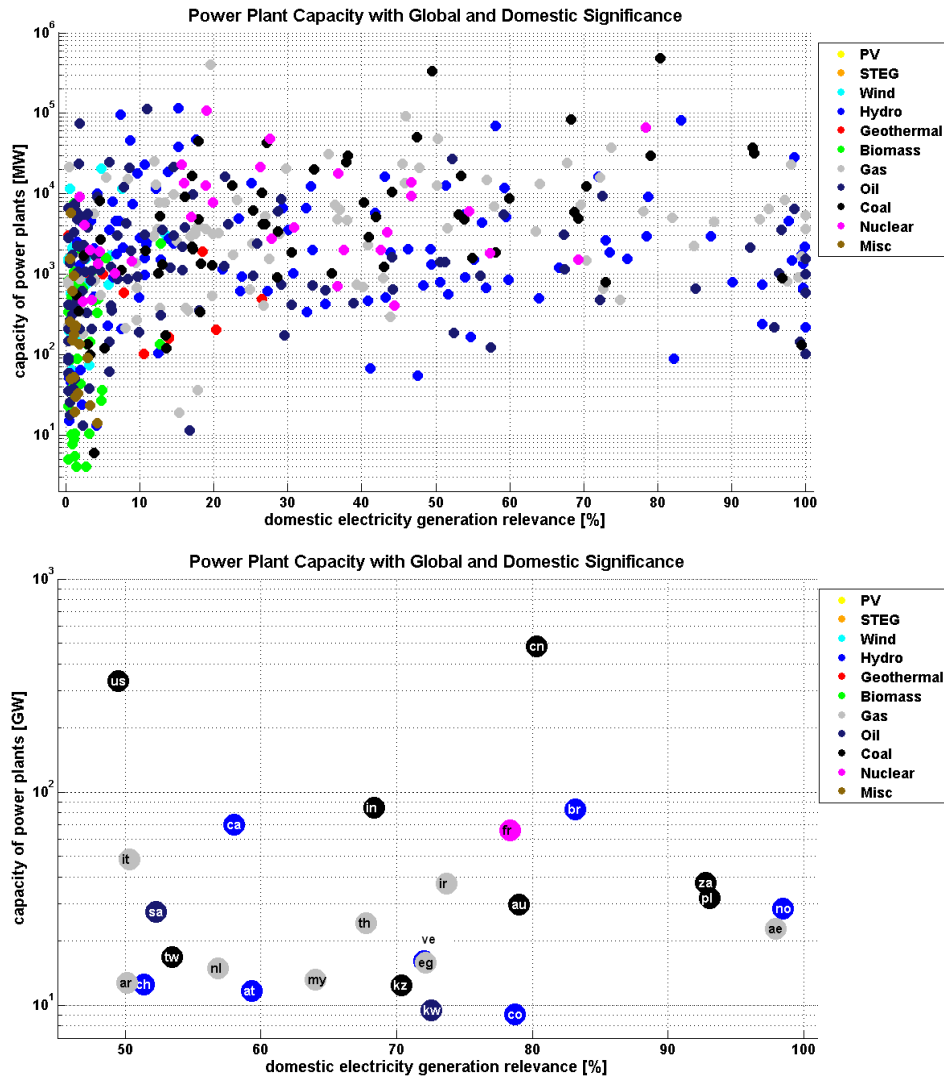


Figure 5.1-12: Power plant capacity in dependence on domestic electricity generation relevance per country and per major power technology for all countries (top) and for large absolute and relative dependence (bottom). Each dot represents a power plant category of one country in the world being named in the bottom by the respective country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database³³ and International Energy Agency³⁴.

Global distribution of power plant technology of highest relative contribution to domestic electricity generation is depicted in Figure 5.1-13 for better understanding of the current status.

³³ Platts, UDI World Electric Power Plants data base, 2009

³⁴ IEA, Key World Energy Statistics 2009, 2009

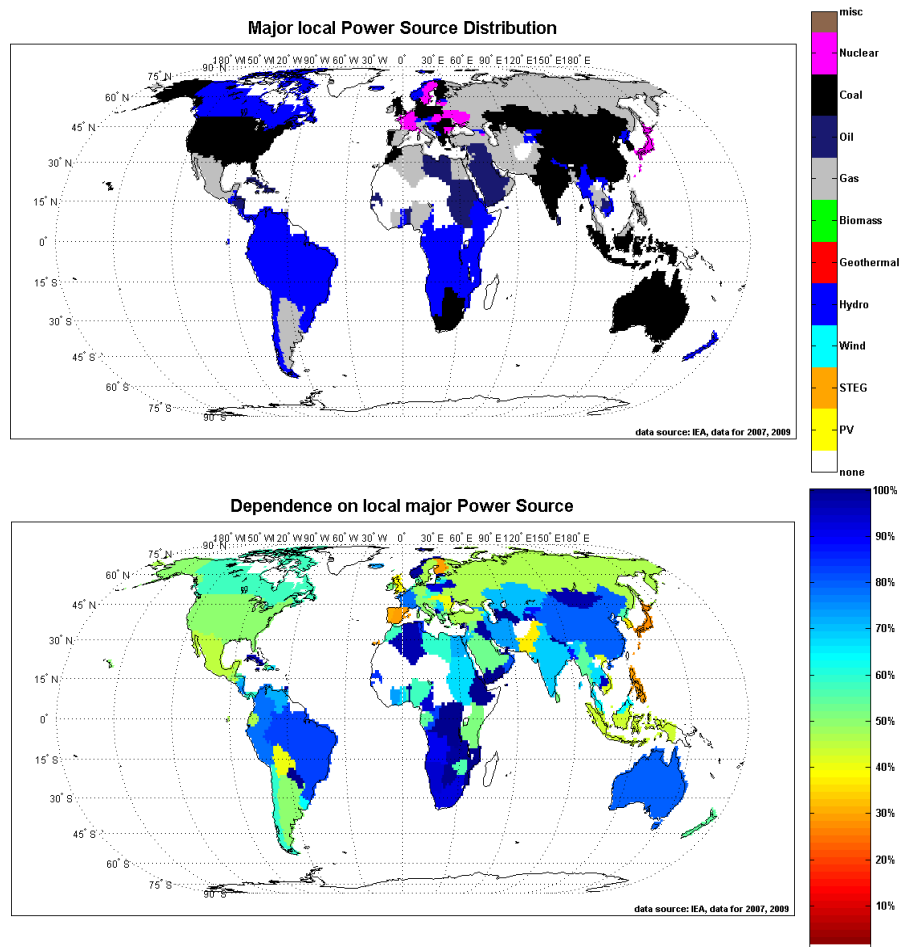


Figure 5.1-13: Global distribution of power plant technologies of largest relative electricity supply by name (top) and contribution (bottom). Data are taken from International Energy Agency ³⁵.

Summing up, global power plant capacity of about 4,700 GW is in average 4,300 full load hours in operation and generate annually about 20,000 TWh of electricity. However, nearly 80% of that capacity has to be counted as non sustainable nuclear and fossil power capacity. Easily accessible technical potential for PV systems is estimated to at least 1,500 GW (section 3.1.1.3) being economically addressable by grid-parity conditions or considerations discussed in chapters 6 and 7. Some countries are strongly dependent on a single source of electricity and might benefit from an upgrade of the respective capacities by PV systems.

5.2 Biomass Power

The resource for biomass and waste power plants is mainly driven by the agricultural production and by municipal residues. However, biomass for power generation will always be limited, as agricultural production is mainly used for food especially for a growing world population becoming richer. Biomass used for energetic purposes is taken for heating, in the transport sector, for power generation and mainly for cooking in developing countries. As a consequence of sustainability criteria, biomass should only be taken for energetic purposes if no local ecosystem is destroyed, no conflicts to local food production are identifiable and the used land can not be taken for a more efficient energy supply. Global potential of biomass

³⁵ IEA, Key World Energy Statistics 2009, 2009

production is depicted in Figure 5.2-1. The map can be taken as a rough indicator of biomass production.

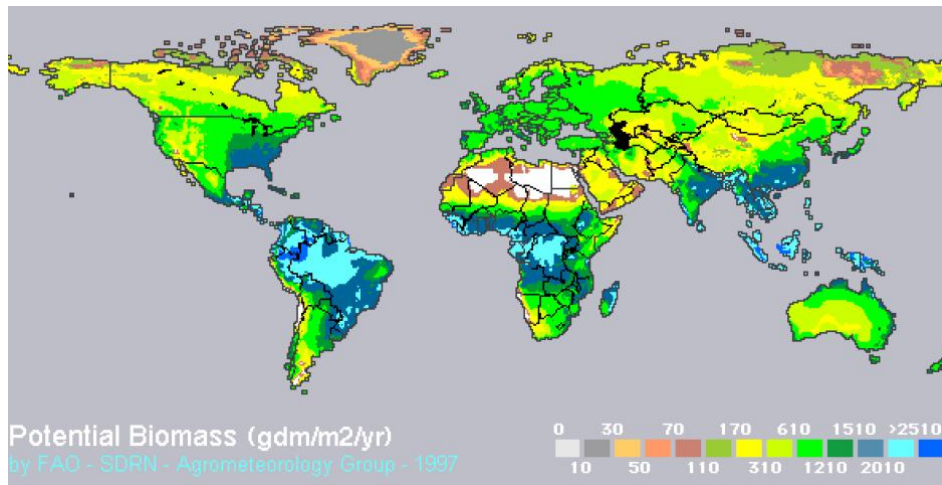


Figure 5.2-1: Global potential of biomass production.³⁶ Biomass potential is given in units of grams of dry mass per square metre and year.

Total global installed biomass and waste power capacity was 52 GW by end of 2008 and generated electricity was 267 TWh in the year 2008, translating to 5,130 full load hours.³⁷

It is necessary to know the coordinates of the biomass and waste power plants for further analysis. Due to that the UDI World Electric Power Plants database³⁸ has been enhanced by coordinates of all 145,000 power plants in the world.³⁹ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. However, a crosscheck reveals a missing capacity of about 20 GW of biomass and waste power plants (31.6 GW in the database versus 52 GW real capacity). It is very likely that most of the missing capacity is included in the ‘miscellaneous/ unknown’ category (Table 5.1-1).

In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration has been taken in these cases. The result of the georeferenced global biomass and waste power plant capacity being in operation is depicted in Figure 5.2-2.

³⁶ Gommers R. et al., Global Climate Maps: Map of biomass potential, 1999

³⁷ IEA, World Energy Outlook 2010, 2010

³⁸ Platts, UDI World Electric Power Plants data base, 2009

³⁹ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

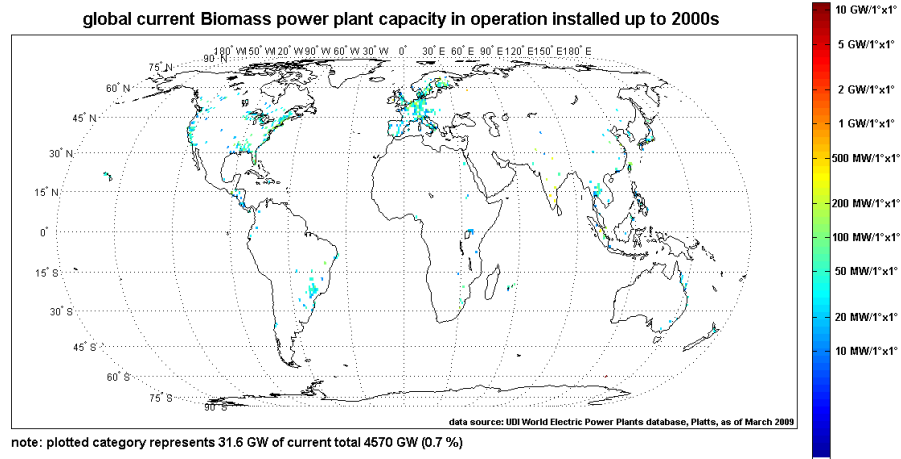


Figure 5.2-2: Global biomass and waste power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. However, only 31.6 GW of total installed 52 GW are recorded in the database leaving capacity of 20 GW dislocated. Data are plotted in a $1^\circ \times 1^\circ$ mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database⁴⁰ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced biomass and waste power plant data (Fig. 5.2-2) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current biomass and waste power plant capacity (Fig. 5.2-3). About 10 GW out of 31.6 GW included in the database are located in areas of more than $1,800 \text{ kWh/m}^2/\text{y}$ irradiation on fixed optimally tilted module surfaces, i.e. 32% of global biomass and waste power installed base is already installed in regions of very good solar resource quality.

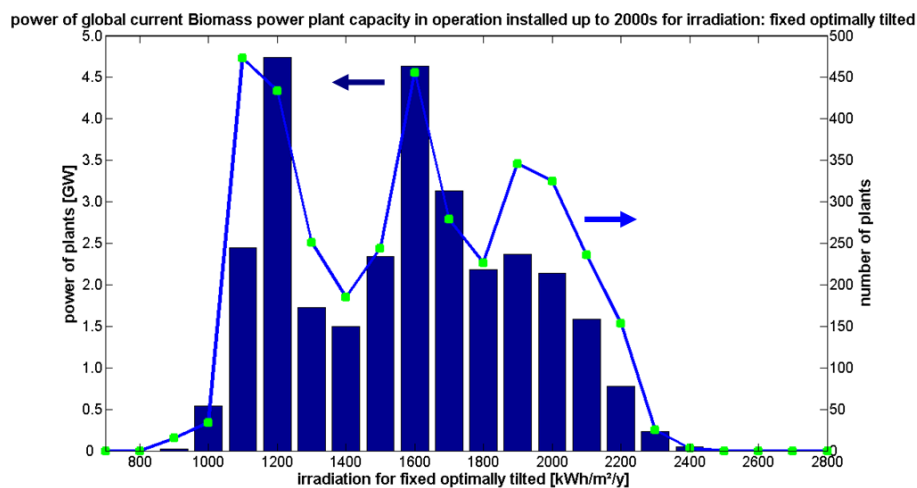


Figure 5.2-3: Global biomass and waste power plant capacity in dependence of respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 5.2-2) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 5.2-4 and shows that most power plants are in the power class of 1 - 10 MW or even smaller in size. However, their contribution to global

⁴⁰ Platts, UDI World Electric Power Plants data base, 2009

power capacity is rather small. Almost 70% of global biomass and waste power plant capacity consists of power plants of 10 – 100 MW in size and 8% in the power class of 100 - 1000 MW.

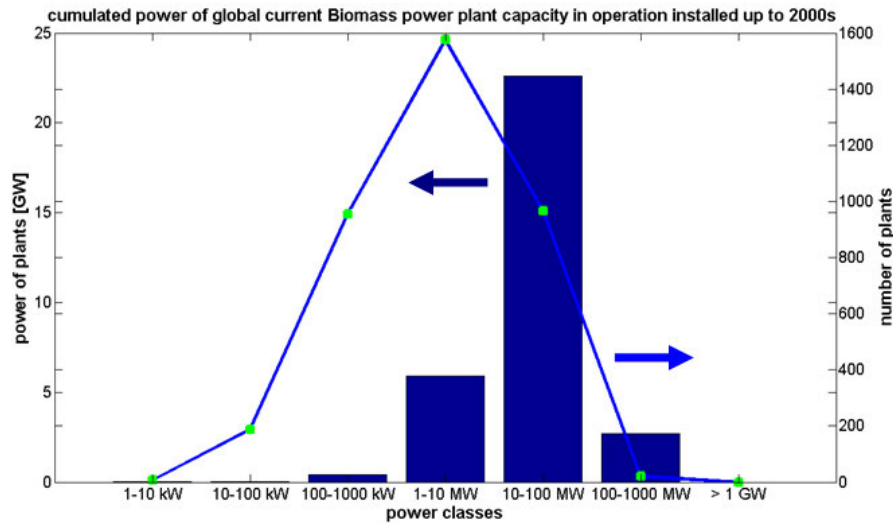
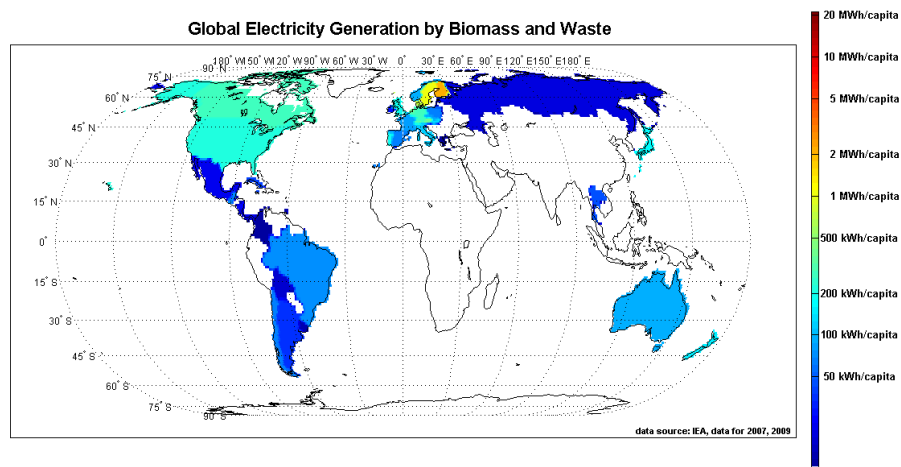


Figure 5.2-4: Global biomass and waste power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent the power plant capacity. Data are taken from UDI World Electric Power Plants database ⁴¹.

Contribution of biomass and waste power to global electricity supply is very low. Global average total electricity generation per capita is about 3.0 MWh_{el} but 5 – 10 MWh_{el} in industrialised countries (sub-chapter 5.1). Leading biomass electricity per capita countries in the world are Finland and Sweden achieving 2.0 and 1.0 MWh_{el} per capita, respectively (Fig. 5.2-5). Most other countries are far below. Comparison of global biomass power generation (Fig. 5.2-2) to global biomass resource (Fig. 5.2-1) reveals a nearly untapped source of power all over the world. Obviously, there might be significantly room for further growth, however biomass should be used for food supply first of all and not only for energy needs.



⁴¹ Platts, UDI World Electric Power Plants data base, 2009

Figure 5.2-5: Global electricity generation by biomass and waste per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency ⁴² and United Nations ⁴³.

Global installed biomass and waste power plant capacity per country is illustrated in Figure 5.2-6. Leading countries by cumulated biomass and waste power capacity are the US, Finland and India by end of 2008. However, the biomass resource (Fig. 5.2-1) is also excellent in South America, Central Africa and Russia, hence significant biomass power installations in these regions might be expected in future, under the constraint of available land for biomass energy supply.

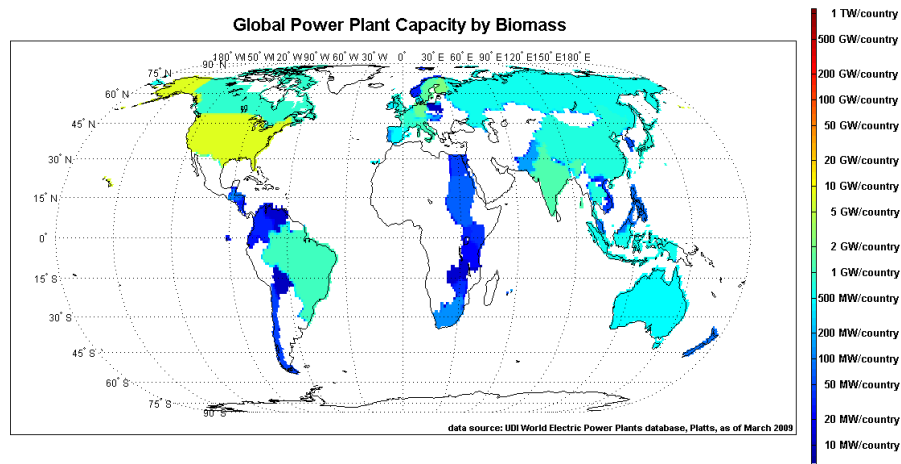


Figure 5.2-6: Global biomass and waste power plant capacity per country by early 2009. Only power plants in operation are regarded. However, only 31.6 GW of total installed 52 GW are recorded in the database leaving capacity of 20 GW dislocated. Data are taken from UDI World Electric Power Plants database ⁴⁴.

The structure of biomass and waste power plant capacity can be illustrated on a per country basis for relevance of respective domestic overall electricity generation (Fig. 5.2-7). This view clearly discloses that biomass and waste power is a limited power technology, as only five countries in the world use biomass and waste power for about 5% or more in relation to the total domestic electricity generation. These countries are Finland (13%), Guatemala (12%), Sweden (6%), Kenya (5%) and Nicaragua (5%). Again, there seems to be significant room for further growth of biomass power plants in the world, under the constraint of available land for biomass energy supply.

⁴² IEA, Key World Energy Statistics 2009, 2009

⁴³ UN, World Population Prospects: The 2008 Revision Highlights, 2009

⁴⁴ Platts, UDI World Electric Power Plants data base, 2009

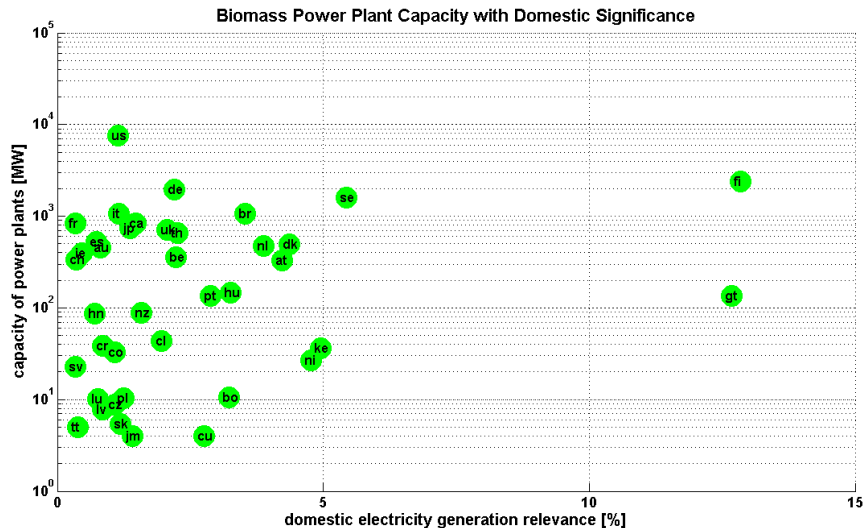


Figure 5.2-7: Biomass and waste power plant capacity in dependence on domestic electricity generation relevance per country. Each dot represents the absolute and relative biomass power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database⁴⁵ and International Energy Agency⁴⁶.

Summing up, global biomass and waste power plant capacity of about 52 GW is in average 5,130 full load hours in operation and generate annually about 267 TWh of electricity, representing 1.1% of total global installed power capacity and 1.3% of global generated electricity. Available global biomass resource is currently used in a very small manner for global power supply. Power generation potential from waste has a potential for further growth, as conventional landfills are still in use in many countries. However, in general biomass potential should not be taken for power generation, in particular in regions of limited food production potential for a growing population.

5.3 Geothermal Power

Geothermal energy is heat from the Earth's molten core and from radioactive decays which reaches the surface. The heat stored in the Earth is inexhaustible by human standards. Every day, an amount several times the global energy demand ascends from the depths of our planet and escapes unused into space. Most of this heat flow originates from the continuous decay of radioactive elements in the mantle and in the Earth's crust, a process which will continue for billions of years. This source of energy can be used practically everywhere (Fig. 5.3-1).⁴⁷

Geothermal power plants can provide power on demand using the ideal storage of the earth's hot interior as reservoir. They can provide peak load, intermediate load or base load electricity. Therefore, the capacity factor of geothermal plants is defined by the load and their operation mode. Assuming a plant availability of 90%, their capacity credit would have the same value. It can be used to compensate the fluctuations from wind power and PV. Geothermal heat at over 200 °C can be delivered from up to 5,000 m deep holes to operate organic Rankine cycles (ORC) or Kalina cycle power machines.⁴⁸

⁴⁵ Platts, UDI World Electric Power Plants data base, 2009

⁴⁶ IEA, Key World Energy Statistics 2009, 2009

⁴⁷ Dürschmidt W. et al., Renewable Energies: Innovations for the Future, 2006, p. 108-111

⁴⁸ Trieb F. et al., Trans-Mediterranean Interconnection for Concentrating Solar Power, 2006, p. 51-52

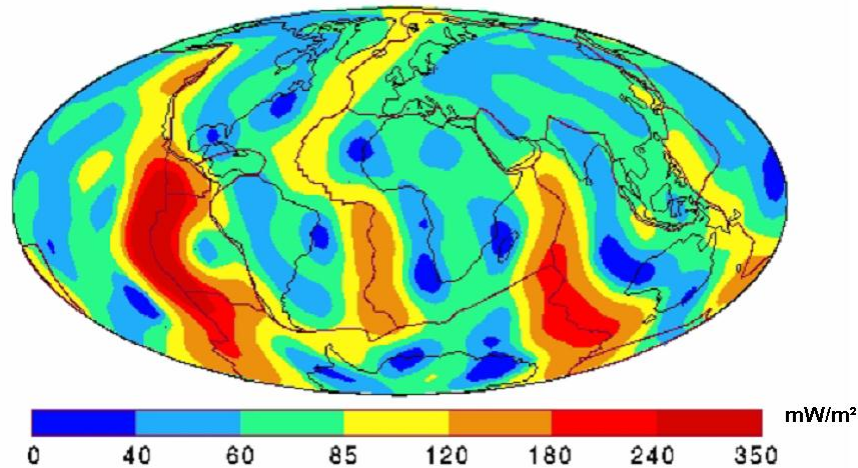


Figure 5.3-1: Global geothermal heat flux.⁴⁹ Increased heat flux is available at edges of tectonic plates.

Total global installed geothermal power capacity was 11 GW by end of 2008 and generated electricity was 65 TWh in the year 2008, translating to 5,910 full load hours.⁵⁰

It is necessary to know the coordinates of the geothermal power plants for further analysis. Due to that the UDI World Electric Power Plants database⁵¹ has been enhanced by coordinates of all 145,000 power plants in the world.⁵² The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. A crosscheck confirms the power capacity of about 11 GW.

In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration has been taken in these cases. The result of the georeferenced global geothermal power plant capacity being in operation is depicted in Figure 5.3-2.

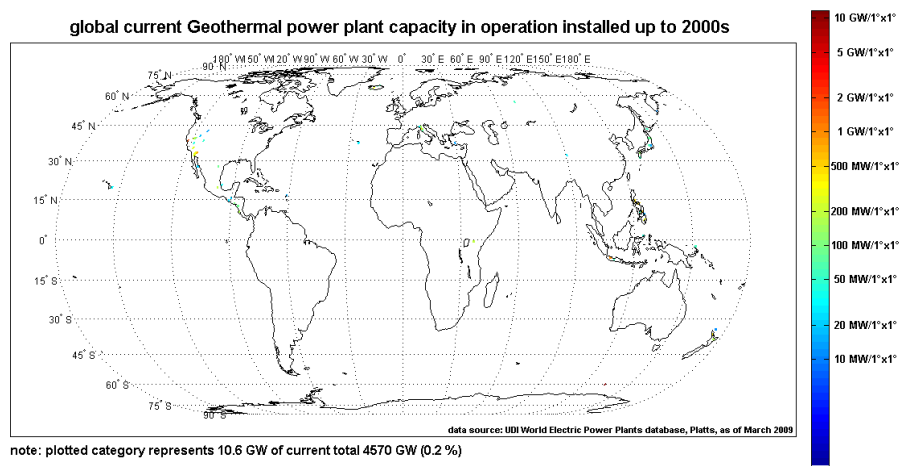


Figure 5.3-2: Global geothermal power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. Data are plotted in a 1°x1° mesh of latitude and longitude. Plants are located

⁴⁹ Czisch G., Szenarien zur zukünftigen Stromversorgung - Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien, 2005, p. 116

⁵⁰ IEA, World Energy Outlook 2010, 2010

⁵¹ Platts, UDI World Electric Power Plants data base, 2009

⁵² Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

e.g. in the US, Costa Rica, Iceland, Italy, Japan, the Philippines and New Zealand. Data are taken from UDI World Electric Power Plants database⁵³ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced geothermal power plant data (Fig. 5.3-2) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current geothermal power plant capacity (Fig. 5.3-3). About 6.4 GW out of 10.6 GW included in the database are located in areas of more than 1,800 kWh/m²/y irradiation on fixed optimally tilted module surfaces, i.e. 60% of global geothermal power installed base is already installed in regions of very good solar resource quality.

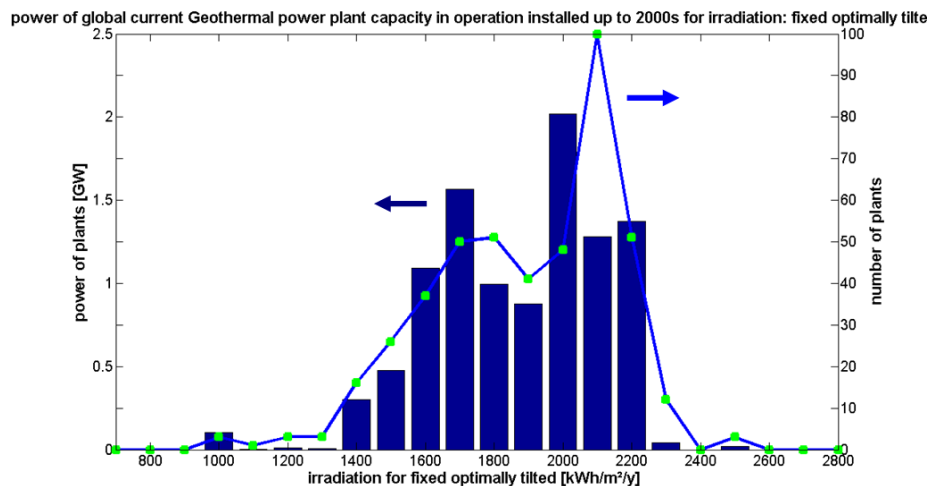


Figure 5.3-3: Global geothermal power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 5.3-2) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 5.3-4 and shows that most power plants are in the power class of 10 - 100 MW and this power class represents about 75% of global geothermal power plant capacity.

⁵³ Platts, UDI World Electric Power Plants data base, 2009

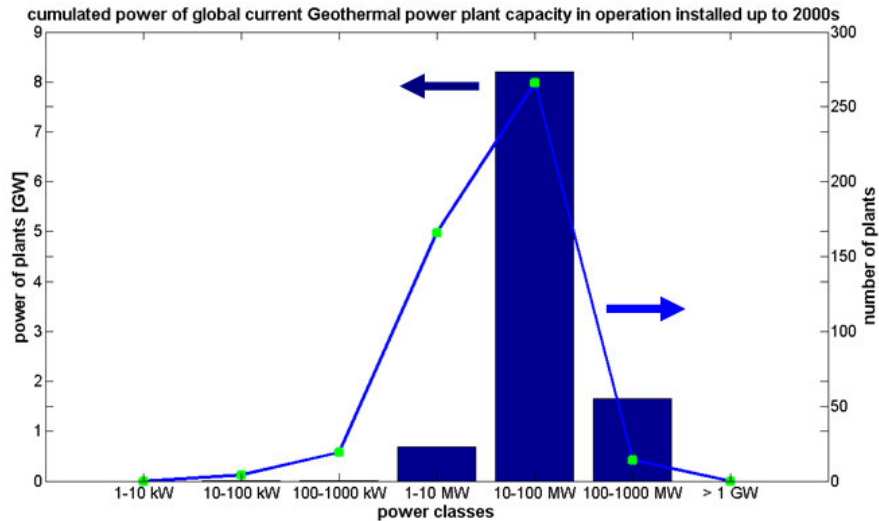


Figure 5.3-4: Global geothermal power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent power plant capacity. Data are taken from UDI World Electric Power Plants database ⁵⁴.

Contribution of geothermal power to global electricity supply is very low. Global average total electricity generation per capita is about 3.0 MWh_{el} but 5 – 10 MWh_{el} in industrialised countries (sub-chapter 5.1). Leading geothermal electricity per capita country in the world is Iceland achieving 8.0 MWh_{el} per capita (Fig. 5.3-5). All other countries are far below.

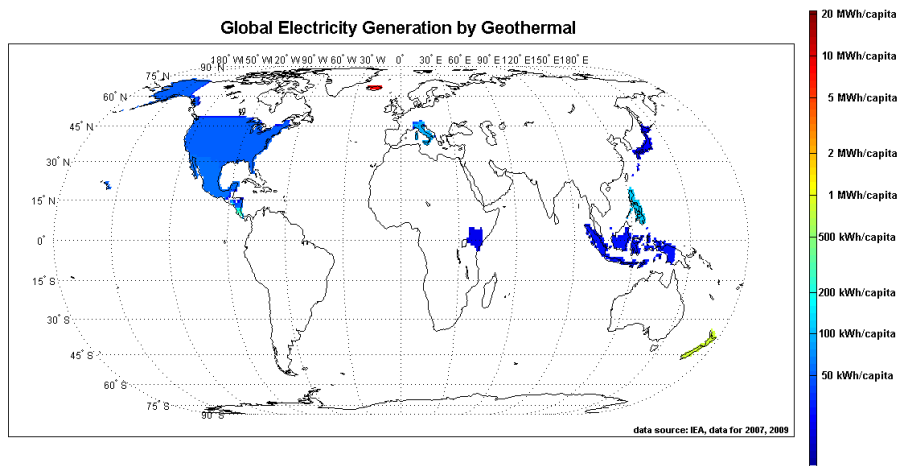


Figure 5.3-5: Global electricity generation by geothermal power per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency ⁵⁵ and United Nations ⁵⁶.

Global installed geothermal power plant capacity per country is illustrated in Figure 5.3-6. Leading countries by cumulated geothermal power capacity are the US and the Philippines by end of 2008.

⁵⁴ Platts, UDI World Electric Power Plants data base, 2009

⁵⁵ IEA, Key World Energy Statistics 2009, 2009

⁵⁶ UN, World Population Prospects: The 2008 Revision Highlights, 2009

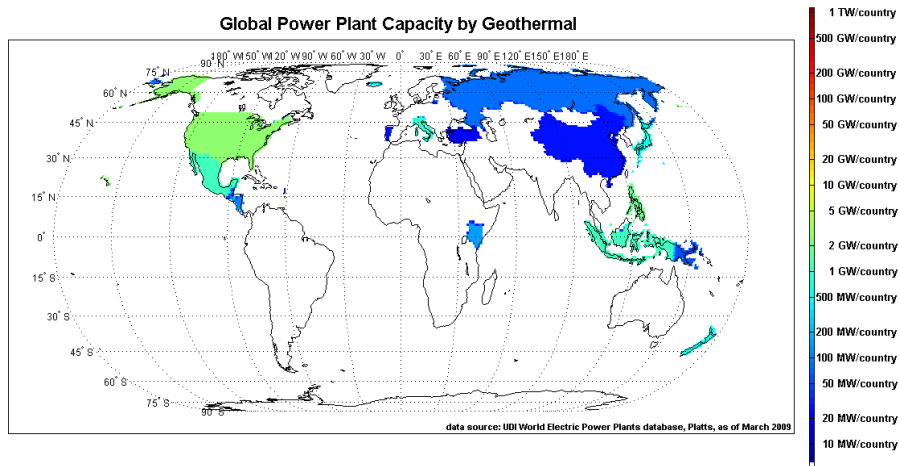


Figure 5.3-6: Global geothermal power plant capacity per country by early 2009. Only power plants in operation are regarded. Data are taken from UDI World Electric Power Plants database ⁵⁷.

The structure of power plant capacity can be illustrated on a per country basis for average annual full load hours (Fig. 5.3-7) and relevance of respective domestic overall electricity generation (Fig. 5.3-8). This view clearly discloses that geothermal power is still a limited power technology, as total installed power capacity is rather low. However, some countries use geothermal energy by at least 10% for their electricity supply. These countries are Iceland (27%), El Salvador (20%), the Philippines (18%), Kenya (14%), Costa Rica (14%) and Nicaragua (10%). There seems to be significant potential for further growth of geothermal power plants in the world.

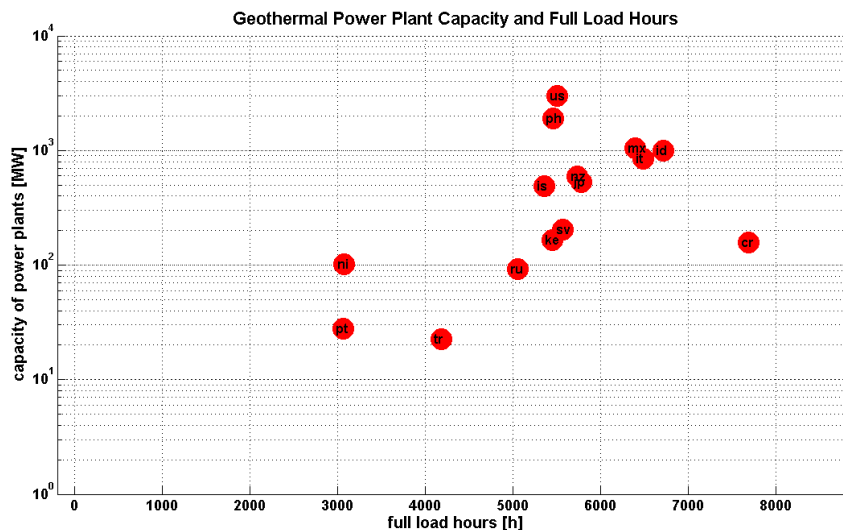


Figure 5.3-7: Geothermal power plant capacity in dependence on full load hours per country. Each dot represents the absolute geothermal power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ⁵⁸ and International Energy Agency ⁵⁹.

⁵⁷ Platts, UDI World Electric Power Plants data base, 2009

⁵⁸ Platts, UDI World Electric Power Plants data base, 2009

⁵⁹ IEA, Key World Energy Statistics 2009, 2009

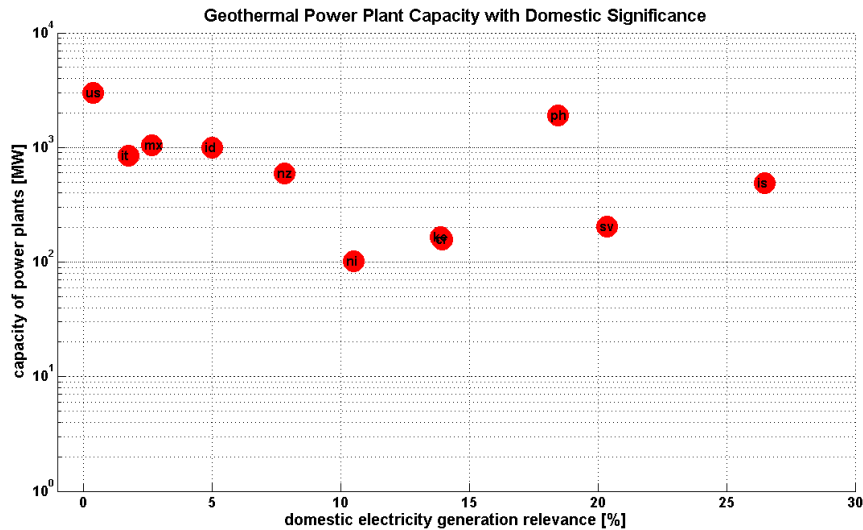


Figure 5.3-8: Geothermal power plant capacity in dependence on domestic electricity generation relevance per country. Each dot represents the absolute and relative geothermal power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database⁶⁰ and International Energy Agency⁶¹.

Summing up, global geothermal power plant capacity of about 11 GW is in average 5,910 full load hours in operation and generate annually about 65 TWh of electricity, representing 0.2% of total global installed power capacity and 0.3% of global generated electricity. Available global geothermal heat flux resource is currently used in a nearly negligible manner for global power supply. Geothermal energy is a valuable renewable energy source being capable of balancing fluctuating renewable sources like wind power and photovoltaic.

5.4 Ocean Power

Ocean energy systems generate electricity by converting marine energy flux. These energy fluxes are induced by various forces like the gravitation force of the moon, marine wind, global ocean currents and differences in temperature and salinity. The main ocean energy systems are tidal power, wave power, tidal and marine current power, thermal gradient power and salinity gradient power. The energy density of ocean energy systems is comparably high and reaches values of 2,000 to 5,000 W/m².⁶² Global annual resource potential is estimated to be about 100,000 TWh.⁶³ However, different ocean energy systems contribute to different orders: wave power (80,000 TWh/y), thermal gradient power (10,000 TWh/y), salinity gradient power (2,000 TWh/y), tidal (marine) current power (800+ TWh/y) and tidal power (300+ TWh/y).⁶⁴ Global resource availability of wave power, the major ocean energy system, is shown in Figure 5.4-1.

⁶⁰ Platts, UDI World Electric Power Plants data base, 2009

⁶¹ IEA, Key World Energy Statistics 2009, 2009

⁶² Khan J. et al., Potential Opportunities and Differences Associated with Integration of Ocean Wave and Marine Current Energy Plants in Comparison to Wind Energy, 2009

⁶³ IEA-OES, Ocean Energy: Opportunity, present status and challenges, 2006

⁶⁴ IEA-OES, Ocean Energy: Opportunity, present status and challenges, 2006

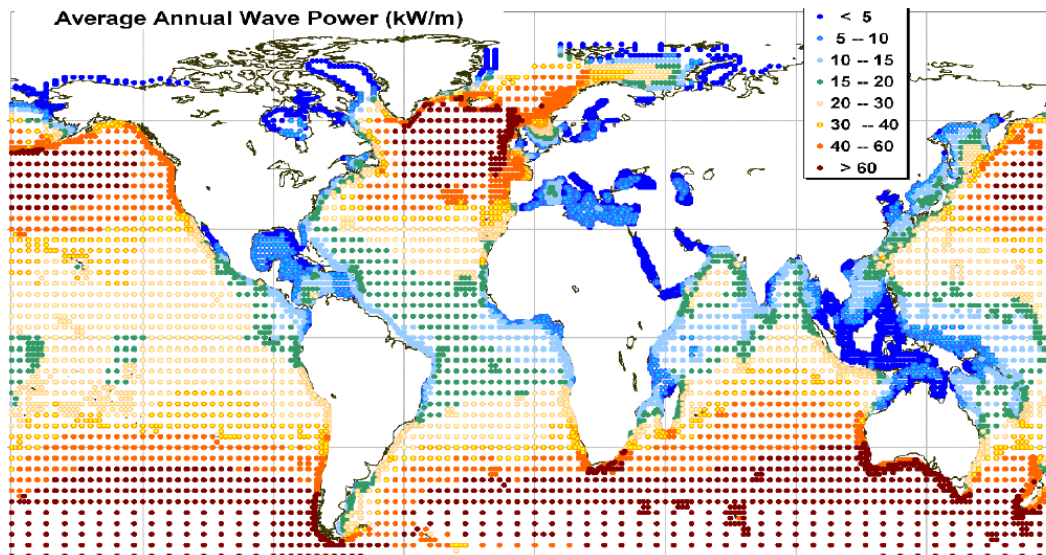


Figure 5.4-1: Global wave power resource potential.⁶⁵ The highest power levels of more than 60 kW/m are found offshore along the coastlines of southern Chile, Africa, Australia, New Zealand, Northwest Canada, west of Scotland (UK) and Ireland.

Total global installed ocean power capacity was about 250 MW by end of 2008⁶⁶ and the generated electricity was about 1 TWh in the year 2008⁶⁷. However, 240 MW of installed ocean power capacity is represented by the tidal power plant in St. Malo in France built in 1966. This power plant achieves about 2,500 full load hours.⁶⁸ The total installed ocean power capacity clearly documents the very early development stage of ocean power systems. However, dozens of systems are under development in the pre-commercial phase in several countries in the world.⁶⁹

An overview on ocean power systems in terms of fundamental considerations, resource availability, technology and system demonstration can be found in several sources, like Kahn and Bhuyan⁷⁰, Kahn et al.⁷¹, Cornett⁷², Pontes and Candelária⁷³, Niemann⁷⁴, Kleemann and Meliß⁷⁵, Graw⁷⁶, Kaltschmitt⁷⁷, Kleemann⁷⁸, Bard⁷⁹ and Lübbert⁸⁰.

Ocean energy systems are at a very early development stage. It is not clear how ocean power and PV would interfere and whether a combination of these two power technologies might generate special benefits.

⁶⁵ Nielsen K. and Pontes T., Report T02-1.1 OES IA Annex II Task 1.2 Generic and site related wave data, 2010

⁶⁶ Platts, UDI World Electric Power Plants data base, 2009

⁶⁷ IEA, World Energy Outlook 2010, 2010

⁶⁸ Niemann N., Meereskraftwerke – Die Energie und Vielfalt der Ozeane, 2010

⁶⁹ Khan J. and Bhuyan G., Ocean Energy: Global Technology Development Status, 2009

⁷⁰ Khan J. and Bhuyan G., Ocean Energy: Global Technology Development Status, 2009

⁷¹ Khan J. et al., Potential Opportunities and Differences Associated with Integration of Ocean Wave and Marine Current Energy Plants in Comparison to Wind Energy, 2009

⁷² Cornett A., Guidance for Assessing Tidal Current Energy Resources, 2008

⁷³ Pontes T. and Candelária A., Wave Data Catalogue for Resource Assessment of IEA-OES Member Countries, 2009

⁷⁴ Niemann N., Meereskraftwerke – Die Energie und Vielfalt der Ozeane, 2010

⁷⁵ Kleemann M. and Meliß M., Regenerative Energiequellen, 1993, p. 9-15

⁷⁶ Graw K.-U., Wellenkraftwerke – Energiereservoir Ozean, 2007

⁷⁷ Kaltschmitt M., Nutzung der Energien des Meeres, 2006

⁷⁸ Kleemann M., Windenergie, Wasserkraft, Gezeitenenergie und Erdwärme, 2002

⁷⁹ Bard J., Meeresenergie, 2007

⁸⁰ Lübbert, D., Das Meer als Energiequelle, 2005

5.5 Nuclear Power

Until 1979, nuclear power had been regarded as an excellent option for overcoming the energy constraints of mankind. But after the nuclear accident in Harrisburg an exodus of excellent nuclear energy scientists started to build up power technologies being really able to fulfil the various sustainability requirements. As already discussed in this thesis nuclear power fulfils no single sustainability criteria (sections 1.3.4 and 3.1.3.4.3).

After Chernobyl in 1986 several countries in the world finally stopped new investments in nuclear power plants, but still proceeded their misallocated public R&D energy investments (section 3.1.3.1). After Fukushima in 2011 the development of mature alternatives is completed for a full switch towards a sustainable power generation. Leading countries in the field of sustainability like Germany prepare now the full restructuring of their non sustainable power system.

However, there are still many nuclear power plants in operation around the world. This sub-chapter gives an overview on these capacities. The distribution of global uranium reserves are depicted in Figure 5.5-1.

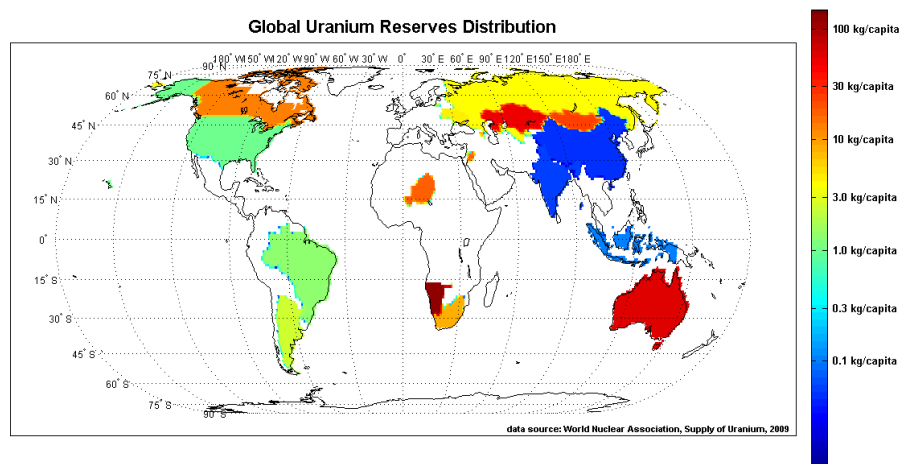


Figure 5.5-1: Distribution of global uranium reserves. Data are taken from World Nuclear Association.⁸¹

Total global installed nuclear power capacity was 391 GW by end of 2008 and generated electricity was 2,730 TWh in the year 2008, translating to 6,980 full load hours.⁸²

It is necessary to know the coordinates of the nuclear power plants for further analysis. Due to that the UDI World Electric Power Plants database⁸³ has been enhanced by coordinates of all 145,000 power plants in the world.⁸⁴ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. A crosscheck confirms the power capacity of about 391 GW.

⁸¹ WNA, Supply of Uranium, 2010

⁸² IEA, World Energy Outlook 2010, 2010

⁸³ Platts, UDI World Electric Power Plants data base, 2009

⁸⁴ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration has been taken in these cases. The result of the georeferenced global nuclear power plant capacity being in operation is depicted in Figure 5.5-2.

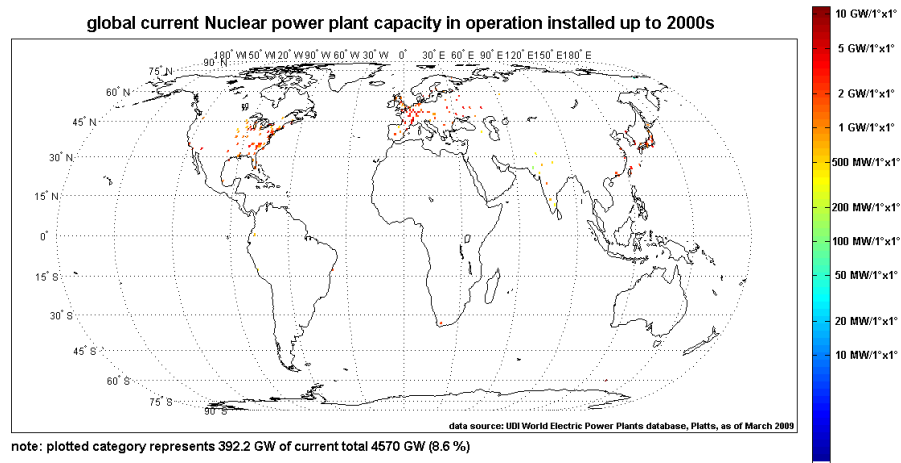


Figure 5.5-2: Global nuclear power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. Data are plotted in a $1^\circ \times 1^\circ$ mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database⁸⁵ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced nuclear power plant data (Fig. 5.5-2) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current nuclear power plant capacity (Fig. 5.5-3). About 52 GW out of 391 GW included in the database are located in areas of more than 1,800 kWh/m²/y irradiation on fixed optimally tilted module surfaces, i.e. 13% of global nuclear power installed base is installed in regions of very good solar resource quality.

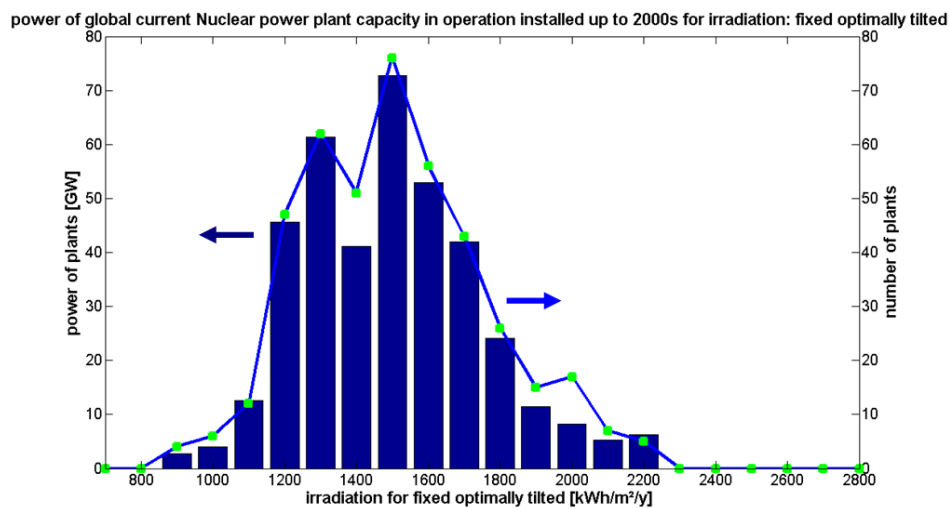


Figure 5.5-3: Global nuclear power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 5.5-2) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

⁸⁵ Platts, UDI World Electric Power Plants data base, 2009

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 5.5-4 and shows that nearly all power plants are in the power class 100 – 1000 MW and above.

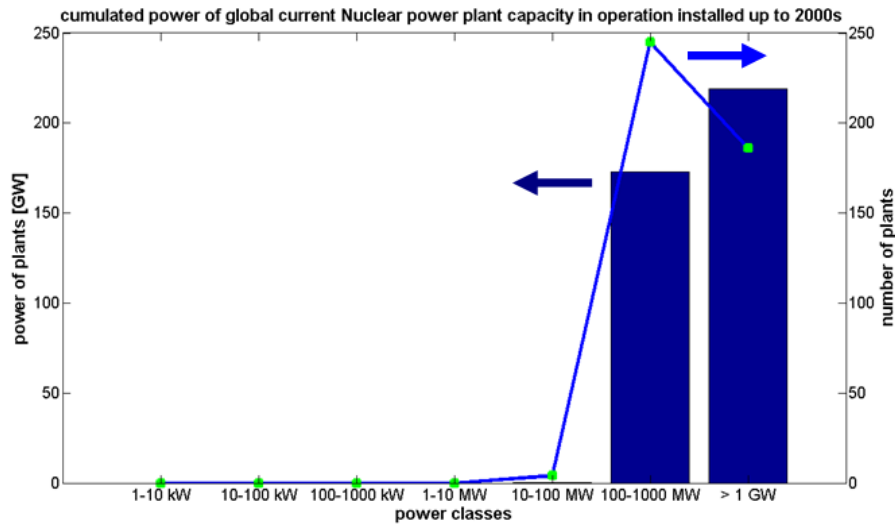


Figure 5.5-4: Global nuclear power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent power plant capacity. Data are taken from UDI World Electric Power Plants database ⁸⁶.

Contribution of nuclear power to global electricity supply is significant. Global average total electricity generation per capita is about 3.0 MWh_{el} but 5 – 10 MWh_{el} in industrialised countries (sub-chapter 5.1). Leading nuclear electricity per capita countries in the world are Sweden and France achieving 7.2 MWh_{el} per capita (Fig. 5.5-5). All other countries are significantly below.

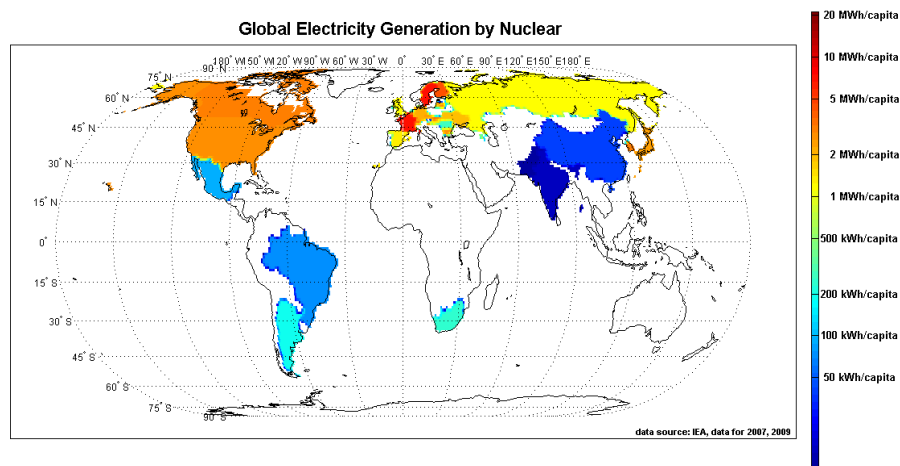


Figure 5.5-5: Global electricity generation by nuclear power per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency ⁸⁷ and United Nations ⁸⁸.

⁸⁶ Platts, UDI World Electric Power Plants data base, 2009

⁸⁷ IEA, Key World Energy Statistics 2009, 2009

⁸⁸ UN, World Population Prospects: The 2008 Revision Highlights, 2009

Global installed nuclear power plant capacity per country is illustrated in Figure 5.5-6. Leading countries by cumulated nuclear power capacity are the US, France and Japan by end of 2008.

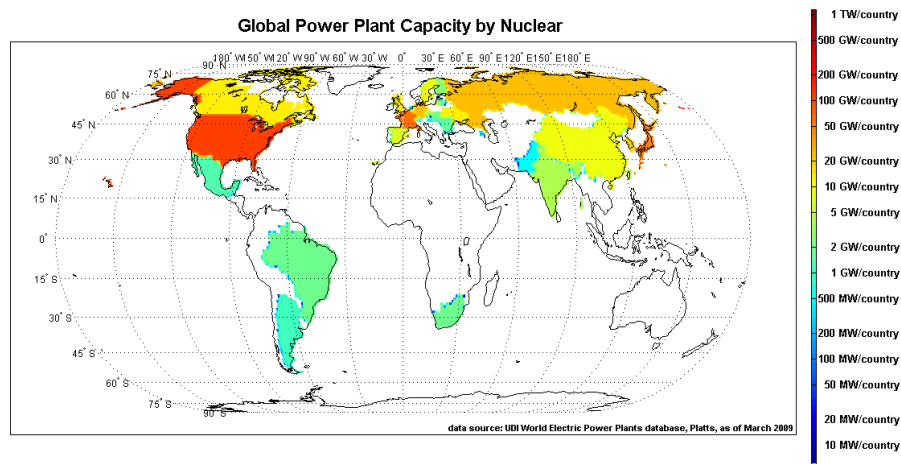


Figure 5.5-6: Global nuclear power plant capacity per country by early 2009. Only power plants in operation are regarded. Data are taken from UDI World Electric Power Plants database ⁸⁹.

The structure of power plant capacity can be illustrated on a per country basis for average annual full load hours (Fig. 5.5-7) and relevance of respective domestic overall electricity generation (Fig. 5.5-8). This view clearly confirms that nuclear is a baseload power technology, as average full load hours are 7,000 and more. High full load hours are a consequence of difficult true economics, i.e. very high Capex need to be scaled by high full load hours, but also on safety constraints, as it is necessary for all components to receive as less stress as possible to prevent failures like in Chernobyl, Forsmark or Harrisburg. Such operation conditions stay in severe conflict to fluctuating solar and wind resources. As nuclear power violates all sustainability criteria, a global phase-out of the technology is only a matter of time. In the long run the disastrous fully loaded economics will end this technological cul-de-sac. Some countries are heavily dependent on nuclear energy by 50% and more of their electricity supply. These countries are France (78%), Lithuania (70%), Slovakia (58%) and Belgium (55%). There seems to be a significant conflict potential caused by nuclear power due to its inflexible characteristics based on security requirements.

⁸⁹ Platts, UDI World Electric Power Plants data base, 2009

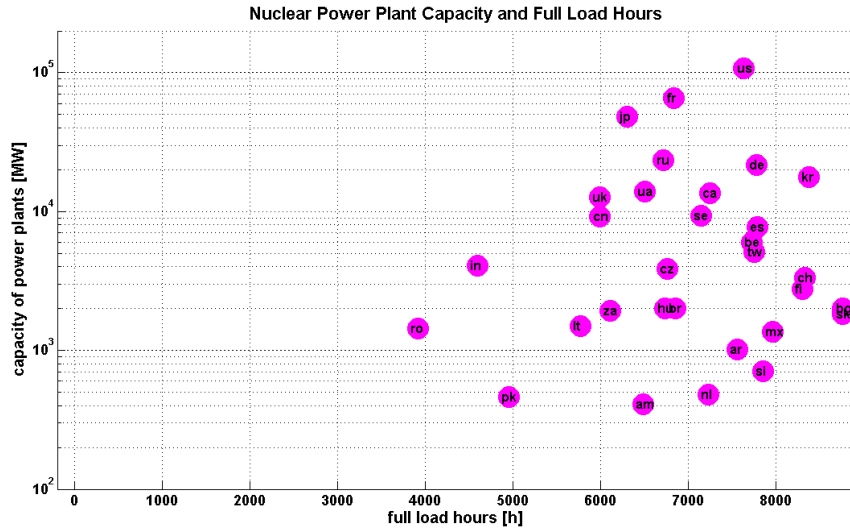


Figure 5.5-7: Nuclear power plant capacity in dependence on full load hours per country. Each dot represents the absolute nuclear power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ⁹⁰ and International Energy Agency ⁹¹.

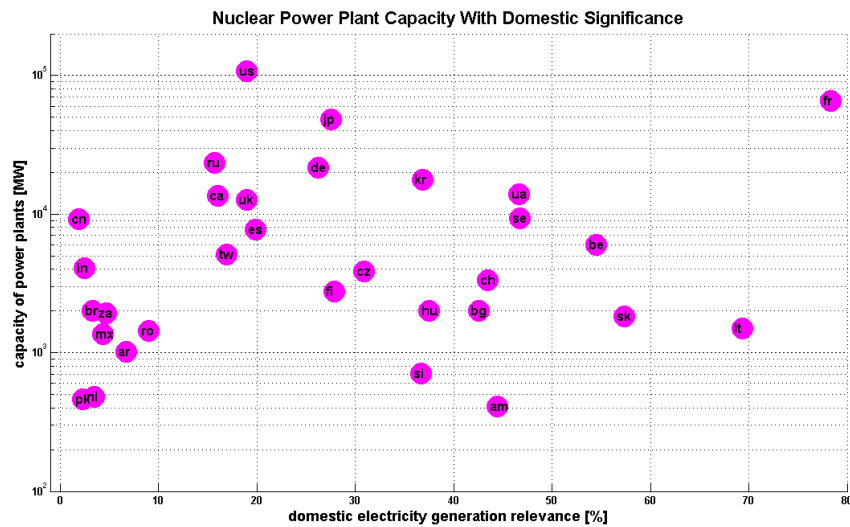


Figure 5.5-8: Nuclear power plant capacity in dependence on domestic electricity generation relevance per country. Each dot represents the absolute and relative nuclear power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ⁹² and International Energy Agency ⁹³.

Summing up, global nuclear power plant capacity of 391 GW is in average 6,980 full load hours in operation and generate annually about 2,730 TWh of electricity, representing 8.3% of total global installed power capacity and 13.7% of global generated electricity. Available nuclear reserves are limited and all sustainability criteria are violated. Fundamental characteristics in economics and security force the plants to be operated in baseload mode. However, fluctuating PV and wind power plants need flexible plants able for balancing. Therefore, severe system conflicts between nuclear and fluctuating PV and wind power are

⁹⁰ Platts, UDI World Electric Power Plants data base, 2009

⁹¹ IEA, Key World Energy Statistics 2009, 2009

⁹² Platts, UDI World Electric Power Plants data base, 2009

⁹³ IEA, Key World Energy Statistics 2009, 2009

very likely. A global phase-out of nuclear power plants is obligatory due to violation of all sustainability criteria and inflexible operation capabilities.

Chapter 6

Hybrid Photovoltaic Fossil Power Plants

Analyses in previous chapters already emphasize the fast increasing beneficial PV economics. However the most relevant reference for PV power plant economics are the fully-loaded and not directly subsidized power generation costs of fossil fuel fired conventional power plants. Due to the fluctuating solar resource availability, the hybrid combination of fossil fuel fired power plants and PV power plants appears financially advantageous. For an integrated economic assessment of hybrid PV-Fossil power plants the preconditions are considered being necessary for a **successful PV hybridization** (sub-chapter 6.1). Based on these requirements the major fossil fuel fired power plants are analysed, i.e. **hybrid PV-Oil power plants** (sub-chapter 6.2), **hybrid PV-Gas power plants** (sub-chapter 6.3) and **hybrid PV-Coal power plants** (sub-chapter 6.4). The results of these analyses are summarized in the **hybrid PV-Fossil power plant demand curve** for the 2010s (sub-chapter 6.5). This economic PV market potential based on fuel-parity is complemented by the **economic PV market potential** derived by grid-parity analyses and compared to existing PV scenarios (sub-chapter 6.6).

6.1 Preconditions for PV Hybridization

Several requirements need to be fulfilled for a successful hybridization of PV and fossil fuel fired power plants. Therefore the fundamental concept of hybridization (section 6.1.1) needs to be applicable for hybrid PV-Fossil power plants. Due to the fluctuating resource of PV power plants, the fossil fuel fired power plant has to be very flexible in its operation modes (section 6.1.2). However, the fluctuating characteristic of the PV sub-component would be much better manageable in case of good predictability in the range of some days and in particular for the next 24 h (section 6.1.3) for a well adjusted operation of the different sub-components. The economics of different fossil fuel fired power plant options for hybridization with PV power plants can be better analysed by applying a price coupling of the major fossil fuels (section 6.1.4). These preconditions for constituting and analysing hybrid PV-Fossil power plants are presented in the following sections.

6.1.1 Fundamentals on Hybridization

There are several definitions for hybrid power systems, but one of the best is as follows: small set of co-operating units, generating electricity or additionally heat or potable water, based on diversified renewable and non-renewable energy sources, while the co-ordination of their operation takes place by utilisation of advanced power electronics systems.¹ Mostly, hybrid power systems are connected to the power grid, but they can also work independently feeding separated receivers, from one or several homes, farms, small industrial plants to large local communities (section 3.4.2). Grid-connected hybrid power systems provide electric power reserves and allow surplus power to be fed back to the grid when hybrid power systems generate more power than receivers and local energy storage systems require. Hybrid power systems are a good way to increase availability and flexibility of power supply systems and to have available and flexible sources of electricity which optimise utilisation of energy sources.

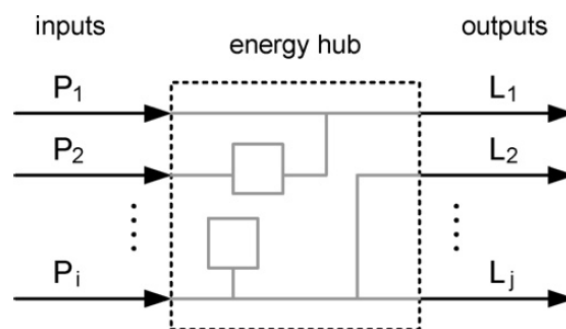
¹ Paska J. et al., Hybrid power systems – An effective way of utilising primary energy sources, 2009

It may be achieved by combining different renewable and non-renewable energy conversion technologies, electrical energy storage facilities and advanced power electronics systems for controlling, monitoring and supervision.²

Similar to hybrid power systems are the so-called virtual power systems. The previous ones are characterized by a close spatial location of the sub-components of the system, whereas the latter ones might be spatially distributed over an entire country or even continent. However, common for both approaches is the integrated controlling and monitoring of the interconnected power systems. For the conditions of Germany a well designed virtual power system has been analysed constituted by 100% renewable energy sources, i.e. PV, onshore and offshore wind power, biogas and pumped hydro storage representing about 1/10,000 of the German electricity needs.^{3,4} This virtual power system confirmed the hypothesis that 100% renewable power systems can be fully adapted to the load profile of an industrialized country and that the resources of the country would be sufficient for a 100% renewable power supply.

Hybrid power systems increase the complexity of the overall power system, thus the control design has an important effect on the system performance. Real et al.⁵ give an overview on the various controlling approaches, like heuristic rules, trial-and-error techniques, fuzzy logic, on-line optimization and control algorithms based on predictions of future conditions. As well as the control design, it is very important that component sizing is taken into account in order to reduce capital expenditures and to achieve good overall performance.⁶ A further optimization dimension would be the inclusion of sustainability criteria for deriving the most comprehensive optimum.⁷

For efficient optimization of hybrid power systems an appropriate formalism describing the various interactions has to be applied. Due to the inclusion of various energy sources, storage facilities and multiple services, these systems are also called multiple energy carrier systems, energy services supply systems or hybrid energy hubs.^{8,9,10} Such a hybrid energy hub is sketched in Figure 6.1-1.



² Paska J. et al., Hybrid power systems – An effective way of utilising primary energy sources, 2009

³ Mackensen R. et al., No limits for a full electricity supply by renewables, 2008

⁴ Mackensen R. et al., Das regenerative Kombikraftwerk, 2008

⁵ Real del A.J. et al., Optimization strategy for element sizing in hybrid power systems, 2009

⁶ Real del A.J. et al., Optimization strategy for element sizing in hybrid power systems, 2009

⁷ Afgan N.H. and Carvalho M.G., Sustainability assessment of a hybrid energy system, 2008

⁸ Geidl M., Integrated Modeling and Optimization of Multi-Carrier Energy Systems, 2007

⁹ Geidl M. and Andersson G., Operational and structural optimization of multi-carrier energy systems, 2006

¹⁰ Geidl M. and Andersson G., Optimal Power Flow of Multiple Energy Carriers, 2007

Figure 6.1-1: General hybrid energy hub diagram.¹¹ Abbreviations stand for: converter input power flow (P) and for converter output power flow (L).

Real et al.¹² discuss and apply a time dependent matrix formalism based on the hybrid energy hub approach including interaction with storage facilities, respective cost structures and appropriate technical constraints for extracting optimised hybrid energy system configurations. The central time dependent matrix equation for the hybrid energy hub is given in Equation 6.1-1:¹³

$$\underline{L}(t) = \underline{C}(t) \cdot \underline{P}(t) - \underline{S}(t) \cdot \partial_t \underline{E}(t) \quad (\text{Eq. 6.1-1})$$

Equation 6.1-1: Hybrid energy hub model equation. Abbreviations of the time dependent matrices stand for: converter output power flow (L), converter coupling (C), converter input power flow (P), storage coupling (S) and stored energy (E).

From the systems perspective, there are two distinct groups in terms of power generation controllability, i.e. controllable sources like biogas, biomass, hydro storage dams, geothermal systems and fossil fired systems, partial controllable sources like STEGs and river run-off plants but also nearly uncontrollable sources like fluctuating solar PV and wind power systems. However, the two latter power systems have become well predictable in recent years (section 6.1.3). Nevertheless, electricity has to be produced exactly at the time of demand. PV and wind hardly fulfil this basic requirement. Therefore, special kinds of power plants should be built to avoid shortages of power and to utilise all available PV or wind power. There are at least two ways to achieve this aim: electricity energy storage or power plants using two or more primary sources with additional control systems. One of the sources must be a controllable power source. Such power plants are hybrid power systems, thereof several variations are discussed in this thesis (Table 6.1-1).

hybrid power system	controllable source	storage	reference
hybrid PV-Oil	yes	no	sub-chapter 6.2
hybrid PV-Gas	yes	no	sub-chapter 6.3
hybrid PV-Coal	yes	no	sub-chapter 6.4
hybrid PV-Hydro	partly	partly	sub-chapter 7.1
hybrid PV-STEG	no	yes	sub-chapter 7.2
hybrid PV-Wind	no	no	sub-chapter 7.3
hybrid PV-Wind-RPM-CCGT	partly	yes	sub-chapter 7.4
hybrid PV-(Wind,Hydro,Biogas)-(Battery,Diesel)	partly	yes	section 3.4.2

Table 6.1-1: Overview on hybrid power systems discussed in this thesis. Abbreviations stand for: renewable power methane (RPM) and combined cycle gas turbine (CCGT).

However, there are many further hybrid power systems discussed in the literature, e.g. hybrid STEG-Geothermal plant¹⁴, hybrid STEG-CCGT plant^{15,16,17}, hybrid Biomass-Geothermal

¹¹ Real del A.J. et al., Optimization strategy for element sizing in hybrid power systems, 2009

¹² Real del A.J. et al., Optimization strategy for element sizing in hybrid power systems, 2009

¹³ Real del A.J. et al., Optimization strategy for element sizing in hybrid power systems, 2009

¹⁴ Astolfi M. et al., Technical and economical analysis of a solar-geothermal hybrid plant based on an Organic Rankine Cycle, 2011

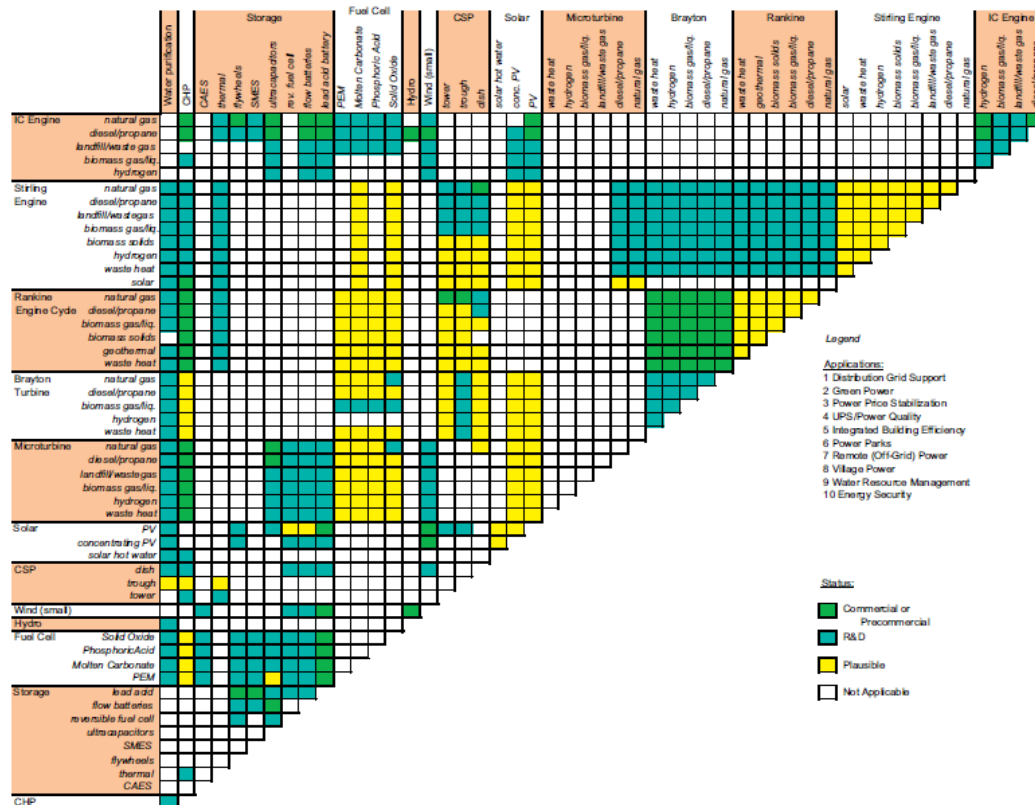
¹⁵ Pitz-Paal R. et al., Ecostar – European Concentrated Solar Thermal Road-Mapping, 2004

¹⁶ Brakmann G., Integrated Solar Combined Cycle Power Plants in Egypt and Morocco, 2007

¹⁷ Schölkopf W., Solarthermie, 2002

plant¹⁸, hybrid Biomass-Wind plant¹⁹, hybrid Geothermal-Fossil plant²⁰, natural gas fuelled hybrid solid oxide fuel cell gas turbine plant^{21,22}, hybrid Hydro-Wind plant^{23,24}, hybrid PV-H₂-Fuel Cell plant²⁵, hybrid Wind-STEg plant²⁶, hybrid Wind-Diesel system^{27,28}, hybrid Wind-Diesel-Battery system²⁹, hybrid Nuclear-Gas plant³⁰ or hybrid Nuclear-Coal plant³¹.

Hybrid power generation systems contain two or more power generation sources in order to balance each other's strengths and weaknesses. In Figure 6.1-2 a matrix is used to illustrate those hybrid combinations that are commercially available, in development or, at a minimum, plausible. The diagram covers a broad variety of possible hybrid combinations.



¹⁸ Borsukiewicz-Gozdur A., Dual-fluid-hybrid power plant co-powered by low-temperature geothermal water, 2010

¹⁹ Pérez-Navarro A. et al., Hybrid biomass-wind power plant for reliable energy generation, 2010

²⁰ Bruhn M., Hybrid geothermal-fossil electricity generation from low enthalpy geothermal resources: geothermal feedwater preheating in conventional power plants, 2002

²¹ Chan S.H. et al., Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant, 2002

²² Cheddie D.F., Thermo-economic optimization of an indirectly coupled solid oxide fuel cell/gas turbine hybrid power plant, 2011

²³ Denault M. et al., Complementarity of hydro and wind power, 2009

²⁴ Jaramillo O.A. et al., Using hydropower to complement wind energy, 2004

²⁵ Harvey L.D.D., Solar-Hydrogen Electricity Generation in the Context of Global CO₂ Emission Reduction, 1995

²⁶ Reichling J.P. and Kulacki F.A., Utility scale hybrid wind-solar thermal electrical generation, 2008

²⁷ Beyer H.G. and Degner T., Assessing the maximum fuel savings obtainable in simple wind-diesel systems, 1997

²⁸ Himri Y. et al., Techno-economical study of hybrid power system for a remote village in Algeria, 2008

²⁹ Beyer H.G. et al., Operational behaviour of wind diesel systems incorporating short-term storage: an analysis via simulation calculations, 1995

³⁰ Sayyaadi H. and Sabzaligol T., Comprehensive exergetic and economic comparison of PWR and hybrid fossil fuel-PWR power plants, 2010

³¹ Sayyaadi H. and Sabzaligol T., Comprehensive exergetic and economic comparison of PWR and hybrid fossil fuel-PWR power plants, 2010

Figure 6.1-2: Hybrid technologies matrix of systems being commercial, pre-commercial in research and development or even plausible.³²

However, several further options could be included like combinations of heat and electricity systems, ocean power systems and renewable power methane storage facilities (sub-chapter 7.4). In the chapters 6 and 7 of this thesis several major sub-components of hybrid power plants are discussed, i.e. renewable sources (PV, wind, STEG and hydro), fossil sources (oil, natural gas and coal) and storage (renewable power methane using CO₂ from air or CCS, thermal energy and sodium sulfur battery). By using only these eleven sub-component one could establish 190 different reasonable hybrid power systems in total and still 105 containing a PV sub-plant. Most of these systems have been never described in detail before, but at least 15 in 190 hybrid power plants are discussed in this thesis and are grouped in Table 6.1-1.

6.1.2 Flexible Operability of Fossil Power Plants

There are various types of fossil fuel fired power plants like natural gas or oil fired combined cycle gas turbines (CCGT) in the typical power range of 60 – 800 MW, natural gas or oil fired gas turbines (GT) in the typical power range of 60 – 250 MW, coal fired steam power plants (ST) in the typical power range of 60 – 800 MW and internal combustion plants already mentioned in section 3.4.2.2.³³ In the last two decades the CCGT power plant has been the most commonly built power plant in the world, except China being more focused on coal fired ST power plants (Fig. 5.1-9 and 5.1-10). The fundamental reason for this substantial growth in new CCGT power plant capacities had been power market liberalization in various markets, relative cheap natural gas fuel, increased risk level in parameters driving the power plant economics, relative reasonable performance in emissions and rather low capital requirements. All this provides a flexibility being described by the capability to follow the market on the supply side, e.g. fuel price and fuel availability, and the demand side, e.g. hourly, daily or seasonal power revenue and ancillary services.³⁴ The operational flexibility comprises fast start-up and shutdown, fast load changes and load ramps, high start-up reliability and load ramps, high load predictability, frequency control and ancillary services.³⁵ The changing parameters on both, supply and demand side, bear risks for plant owners. CCGT power plants need to be profitable as baseload plants, but also in the intermediate or cycling operational regime. A plant solely designed for baseload duty may not be able to efficiently follow those changes in market environment. Additionally, the liberalization provides market opportunities like ancillary products that can add to the revenue stream if the services can be supported by a flexible plant.³⁶ CCGT power plants are built up by several major components, like gas turbines, steam turbines, pumps, heat recovery steam generators, condensers, cooling towers, generators, motors, switch gears, fuel piping, fuel storage, bearings, lubrication systems, control systems and condition monitoring, all discussed in much detail by Boyce³⁷. The heat balance of a modern CCGT power plant and the respective energy flows are depicted in Figure 6.1-3.

³² Burch G.D., Hybrid renewable energy systems, 2001

³³ Kehlhofer R. et al., Combined-Cycle Gas & Steam Turbine Power Plants, 2009, p. 18

³⁴ Hofmann D. and Emberger H.-M., Taking Advantage of Market Opportunities through Siemens Reference Power Plants, 2006

³⁵ Henkel N. et al., Operational Flexibility Enhancements of Combined Cycle Power Plants, 2008

³⁶ Hofmann D. and Emberger H.-M., Taking Advantage of Market Opportunities through Siemens Reference Power Plants, 2006

³⁷ Boyce M.P., Handbook for Cogeneration and Combined Cycle Power Plants, 2010

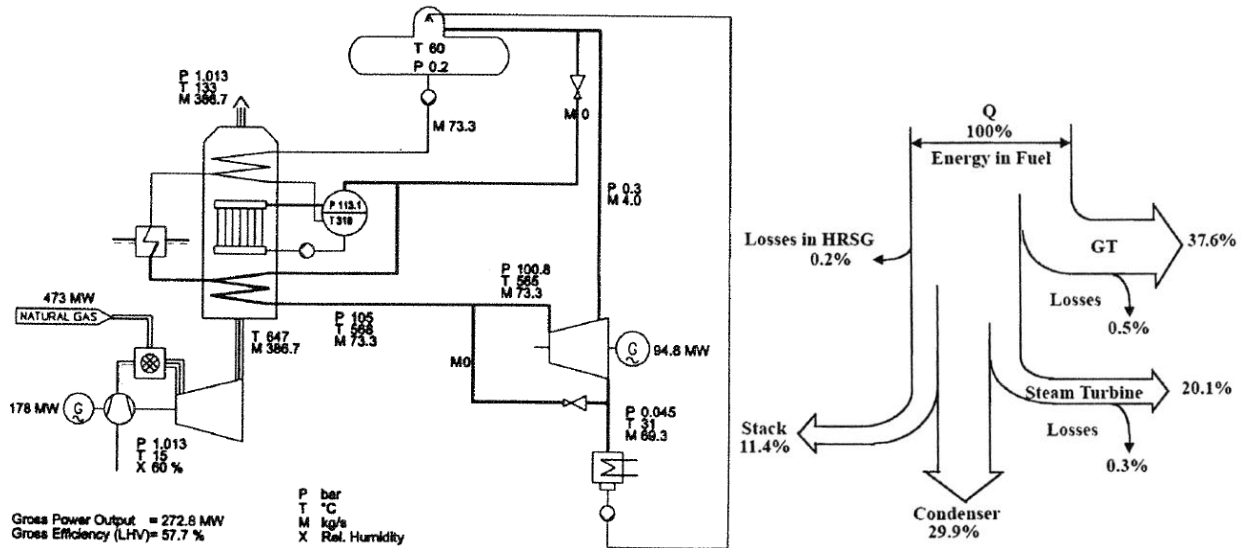


Figure 6.1-3: The heat balance (left) and energy flows of a modern approximately 58% efficient single-pressure CCGT.³⁸

The definitions for modern flexible CCGT power plants are about 200 annual starts after overnight shutdown (duration 8 – 16 h), about 50 annual starts after weekend shutdown (duration 16 – 64 h) and two annual starts after extended shutdown (> 64 h).³⁹ Since starting up to twice a day is a typical operation mode for CCGT power plants, reduction in operational expenditures is a significant driver for improved dispatchability and increased net cash flow. Units that are operationally flexible and can follow the load are able to cycle on and off more economically which will allow improved dispatchability and a competitive edge in the current market.⁴⁰ Competitive CCGT technology providers are able to offer turbines well adapted to these requirements. In the meantime not only newly built CCGT power plants fulfil the flexibility requirements, but also earlier commissioned power plants can be upgraded on a comparably flexible level.⁴¹ Modern flexible CCGT power plants show the improved start-up capabilities shown in Figure 6.1-4. The ramp rates of these power plants are 2.5% of full capacity per minute and even higher during the start-up sequence. Latest progress in CCGT technology led to 60% efficient turbines⁴² and a very fast start-up of 10 minutes⁴³.

³⁸ Kehlhofer R. et al., Combined-Cycle Gas & Steam Turbine Power Plants, 2009, p. 76f

³⁹ Emberger H. et al., Fast Cycling Capabilities for New Plants and Upgrade Opportunities, 2005

⁴⁰ Nag P. et al., Low Load Operational Flexibility for Siemens G Class Gas Turbines, 2008

⁴¹ Henkel N. et al., Operational Flexibility Enhancements of Combined Cycle Power Plants, 2008

⁴² Fischer W.J., SGT5-8000H / Irsching 4, on the way to 60% world record efficiency and path to 60 Hz SGT6-8000H, 2010

⁴³ DeLeonardo G. et al., FlexEfficiency* 50: Combined Cycle Power Plant, 2011

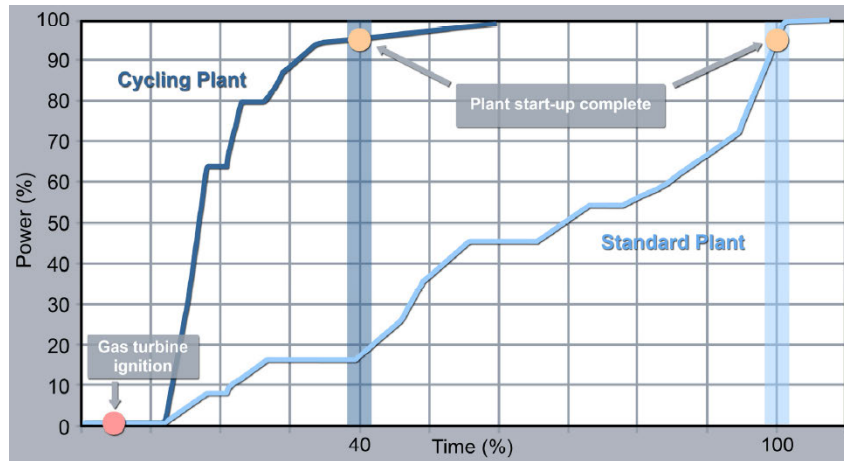
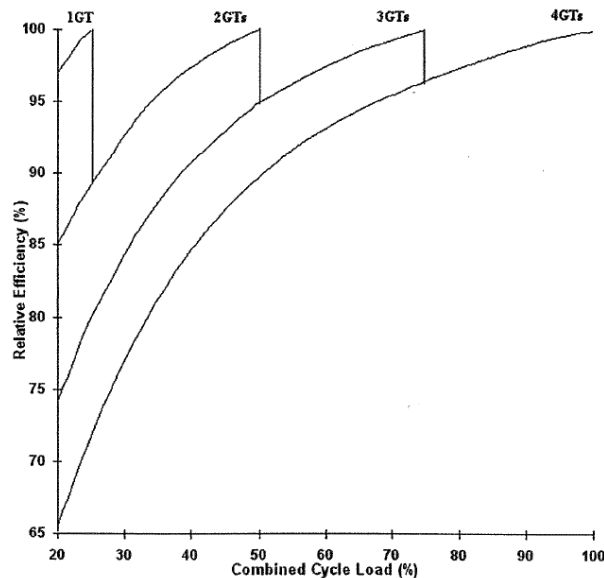


Figure 6.1-4: Start-up capability of modern CCGT power plants in contrast to conventional older ones.⁴⁴ The start-up time is reduced by about 60% from former approximately 90 minutes to less than 40 minutes in the so-called hot start mode, i.e. after an 8 hours overnight shutdown.

The progress in shorting the start-up time for increasing CCGT power plant flexibility has been enabled in only a few years, since the standard plant start-up characteristic was introduced in the 1990s. This increase in flexibility has been realised for warm start (64 h shutdown) and cold start (> 120 h shutdown) as well.^{45,46} The flexibility has been further increased by improving the maintenance need, i.e. longer maintenance intervals have been enabled, hence improving the power plant availability and reducing operational expenditures.⁴⁷ The power plant energy conversion efficiency is typically substantially reduced in case of part load operation, however an appropriate power plant design allows relative part load efficiencies not lower than 90% - 95% of full load efficiency even for a part load of 20% (Fig. 6.1-5). This is an enormous contribution for a high operational flexibility while hardly increasing power generation cost.



⁴⁴ Henkel N. et al., Operational Flexibility Enhancements of Combined Cycle Power Plants, 2008

⁴⁵ Emberger H. et al., Fast Cycling Capabilities for New Plants and Upgrade Opportunities, 2005

⁴⁶ Kehlhofer R. et al., Combined-Cycle Gas & Steam Turbine Power Plants, 2009, p. 254

⁴⁷ Hofmann D. and Emberger H.-M., Taking Advantage of Market Opportunities through Siemens Reference Power Plants, 2006

Figure 6.1-5: Part load efficiency of CCGT power plants with four single-shaft blocks.⁴⁸

Demand for flexible power plants as a consequence of altered supply and demand characteristics has led to a technological evolution in the field of oil and natural gas fired GT and CCGT power plants. This success is extended to coal fired power plants and realised in the integrated gasification combined cycle (IGCC) power plant which can be fuelled with any type of fossil fuels, in particular any types of coal.⁴⁹ The first IGCC demonstration power plants suffered from quite low efficiencies⁵⁰, but this will be overcome in next generation plants by addressing levels of about 44% without carbon capture and storage (CCS), whereas this will be again reduced to a comparably low 34% level in case of CCS inclusion⁵¹. The IGCC power plants would also be able to operate as flexible as the oil and natural gas fired GT and CCGT power plants. Some major characteristics of oil, natural gas, coal and uranium fired thermal power plants are summarized in Table 6.1-2.

type of plant	size	net efficiency	construction time	availability	reliability	flexibility	
	[MW]	[%]	[months]	[%]	[%]	now	next gen
CCGT (oil, gas)	800	55-60	20-30	90-94	95-98	yes	yes
CCGT (oil, gas)	60	50-54	20-30	90-94	95-98	yes	yes
GT (oil, gas)	250	38-40	12-24	90-95	97-99	yes	yes
GT (oil, gas)	60	35-42	12-24	90-95	97-99	yes	yes
ST (coal)	800	42-47	40-50	88-92	94-98	no	yes
ST (coal)	60	30-35	40-50	88-92	94-98	no	yes
Nuclear	1250	35	60-80	88-92	94-98	no	no

Table 6.1-2: Characteristics of fossil and nuclear fuelled thermal power plants.^{52,53}

Summing up, modern oil and natural gas fired GT and CCGT power plants can be operated in a very flexible mode without decreasing plant lifetime and operational cost per generated energy. Two start-up and shutdown sequences a day are part of standard power plant design. An upgrade option for older GT and CCGT power plants is available. Besides the flexibility requirement of last two decades the arising need for flexibility due to fast growing fluctuating renewable PV and wind power plants can be provided by these plants which positions them as nearly ideal balancing power plants. In near term even coal fired power plants will be able to be operated in such a flexible manner. This will not be the case for nuclear power plants, hence they are in principle not appropriate for future flexibility requirements and therefore will have to be substituted.

6.1.3 Energy Meteorology

The interdisciplinary field of energy meteorology integrates the physics of the atmosphere and energy system engineering for tackling the various impacts of weather and climate on conversion, transmission and consumption of energy. Several different disciplines are needed for high performing energy meteorology services, like meteorology, physics, engineering,

⁴⁸ Kehlhofer R. et al., Combined-Cycle Gas & Steam Turbine Power Plants, 2009, p. 238

⁴⁹ Kehlhofer R. et al., Combined-Cycle Gas & Steam Turbine Power Plants, 2009, p. 254

⁵⁰ Horlock J.H., Combined Power Plants, 2002, p. 258-262

⁵¹ Kehlhofer R. et al., Combined-Cycle Gas & Steam Turbine Power Plants, 2009, p. 313

⁵² Kehlhofer R. et al., Combined-Cycle Gas & Steam Turbine Power Plants, 2009, p. 287-320

⁵³ Fischer W.J., SGT5-8000H / Irsching 4, on the way to 60% world record efficiency and path to 60 Hz SGT6-8000H, 2010

information technology and economics.⁵⁴ High quality energy meteorology is essential for PV, since fast increasing cumulative installed PV capacities (Fig. 3.1-1, 3.1-20 and 3.1-23) need to be properly integrated in existing local power systems. The operation modes of existing peaking power plants, e.g. oil and natural gas fired power plants (sub-chapters 6.2 and 6.3), intermediate load power plants, e.g. natural gas and hard coal fired power plants (sub-chapters 6.3 and 6.4), but also storage facilities (section 7.4.1) need to be adapted to fluctuating feed-in power sources like wind power and PV. By accurate forecasting of solar resource availability, and hence PV power feed-in, the necessary capacity to be provided by conventional power plants can be planned at least one day ahead. Furthermore, good prognosis tools significantly reduce the cost of PV integration into conventional power systems, already documented by respective tools for wind power prediction which lowered the regulation cost by 40% and even the knowledge of the uncertainty on the short-term reduced the cost by further 40%⁵⁵.

In Germany the first PV power forecasting tool has been introduced in the year 2006⁵⁶ and steadily improved ever since. Since the year 2010 all four German transmission service operators (TSO) have to publish PV power forecasts based on the prognosis for all local distribution service operators (DSO). The relative root mean square error (rmse) of the day-ahead (24 hour) forecast has been continuously reduced from about 35% - 40% in the year 2004 to less than 4% in the year 2011.^{57,58,59,60} This is already better than wind power prognosis in the mid 2000s.⁶¹ The fast progress in PV power forecast quality has been made possible by several factors. Several thousand locally monitored PV systems are taken as reference, either by measurements of meteocontrol or SMA systems.^{62,63} Considering thousands of representative spatially distributed PV systems is very important, since in 2010 the largest source of PV power related instability of the power system in Germany was caused by false and incorrect measurement of existing PV systems at the DSO level.^{64,65} Correct inclusion of various cloud conditions further improves the PV power prediction.^{66,67,68} Weather services show a different quality profile for different weather situations. Knowing which weather service is better performing for a special weather constellation further improves the PV power forecast, an effect known since years in wind power forecasting.^{69,70} In the winter 2009/2010 snow coverage on PV modules induced a significant deviation of PV prediction and real power feed-in. However the questions, where at what time the snow was and when it would slip down the modules has been solved by inclusion of a specialized snow

⁵⁴ Heinemann D., *Energiemeteorologie: Ein Überblick*, 2006

⁵⁵ Petersen E.L., *State of the Art and Challenges in Wind Power Meteorology*, 2006

⁵⁶ Bofinger S. and Heilscher G., *Solar Electricity Forecast – Approaches and First Results*, 2006

⁵⁷ Lorenz E., *Solarstrahlungsvorhersage und ihre Anwendung in der Solarenergie*, 2006

⁵⁸ Lorenz E. et al., *Regional PV power prediction for improved grid integration*, 2010

⁵⁹ Schmelter J. and Focken U., *Operationelle Erfahrungen mit kombinierten Solarleistungsvorhersagen für deutsche ÜNBs und VNBs*, 2011

⁶⁰ Focken U., *Feed in of PV-power: Benefits of a good prognosis*, 2011

⁶¹ Bremen von L. et al., *Meteorological Models for Prediction and Simulation of Wind Power*, 2006

⁶² Lorenz E. et al., *Regional PV power prediction for improved grid integration*, 2010

⁶³ Focken U., *Feed in of PV-power: Benefits of a good prognosis*, 2011

⁶⁴ Schmelter J. and Focken U., *Operationelle Erfahrungen mit kombinierten Solarleistungsvorhersagen für deutsche ÜNBs und VNBs*, 2011

⁶⁵ Focken U., *Feed in of PV-power: Benefits of a good prognosis*, 2011

⁶⁶ Beyer H.G. et al., *Analysis and Synthesis of Cloud Pattern for Radiation Field Studies*, 1994

⁶⁷ Beyer H.G. et al., *Zeitlich/ räumliche Eigenschaften meteorologischer Felder zur Charakterisierung einer verteilten Erzeugung aus regenerativen Quellen*, 2006

⁶⁸ Zehner M. et al., *Europaweite Untersuchung des Irradiance Enhancement Effects und erste Analysen der Bedeutung im PV-System*, 2011

⁶⁹ Focken U., *Feed in of PV-power: Benefits of a good prognosis*, 2011

⁷⁰ Lorenz E. et al., *Regional PV power prediction for improved grid integration*, 2010

sub model into the PV power prognosis and showed very good results in the following winter.^{71,72} Still not solved is the proper modeling of fog, but this is being addressed for improving the forecast quality.⁷³ Technically it is possible to reduce the one hour forecast interval to the 15 minutes interval typically used in the power industry but even a 5 minutes interval used in the US is manageable.⁷⁴ Lorenz et al.⁷⁵ give an overview on further relevant literature.

Summing up, the forecast deviations for PV power feed-in in Germany can still be further optimised but has already achieved a relative sophisticated level. The prognosis tools could be spread all around the world, currently performed for the US, by adaption to special local weather conditions, and should not be a large obstacle. Finally, the energy meteorology tools available for PV power feed-in are an excellent basis for well performing hybrid PV-Fossil power plants.

6.1.4 Price Coupling of Fossil Fuels

A major driving force for oil, natural gas and coal prices, is the price setting for crude oil. The crude oil price might have already entered the era of peak-oil, i.e. degrading and diminishing resources, which will maintain high fossil fuel prices (sub-chapter 1.3). Fossil fuel prices for crude oil, natural gas and steam coal considerably deviate in different markets in the world, but the overall price trend is similar and relative price differences decreased in the last decade (Fig. 6.1-6). Long-term price escalation as a consequence of increase in demand and degrading and diminishing resources is reflected in fossil fuel prices. A dependence of natural gas and coal prices on the crude oil price can be found within market fluctuations over the entire period of time. For comparison reasons all fossil fuel prices have been recalculated on thermal energy units to USD per barrel. The long-term price ratio of natural gas to crude oil is about 0.7 – 0.9, whereas the ratio of coal to crude oil is about 0.2 – 0.45. Coupling of natural gas and coal on crude oil is reasonable due to their thermal energy content, but ranges on a different level due to relative availability, local energy logistics and respective power plant efficiencies. Coupling of crude oil related oil fuels and respective consequences for diffusion of PV systems is discussed in section 3.4.2.2.

⁷¹ Lorenz E. et al., Regional PV power prediction for improved grid integration, 2010

⁷² Focken U., Feed in of PV-power: Benefits of a good prognosis, 2011

⁷³ Focken U., Feed in of PV-power: Benefits of a good prognosis, 2011

⁷⁴ Focken U., private communication, 2011

⁷⁵ Lorenz E. et al., Regional PV power prediction for improved grid integration, 2010

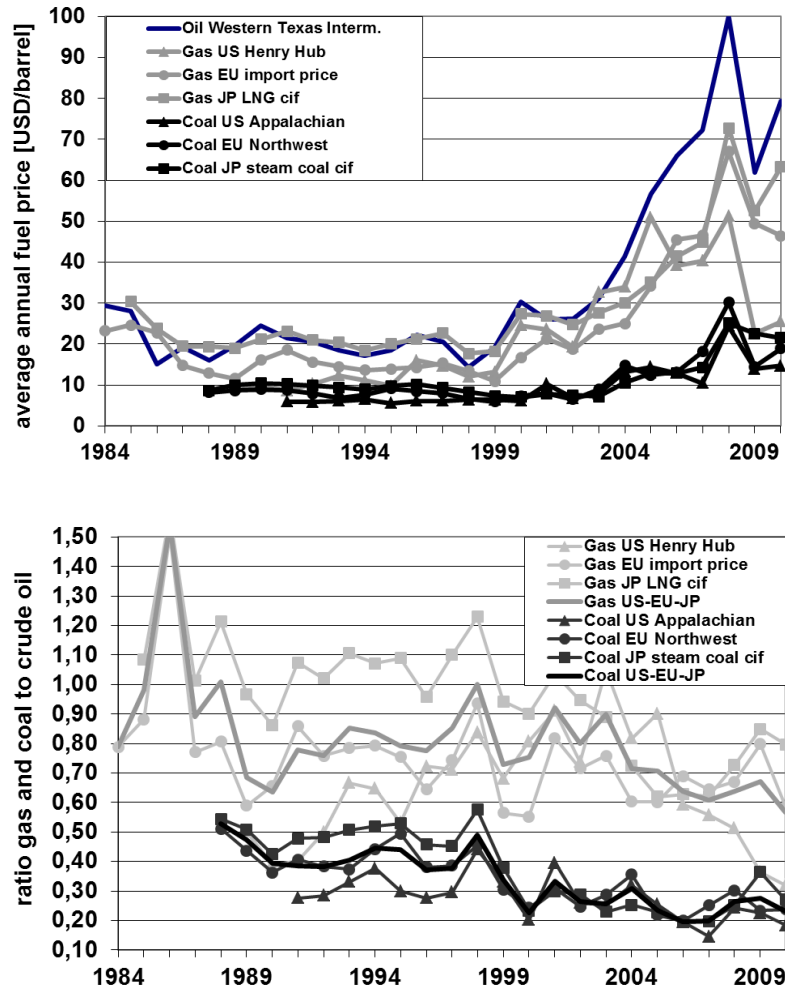


Figure 6.1-6: Fossil fuel prices in absolute financial units (top) and normalized to crude oil (bottom) on thermal energy units for major trade centres in the years 1984 to 2010. Long-term price escalation as a consequence of increase in demand and diminishing resources is reflected in prices. Dependence of natural gas and coal price on crude oil price can be found within market fluctuations over the entire period of time. Long-term price ratio of natural gas to crude oil is about 0.7 – 0.9, whereas ratio of coal to crude oil is about 0.2 – 0.45. Data are taken from BP ⁷⁶.

The analyses in this chapter are focused on the upgrading of existing fossil fuel fired power plants with PV power plants, hence the development of fossil fuel prices is very relevant for the economics of such hybrid PV-Fossil power plants. Best possible estimates for the price trends of oil, natural gas and steam coal have to be taken into account. An overview on long-term crude oil price expectation and price coupling factors for natural gas and coal from various sources is depicted in Figures 6.1-7 and 6.1-8.

⁷⁶ BP, Statistical Review of World Energy, 2011

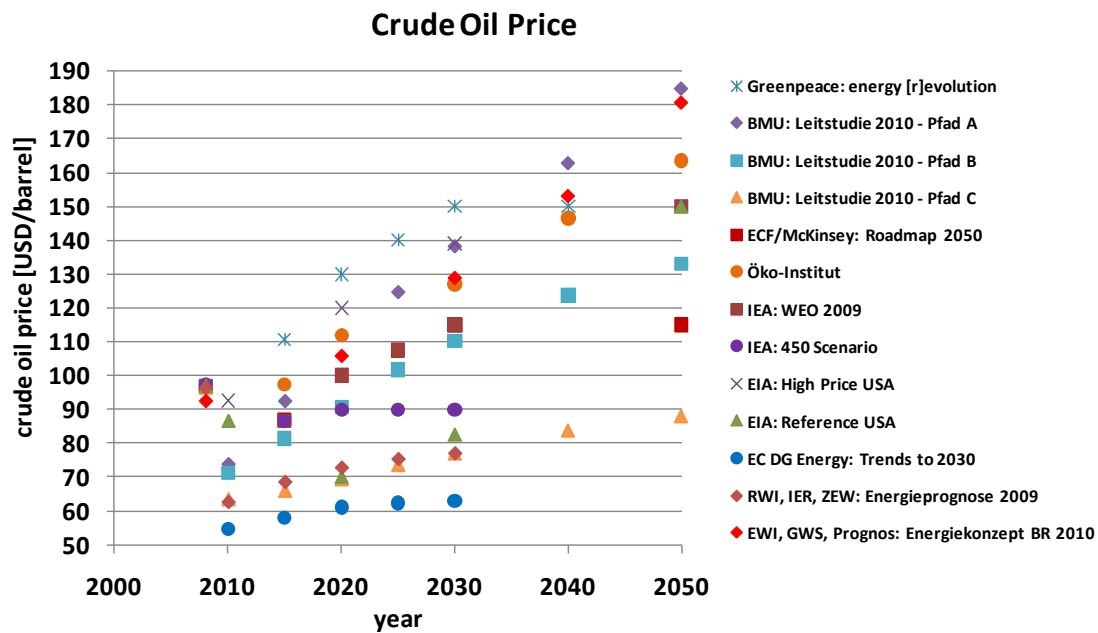
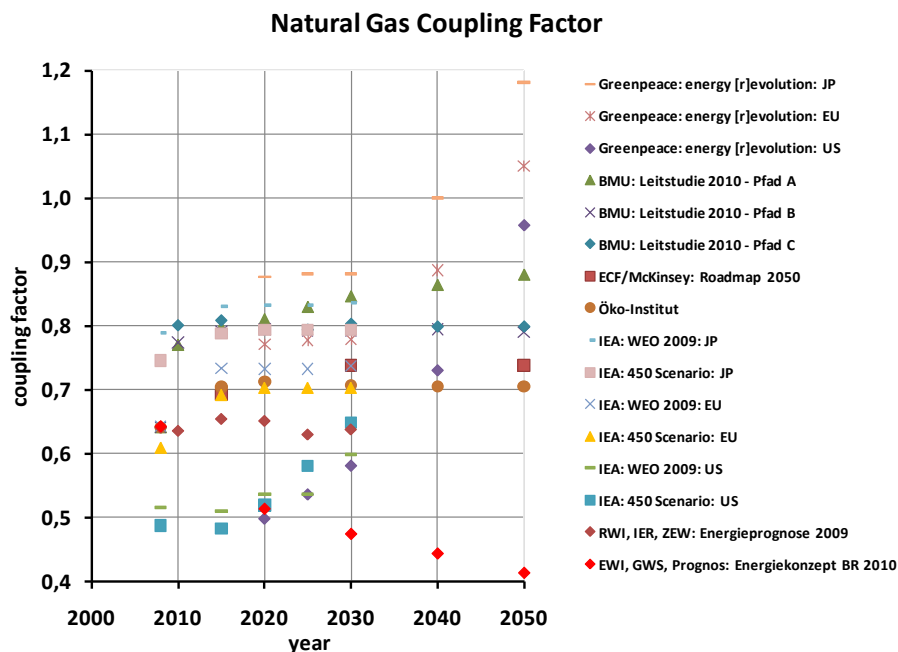


Figure 6.1-7: Crude oil price expectation of various sources for the years 2010 to 2050. The high difference in price expectations reflects the range from business-as-usual to high uncertainty in future crude oil supply. Data are taken from Greenpeace ⁷⁷, BMU ⁷⁸, ECF/McKinsey ⁷⁹, Öko-Institut ⁸⁰, IEA ⁸¹, EIA ⁸², EC ⁸³, RWI et al. ⁸⁴ and EWI et ⁸⁵



⁷⁷ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

⁷⁸ BMU, Leitstudie 2010, 2010

⁷⁹ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

⁸⁰ Matthes F.C., Energiepreise für aktuelle Modellierungsarbeiten, 2010

⁸¹ IEA, Projected Costs of Generating Electricity 2010 Edition, 2010

⁸² EIA, Annual Energy Outlook 2008 – With Projections to 2030, 2008

⁸³ EC, European Energy and Transport: Trends to 2030 – update 2007, 2008

⁸⁴ Fahl U. et al., Die Entwicklung der Energiemärkte bis 2030: Energieprognose 2009, 2010

⁸⁵ BMWi, Energieszenarien für ein Energiekonzept der Bundesregierung, 2010

Hard Coal Coupling Factor

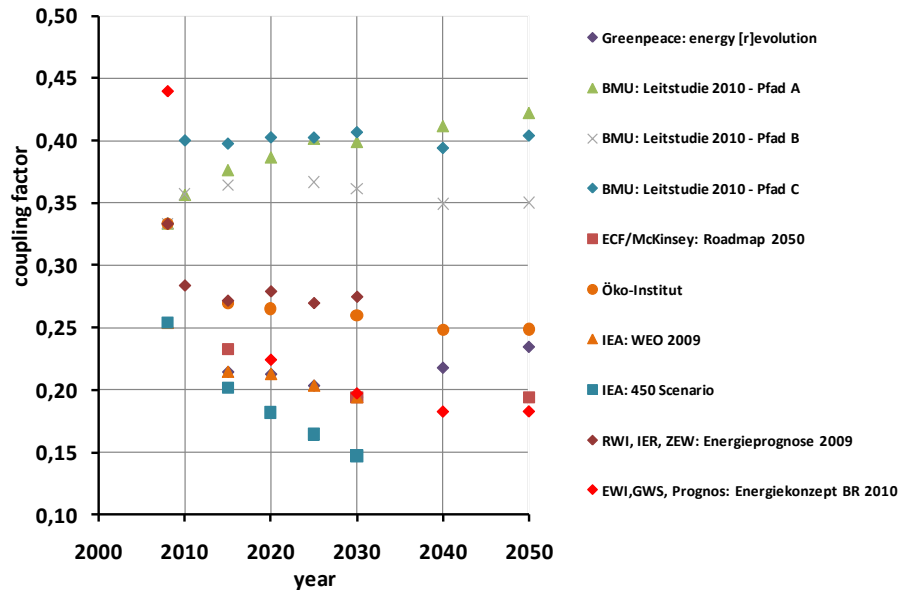
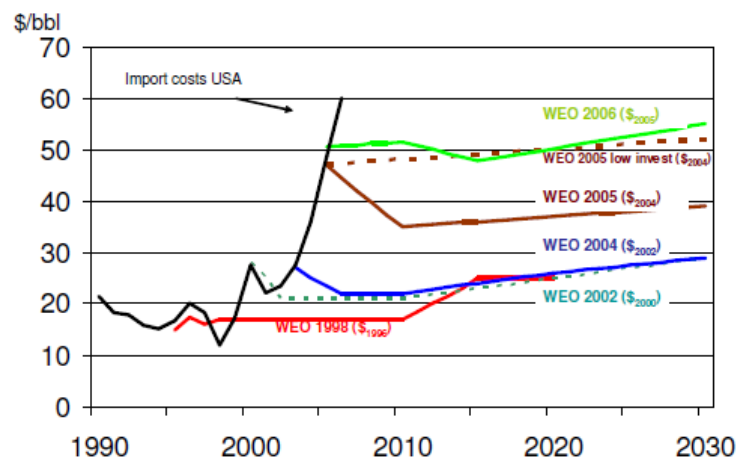


Figure 6.1-8: Price coupling factor expectations for natural gas (top) and hard coal (bottom) to crude oil of various sources for the years 2010 to 2050. The high difference in price coupling factors is to the lower part due to inhomogenous global energy prices but mainly a consequence of different fundamental market insights. Data are taken from Greenpeace⁸⁶, BMU⁸⁷, ECF/McKinsey⁸⁸, Öko-Institut⁸⁹, IEA⁹⁰, RWI et al.⁹¹ and EWI et al.⁹².

A major source of energy related analyses is the International Energy Agency. Most of the other sources for fossil fuel prices refer indirectly to the IEA and discuss their analyses in contrast to the IEA results. However the short-, mid- and long-term crude oil estimates of the IEA have been shown as misleading and in vast contrast to real market development (Fig. 6.1-9). The systematic prognosis errors might be partly caused by only limited market insights and outdated assumptions, but also by the fundamental political targets of the organization discussed by Gredler⁹³.



⁸⁶ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

⁸⁷ BMU, Leitstudie 2010, 2010

⁸⁸ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

⁸⁹ Matthes F.C., Energiepreise für aktuelle Modellierungsarbeiten, 2010

⁹⁰ IEA, Projected Costs of Generating Electricity 2010 Edition, 2010

⁹¹ Fahl U. et al., Die Entwicklung der Energiemärkte bis 2030: Energieprognose 2009, 2010

⁹² BMWi, Energieszenarien für ein Energiekonzept der Bundesregierung, 2010

⁹³ Gredler C., Das Wachstumspotenzial der Photovoltaik und der Windkraft – divergierende Wahrnehmungen zentraler Akteure, 2008

Figure 6.1-9: Crude oil price projection of the International Energy Agency and real price development for the 1990s to the 2020s.⁹⁴ The price data in the diagram ends in the year 2007, but in June 2008 the crude oil price reached an all time high of 147 USD/barrel and shortly after the end of the financial crisis the crude oil price returned to more than 120 USD/barrel in March 2011.

The different institutions strongly deviate in their price prognosis for crude oil and the mid- to long-term price coupling (Fig. 6.1-7 to 6.1-9). The reasons might be different, as some institutions are not independent enough from political and corporate bodies and tend to fulfil respective expectations but others do not draw the obvious conclusions on rapid declining global energy resources (sub-chapter 1.3). Fossil fuel price estimates of institutions closely related to the IEA analyses seem to be not relevant due to systematic prognosis errors in the past decades. As discussed earlier the fundamental price coupling mechanism is expected to be stable as a consequence of respective substitution processes in the global energy system.

Nevertheless, the long-term crude oil price trend is expected by all institutions to continue rising, as depicted in Figure 6.1-7. The price coupling of natural gas to crude oil is assumed to fluctuate mainly within a band of 0.6 – 0.9 (Fig. 6.1-8). The data points below a price coupling of 0.6 are largely influenced by short-term shale gas production increase in the US based on lowering environmental legislations and socializing the respective long-term risk of damage cost (section 1.3.2). Only one study outside the US assumes a stable decoupling trend of natural gas and crude oil prices.⁹⁵ But no single word in that study explains this historically new decoupling effect which is not expected by all the other institutions. Due to these curious circumstances the scientific basis of this study is assumed to be rather small. The price coupling of hard coal to crude oil is assumed to stay mainly within a band of 0.2 – 0.4 (Fig. 6.1-8). Two groups of prognoses can be identified. One group of studies assumes a decoupling tendency of coal and oil whereas the other group assumes a slightly increasing coupling tendency. Due to the fact that coal can be largely used for substituting fast declining natural gas and even oil in case of coal to liquid (CTL) technology^{96,97}, there seems to be no fundamental reason for a price decoupling trend of coal from oil.

A high deviation between cost and price of energy is the reality in the global energy business. In many cases the cost are much lower than the respective market price. However in general, the costs are significantly higher than the prices. Additionally, fossil fuels are also a burden for today's and next generations in respect to sustainability criteria. High social costs of fossil fuels are mainly due to climate change impact (sub-chapter 1.2), general subsidy schemes, general high negative environmental impact and military conflicts. Climate change costs are estimated by Lord Nicholas Stern simply by the statement, that the existence of climate change would be the greatest and widest-ranging market failure ever seen.⁹⁸ Global fossil fuel subsidies are high. In 2008 global energy subsidies had been about 710 bnUSD, composed by fossil energy consumption 553 bnUSD (78%), fossil fuel production 100 bnUSD (14%) and for the year 2009 renewable energy technologies 57 bnUSD (8%).⁹⁹ The lion's share of the energy subsidies are paid in non-OECD countries. Furthermore, environmental tragedies of fossil energy use cause high social cost, e.g. tar sand oil production in Canada, off-shore oil-production in Gulf of Mexico and significant heavy metal emissions of coal-fired power plants (section 3.1.7.2). Military involvement of US forces in Persian Gulf region is mainly

⁹⁴ Schindler J. and Zittel W., (eds.), *Crude Oil - The supply outlook*, 2008

⁹⁵ BMWi, *Energieszenarien für ein Energiekonzept der Bundesregierung*, 2010

⁹⁶ Hao X. et al., *Coal to Liquid (CTL): Commercialization Prospects in China*, 2007

⁹⁷ Schmetz E., *Coal to Liquid Fuels*, 2005

⁹⁸ Stern N. (ed.), *Stern Review on the economics of climate change*, 2006

⁹⁹ IEA, *World Energy Outlook 2010*, 2010, p. 567-614

caused by US energy supply constraints. For the time period of 1976 – 2007 cumulated capital investments for this engagement is estimated to about 6,800 bnUSD.¹⁰⁰ The true costs of fossil energy consumption can be expected to be significantly higher than current prices. Overcoming this fundamental market failure would instantly induce accelerating growth rates of renewable energy technologies, being typically free of such financial burden.

Summing up, as a consequence of substitution processes between crude oil, natural gas and hard coal the respective fossil fuel prices have been loosely coupled during the last decades. The price coupling referring to the primary energy content of natural gas to crude oil has been within a range of 0.7 – 0.9, whereas the range for the coupling of hard coal to oil has been about 0.2 – 0.45. The crude oil price is largely price setting for natural gas and coal, hence the focus can be laid on the projections of the crude oil price. All studies taken into account by various sources show an escalating price trend for crude oil in the decades to come. Most sources assume ongoing price coupling for natural gas to crude oil within a range of 0.6 – 0.9 and for coal to crude oil within a range of 0.2 – 0.4.

6.2 Hybrid PV-Oil Power Plant

Oil fired power plants are used for power supply all around the world (section 6.2.1) but depending on local conditions on a vast range of intensity. The economics of oil power generation (section 6.2.2) are the financial basis for a successful hybridization of PV power plants and oil fired power plants. This builds the fundament for the derivation of a global demand curve for hybrid PV-Oil power plants in the 2010s (section 6.2.3). In contrast to end-user prices driven grid-parity, the most decisive economic criteria in the power plant sector is the fuel-parity, i.e. competitive PV power generation cost in reference to total and fuel-only power generation cost of conventional power plants. The already discussed preconditions for a successful hybridization (sub-chapter 6.1) of PV and oil power plants are expanded and analysed in this sub-chapter in a special focus on the economics.

6.2.1 Global Overview on Oil Power Capacity

The present and future relevance of a power technology can be assessed by its resource availability (sub-chapter 1.3), the installed power capacity, utilization of the available power capacity and the local power supply contribution. These dimensions will be presented and discussed in the following for oil fired power plants. The distribution of global crude oil reserves is depicted in Figure 6.2-1.

¹⁰⁰ Stern R.J., United States cost of military force projection in the Persian Gulf 1976 – 2007, 2010

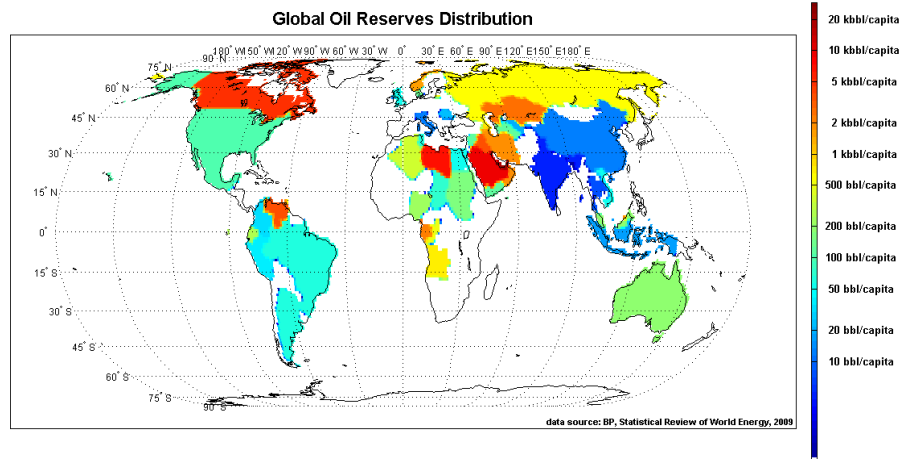
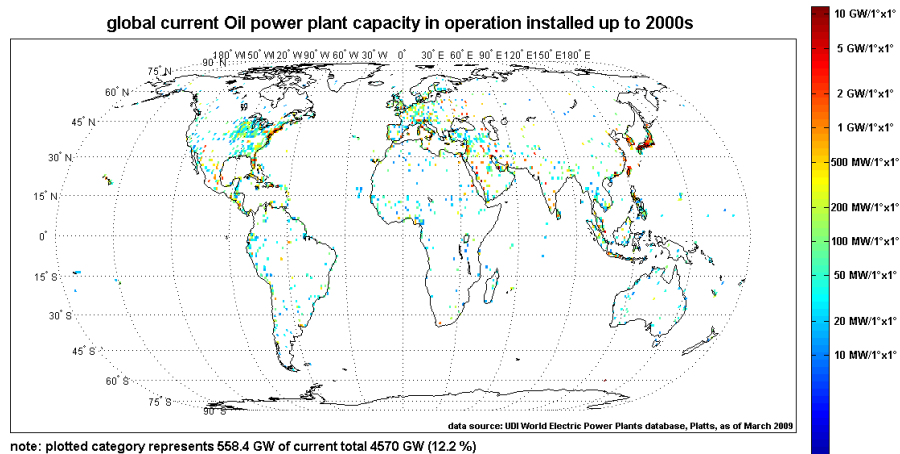


Figure 6.2-1: Distribution of global crude oil reserves. Data are taken from BP ¹⁰¹.

Total global installed oil power capacity was 438 GW by end of 2008 and generated electricity was 1,104 TWh in the year 2008, translating to 2,520 full load hours.¹⁰²

It is necessary to know the coordinates of the oil power plants for further analysis. Due to that the UDI World Electric Power Plants database ¹⁰³ has been enhanced by coordinates of all 145,000 power plants in the world.¹⁰⁴ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. However, a crosscheck reveals a capacity of about 558 GW of oil power plants in the database versus 438 GW denominated in the IEA dataset. The deviation of about 120 GW might be caused by fuel shifts between oil and natural gas (section 6.3.1).

In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration has been taken in these cases. The result of the georeferenced global power plant capacity being in operation is depicted in Figure 6.2-2.



¹⁰¹ BP, Statistical Review of World Energy, 2009

¹⁰² IEA, World Energy Outlook 2010, 2010

¹⁰³ Platts, UDI World Electric Power Plants data base, 2009

¹⁰⁴ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

Figure 6.2-2: Global oil power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. Data are plotted in a $1^\circ \times 1^\circ$ mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database¹⁰⁵ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced oil power plant data (Fig. 6.2-2) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current oil fired power plant capacity (Fig. 6.2-3). About 220 GW out of 558 GW included in the database are located in areas of more than $1,800 \text{ kWh/m}^2/\text{y}$ irradiation on fixed optimally tilted module surfaces, i.e. 39% of global oil power installed base is already installed in regions of very good solar resource quality. Oil power plants operated during daytime match in an excellent way to feed-in profile of PV power plants and can be operated very flexibly (section 6.1.2 and 3.4.2.2), hence detailed analysis on the economics of hybrid PV-Oil power plants is performed and discussed in sections 6.2.2 and 6.2.3.

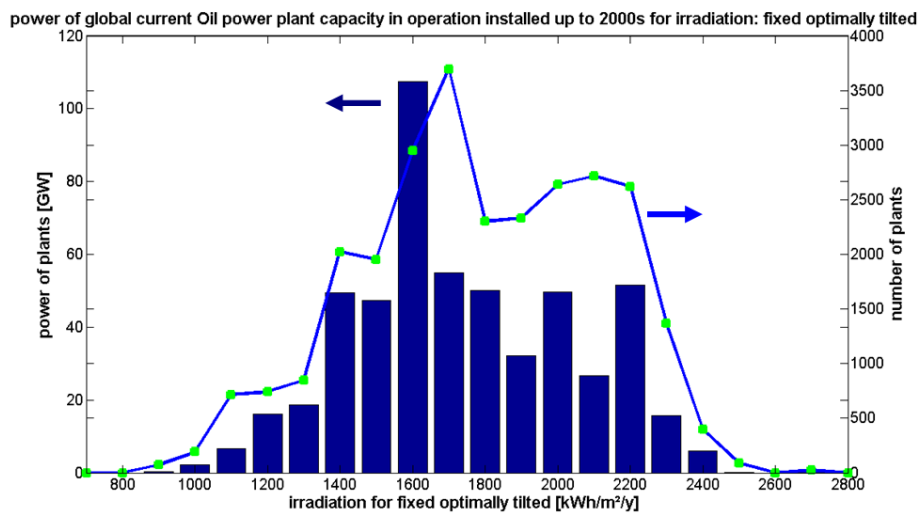


Figure 6.2-3: Global oil fired power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 6.2-2) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 6.2-4 and shows that most power plants are in the power class of 1 - 10 MW or even smaller in size. However, their contribution to global power capacity is very small. Almost 30% of global oil power plant capacity consists of power plants of 10 - 100 MW in size and 56% in the power class of 100 - 1000 MW.

¹⁰⁵ Platts, UDI World Electric Power Plants data base, 2009

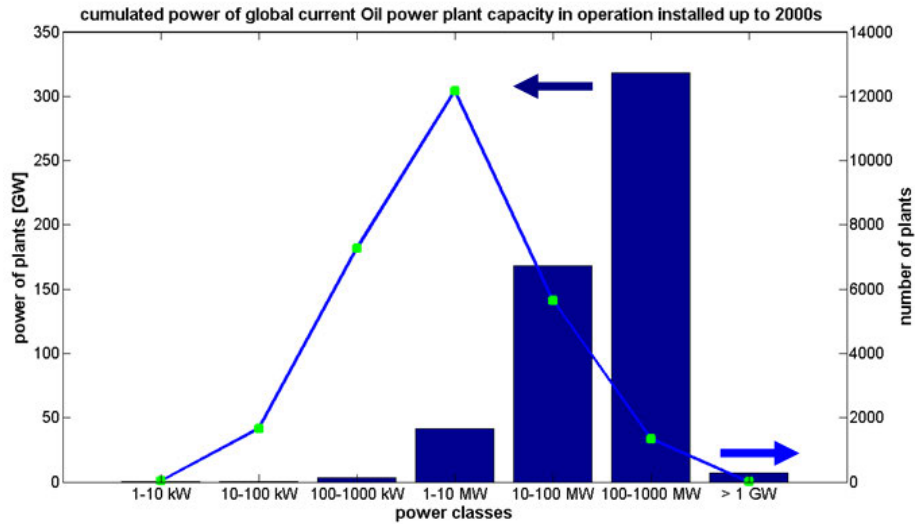


Figure 6.2-4: Global oil power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent power plant capacity. Data are taken from UDI World Electric Power Plants database ¹⁰⁶

Contribution of oil power to global electricity supply is moderate and accounts for about 5.5%. Global average total electricity generation per capita is about 3.0 MWh_{el} but 5 – 10 MWh_{el} in industrialised countries (sub-chapter 5.1). Leading oil electricity per capita country in the world is Kuwait achieving 11 MWh_{el} per capita (Fig. 6.2-5). Several other countries reach a high level of oil power supply per capita, as well.

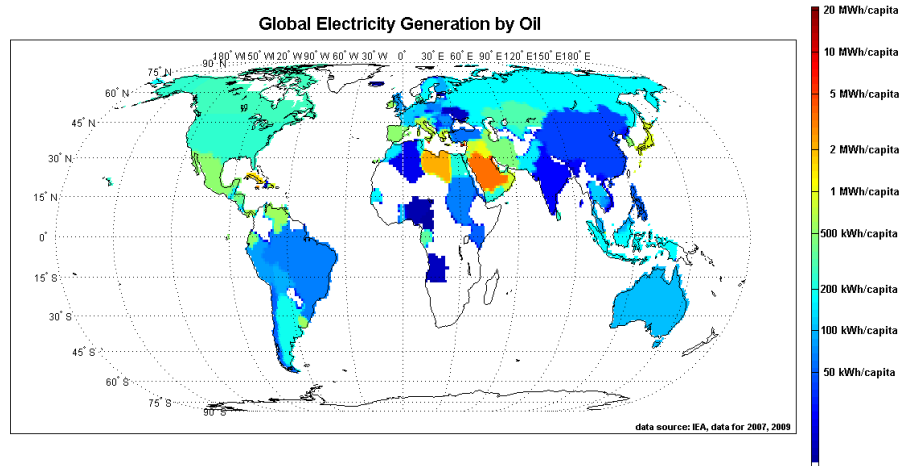


Figure 6.2-5: Global electricity generation by oil per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency ¹⁰⁷ and United Nations ¹⁰⁸.

Global installed oil power plant capacity per country is illustrated in Figure 6.2-6. Leading countries by cumulated oil power capacity are Japan, the US, Saudi Arabia, China, Italy and Korea by end of 2008. However, Japan, the US and Korea use their oil power plants only as peakers for about 1,000 full load hours per year (Fig. 6.2-7).

¹⁰⁶ Platts, UDI World Electric Power Plants data base, 2009

¹⁰⁷ IEA, Key World Energy Statistics 2009, 2009

¹⁰⁸ UN, World Population Prospects: The 2008 Revision Highlights, 2009

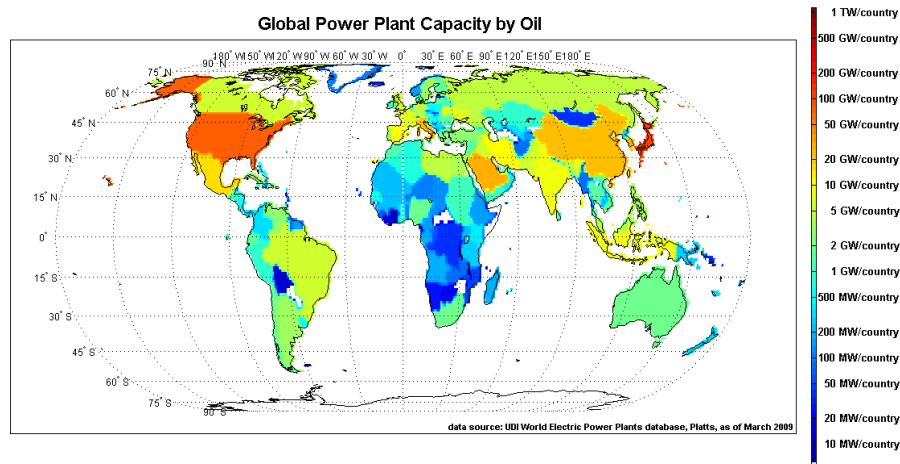


Figure 6.2-6: Global oil power plant capacity per country by early 2009. Only power plants in operation are regarded. Data are taken from UDI World Electric Power Plants database¹⁰⁹.

The structure of power plant capacity can be illustrated on a per country basis for average annual full load hours (Fig. 6.2-7) and relevance of respective domestic overall electricity generation (Fig. 6.2-8). Oil power can be used in different operation modes, i.e. baseload, intermediate and peaking power supply. There are several countries in the world achieving an oil power supply contribution of more than 50% at a high absolute installed power capacity, e.g. Saudi Arabia, Kuwait, Iraq, Libya and Cuba. Full load hours of oil power plants are dependent on the operation mode and obviously on crude oil resource availability. Combination of PV and oil power is a real option and is discussed later in this sub-chapter.

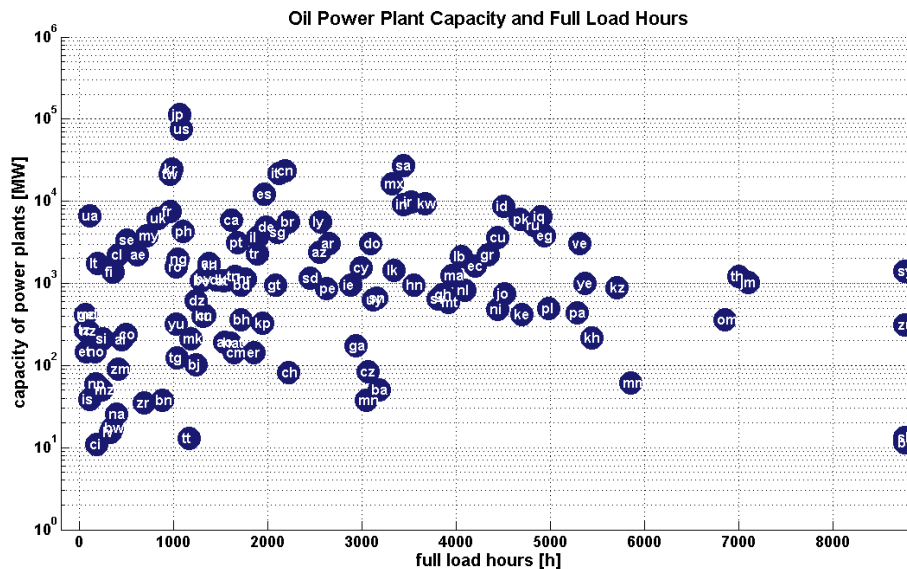


Figure 6.2-7: Oil power plant capacity in dependence on full load hours per country. Each dot represents the absolute oil power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database¹¹⁰ and International Energy Agency¹¹¹.

¹⁰⁹ Platts, UDI World Electric Power Plants data base, 2009

¹¹⁰ Platts, UDI World Electric Power Plants data base, 2009

¹¹¹ IEA, Key World Energy Statistics 2009, 2009

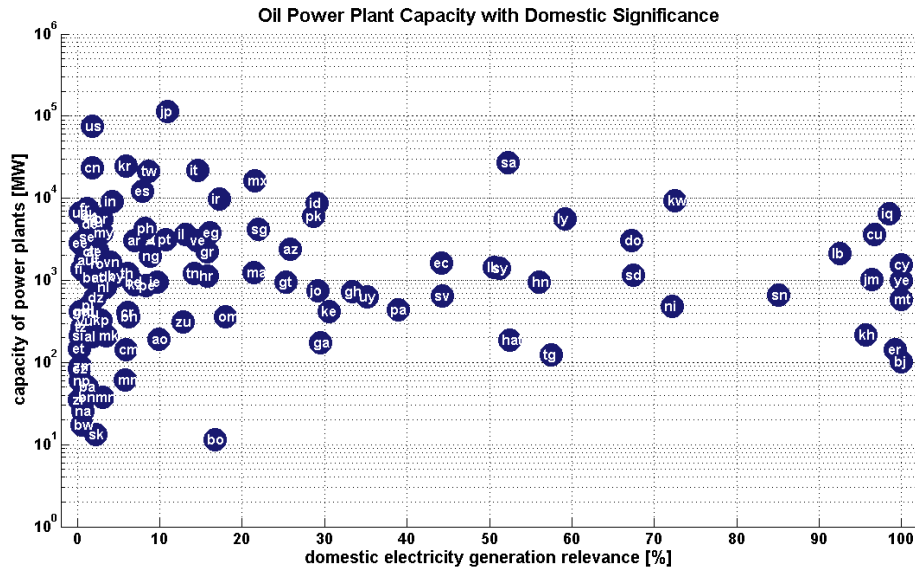
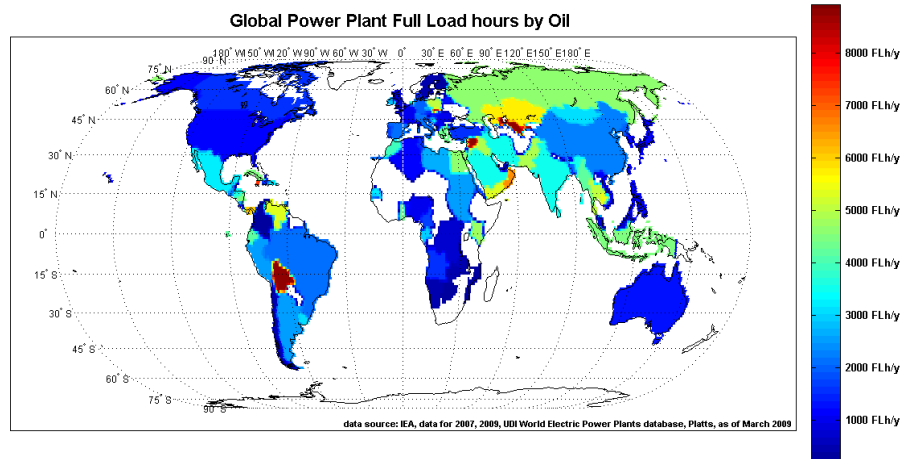


Figure 6.2-8: Oil power plant capacity in dependence on domestic electricity generation relevance per country. Each dot represents the absolute and relative oil power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ¹¹² and International Energy Agency ¹¹³.

Global distribution of full load hours and ratio to total domestic electricity generation is depicted in Figure 6.2-9 for visualising purposes. Identical information is given in Figures 6.2-7 and 6.2-8, but for subjective perception and for an analysis coordinate wise this kind of illustration is very helpful.



¹¹² Platts, UDI World Electric Power Plants data base, 2009

¹¹³ IEA, Key World Energy Statistics 2009, 2009

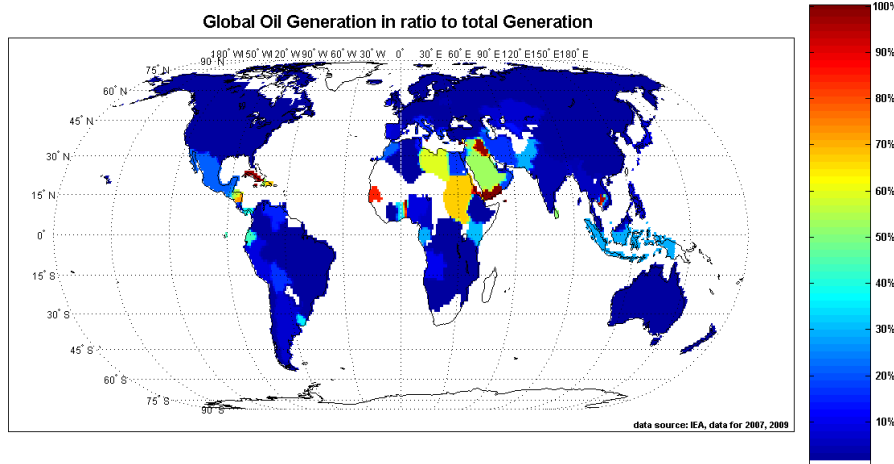


Figure 6.2-9: Global distribution of oil power plant full load hours (top) and the ratio to total domestic electricity generation (bottom). Data are taken from UDI World Electric Power Plants database ¹¹⁴ and International Energy Agency ¹¹⁵.

Summing up, global oil power plant capacity of 438 GW is in average 2,520 full load hours in operation and generate annually about 1,100 TWh of electricity, representing 9.3% of total global installed power capacity and 5.5% of global generated electricity. In oil producing countries significantly more oil power plants are in operation for much higher full load hours than in oil importing industrialised or emerging countries. Developing countries are often dependent on oil power plants, but typically on a low absolute capacity. Oil power plants operated during daytime match in an excellent way to the feed-in profile of PV power plants and can be operated very flexibly. In the following section, hybrid PV-Oil plants are discussed in more detail.

6.2.2 Oil Power Economics

A cost model for oil fired power plants enables the calculation of oil power levelized cost of electricity (LCOE) for all coordinates by applying average local full load hours (FLh) shown in Figure 6.2-9. These oil FLh contain all relevant data on local oil power plant operation patterns and can be used as an indicator for combining PV and oil power plants to a hybrid PV-Oil power plant. Besides typical capital expenditures (Capex) and operational expenditures (Opex) major current and future cost positions are expenditures for fuel and related carbon emissions. Both fuel and carbon emission expenditures are directly related to the power conversion efficiency of the oil power plant. Such derived oil LCOE make it possible to compare oil LCOE to LCOE of other renewable and conventional power plant technologies.

Methodology of calculating oil power LCOE is based on that of PV (section 3.2.1 and Eqs. 3.2-1). Adjustments are needed for specific differences of oil power and PV, summarized in Equations 6.2-1:

$$LCOE = \frac{Capex \cdot crf + Opex_{fix}}{FLh_{oil,el}} + Opex_{var} + \frac{fuel_{oil}}{PE_{th,oil} \cdot \eta_{oil,el}} + \frac{carbon \cdot GHG_{oil}}{\eta_{oil,el}} \quad (\text{Eq. 6.2-1a})$$

¹¹⁴ Platts, UDI World Electric Power Plants data base, 2009

¹¹⁵ IEA, Key World Energy Statistics 2009, 2009

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (\text{Eq. 6.2-1b})$$

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \quad (\text{Eq. 6.2-1c})$$

$$fuel_{oil} = fuel_{crudeoil} \cdot cf_{oil} \quad (\text{Eq. 6.2-1d})$$

$$fuel_{crudeoil} = fuel_{crudeoil,2010} \cdot (1 + r_{crudeoil})^{y-2010} \quad (\text{Eq. 6.2-1e})$$

$$\eta_{oil,el} = \eta_{oil,el,2010} + (y - 2010) \cdot r_{\eta,oil} \quad (\text{Eq. 6.2-1f})$$

$$carbon = carbon_{2010} \cdot (1 + r_{carbon})^{y-2010} \quad (\text{Eq. 6.2-1g})$$

Equation 6.2-1: Levelized cost of electricity (LCOE) for oil power plants. Abbreviations stand for: capital expenditures (*Capex*), annuity factor (*crf*), annual operation and maintenance expenditures (*Opex*), annual fixed Opex (*Opex_{fix}*), variable Opex (*Opex_{var}*), annual full load hours of oil power plants (*FLh_{oil,el}*), fuel cost for oil fired power plants (*fuel_{oil}*), thermal energy conversion factor (*PE_{th,oil}*), primary to electric energy conversion efficiency of oil fired power plants (*η_{oil,el}*), carbon emission cost (*carbon*), carbon emission intensity per thermal energy of oil fired power plants (*GHG_{oil}*), weighted average cost of capital (*WACC*), lifetime of oil power plants (*N*), equity (*E*), debt (*D*), return on equity (*k_E*), cost of debt (*k_D*), fuel cost of crude oil (*fuel_{crude oil}*), fuel cost of crude oil in the year 2010 (*fuel_{crude oil,2010}*), annual escalation rate of crude oil price (*r_{crude oil}*), year (*y*), ratio of oil to crude oil as coupling factor (*cf_{oil}*), primary to electric energy conversion efficiency of oil fired power plants in the year 2010 (*η_{oil,el,2010}*), annual increase of primary to electric energy conversion efficiency of oil fired power plants (*r_{η,oil}*), specific greenhouse gas emission cost (*carbon*), specific greenhouse gas emission cost in the year 2010 (*carbon₂₀₁₀*) and annual escalation rate of greenhouse gas emission cost (*r_{carbon}*).

The scenario assumptions for calculating LCOE of oil power plants are summarized in Table 6.2-1. Major LCOE component of oil power plants are the fuel cost which are directly coupled to the crude oil price and its fluctuations and tendency for long-term escalation. Applied base case scenario assumes a moderate crude oil price of 80 USD/barrel. This core assumption might be too conservative, in particular due to a further assumed annual crude oil escalation rate of 3% in real terms.

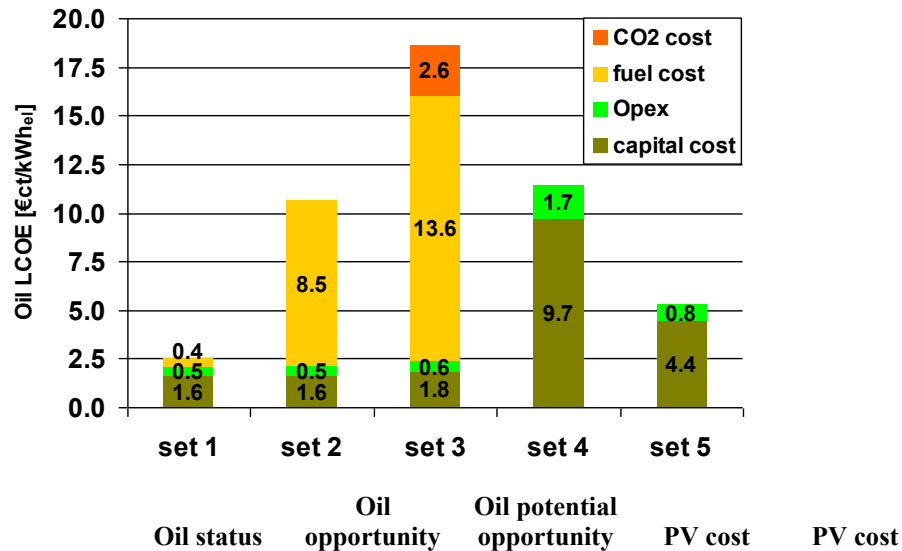
Parameters	units	scenario base case
Capex_Oil	[€/kW]	800
fin_RoE	[%]	10.0%
fin_interest	[%]	6.0%
fin_WACC	[%]	6.80%
fin_equityRatio	[%]	20%
exchange_rate	[USD/€]	1.40
plant_lifetime	[y]	30
plant_Opex_fix	[€/kW/y]	17
plant_Opex_var	[€/MWh _{el}]	1
plant_turbine_efficiency_2010	[%]	40%
plant_turbine_efficiency_2020	[%]	50%
plant_turbine_efficiency_increase	[%/y]	1%
coupling_factor_oil-to-crude oil	[-]	1.0
fuel_price_crude oil_2010	[USD/barrel]	80.0
escalation_rate_crude oil_price	[%/y]	3%
carbon_price_2010	[€/t _{CO2}]	0.0
escalation_rate_carbon_price	[%/y]	0%

thermal energy conversion oil	[MWh _{th} /barrel]	1.68063
greenhouse gas intensity oil	[t _{CO2} /MWh _{th}]	0.264

Table 6.2-1: Scenario assumptions for oil power plant economics. The base case scenario covers a business-as-usual approach, whereas the assumptions on the crude oil price and its escalation as the most relevant cost factor might be too conservative. Numbers mentioned are for oil power plants of multi-100 MW. The methodology is comparable to that of PV, STEG and wind power LCOE calculation (Tables 3.2-1, 4.1-1 and 4.2-1). General parameters are set identical as far as possible or at least comparable, in particular for the financial parameters, although fossil WACC should be higher than that of renewable energy technologies due to a higher price risk profile (section 3.2.1) ¹¹⁶. Abbreviations stand for: capital expenditures (Capex), return on equity (RoE), weighted average cost of capital (WACC), operational expenditures (Opex), annual fixed Opex (Opex_{fix}) and variable Opex (Opex_{var}). Data are taken from various sources like European Climate Foundation ¹¹⁷, Greenpeace ¹¹⁸, IEA ^{119,120} and IPCC ¹²¹.

Oil power plant LCOE structure is illustrated in Figure 6.2-10 and is mainly driven by scenario assumptions of the base case definition for oil power plants (Table 6.2-1). Parameter settings are varied for crude oil price, greenhouse gas emission cost, energy conversion efficiency and full load hours. These scenario variations are compared to expected PV LCOE structure in 2010 and 2020 in sunny regions (based on Table 3.2-1).

Parameter setting of ‘set 2’ is representative for LCOE structure of oil power plants in late 2010. Total oil LCOE of 10.6 €/kWh are composed by capital cost of about 15% (1.6 €/kWh), Opex of about 5% (0.5 €/kWh) and fuel cost of 80% (8.5 €/kWh) based on a crude oil price of 80 USD/barrel. Such a cost structure is highly vulnerable to crude oil price fluctuations. Therefore, mid- to long-term price escalations are unfavourable for oil power plant economics. On the contrary, LCOE structure of PV power plants is dominated by capital cost being fixed by the investment decision and stable during the entire investment period. Moreover, low PV Opex enable excellent economics after the investment period for power plants being still in operation.



¹¹⁶ Awerbuch S., Portfolio-based electricity generation planning: policy implications for renewables and energy security, 2006

¹¹⁷ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

¹¹⁸ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

¹¹⁹ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008

¹²⁰ IEA, Projected Costs of Generating Electricity 2010 Edition, 2010

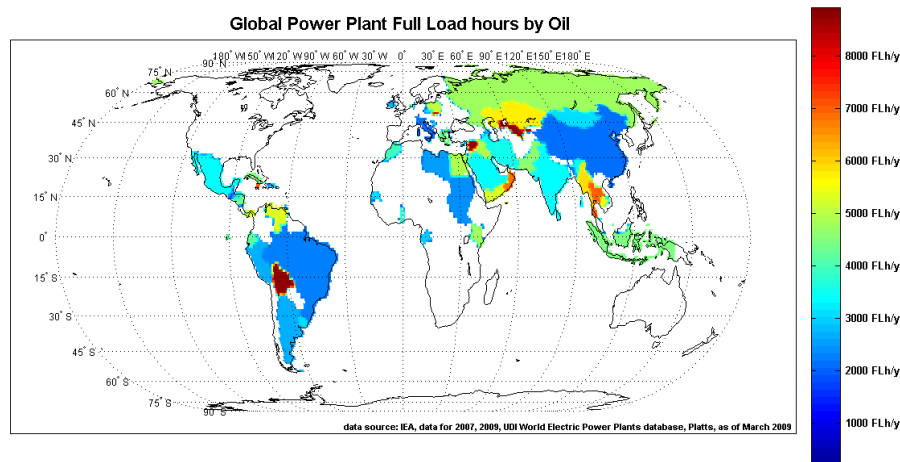
¹²¹ Bolin B. (ed.), Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3), 1996

		cost		cost		
		today	today market based	mid-term	today	end 2010s
		set 1	set 2	set 3	set 4	set 5
full load hours	[h/y]	4,000	4,000	3,500	1,725	1,800
efficiency	[%]	40%	40%	50%	-	-
CO ₂ cost	[€/t _{CO2}]	0	0	50	0	0
crude oil price	[\$/barrel]	4	80	160	0	0
Capex	[€/kW]	800	800	800	2,000	1,000
Opex	[€/kW/y]	17	17	17	30	15
lifetime	[y]	30	30	30	25	30
WACC	[%]	6.8%	6.8%	6.8%	6.8%	6.8%

Figure 6.2-10: LCOE structure of oil fired and PV power plants (top) based on major driving forces (bottom). Major variations for oil fired power plants are the crude oil price, the power conversion efficiency and greenhouse gas emission cost and for PV power plants the Capex. Other parameters are set according to the base case scenario defined in Table 6.2-1.

Full oil extraction cost in oil rich MENA countries are about 4 USD/barrel, whereas the base case scenario is set to 80 USD/barrel and mid-term 160 USD/barrel. The world market oil price represents the real current value of crude oil, i.e. in case of burning oil for less is identical to an energy subsidy and need to be accounted as opportunity cost, since it could be sold for the world market price. Greenhouse gas emissions, i.e. mainly CO₂, need to be priced for covering the enormous social cost of climate change (sub-chapter 1.2). Not charged CO₂ emissions are a subsidy due to social cost not covered by the electricity price.

Key indicator for combining PV and oil fired power plants to hybrid PV-Oil power plants are the full load hours (FLh) of oil power plants. 2,000 FLh of oil power plants are assumed to be a necessary threshold for beneficial hybridization. Oil power plants only in operation under special peak load conditions of one season or after sunset cannot be used for hybrid operation. Several countries use such peakers for stabilizing their electricity grids, e.g. the US, Japan, Australia and most European countries. Figure 6.2-11 illustrates the countries in the world operating oil power plants of in average at least 2,000 FLh per year.



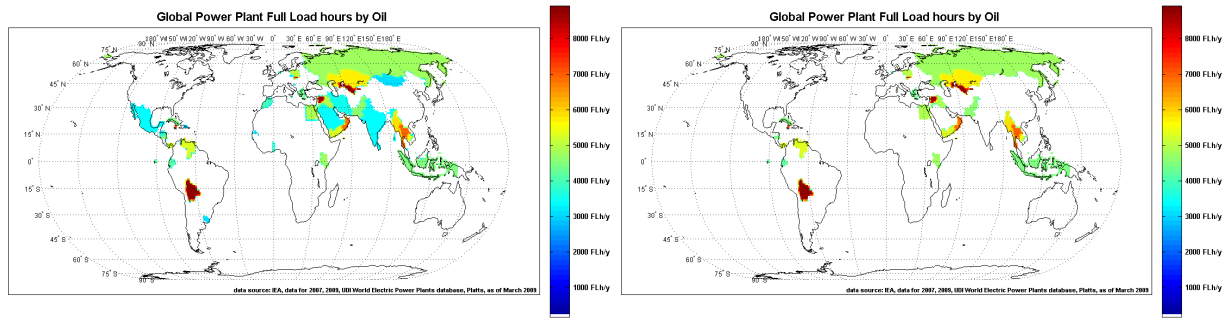


Figure 6.2-11: Global average oil power plant full load hours of at least 2,000 FLh (top), 3,000 FLh (bottom, left) and 4,000 FLh (bottom, right). Further visualization of oil power plant FLh can be found in Figures 6.2-7 and 6.2-9. Data are taken from UDI World Electric Power Plants database¹²² and International Energy Agency¹²³

Several countries in the world achieve a relative high contribution of oil power supply to overall electricity supply in combination with at least 2,000 FLh and based on significant power capacities, e.g. Mexico, Cuba, Spain, Italy, Libya, Saudi Arabia, Kuwait, Iraq, Iran, India, and Indonesia (Fig. 5.1-13, 6.2-7, 6.2-8 and 6.2-11). In the following, only regions are considered in which oil power plants are characterized by in average at least 2,000 FLh per year.

Base case scenario assumptions summarized in Table 6.2-1 are used for assessing oil power plant economics. However, in the following a broader parameter variation is taken into account for a better understanding of the range of oil LCOE. Precondition for all variations is a minimum average level of 2,000 FLh. Calculations are based on crude oil prices of 45, 80, 120 and 160 USD/barrel, respectively. With all these price regimes a variation in power plant energy conversion efficiency is applied for values of 40%, 45% and 50%, respectively. Moreover, CO₂ emission cost are taken into account for the range of 0, 30 and 50 €/tCO₂, respectively. Within one crude oil price domain the least LCOE are achieved for highest efficiency (50%) and lowest carbon emission cost (0 €/tCO₂) and the highest LCOE are reached for lowest efficiency (40%) and highest carbon emission cost (50 €/tCO₂). The crude oil price level has the highest impact on LCOE, therefore variations in efficiency and carbon emission cost can be considered as first order effects on the LCOE. Assumed parameter range for the power conversion efficiency is optimistic, since global average of oil power plant energy conversion efficiency is 33%, based on a fuel consumption of 3,340 MWh_{th} (271 Mtoe) and resulting 1,100 TWh_{el} feed-in the grid.¹²⁴ Greenhouse gas emission cost of 0 €/tCO₂ assumes a failure in global climate change diplomacy, which is possible but would result in a collapse of our global human society (sub-chapter 1.2), and cost of 50 €/tCO₂ is still below social cost of 70 €/tCO₂ or even more. Thus both power plant efficiency and carbon emission cost are optimistic and real cost might be significantly higher in the years to come. Crude oil price assumptions of 45 to 160 USD/barrel might be too optimistic, as well. Price spiked in 2008 on 147 USD/barrel and might reach a long-term level of 200 USD/barrel for an oil constraint potentially near future (sections 1.3.1 and 6.1.4).

Oil LCOE for a crude oil price of 45, 80, 120 and 160 USD/barrel are shown in Figures 6.2-12 to 6.2-15. Each oil price level is further differentiated by efficiency and carbon emission price for the cases of efficiency and carbon emission price of 50% and 0 €/tCO₂, 45% and 0 €/tCO₂, 45% and 30 €/tCO₂ and 40% and 50 €/tCO₂. The parameter variation results in an oil LCOE range for each crude oil price level and takes into account the local average FLh.

¹²² Platts, UDI World Electric Power Plants data base, 2009

¹²³ IEA, Key World Energy Statistics 2009, 2009

¹²⁴ IEA, World Energy Outlook 2010, 2010

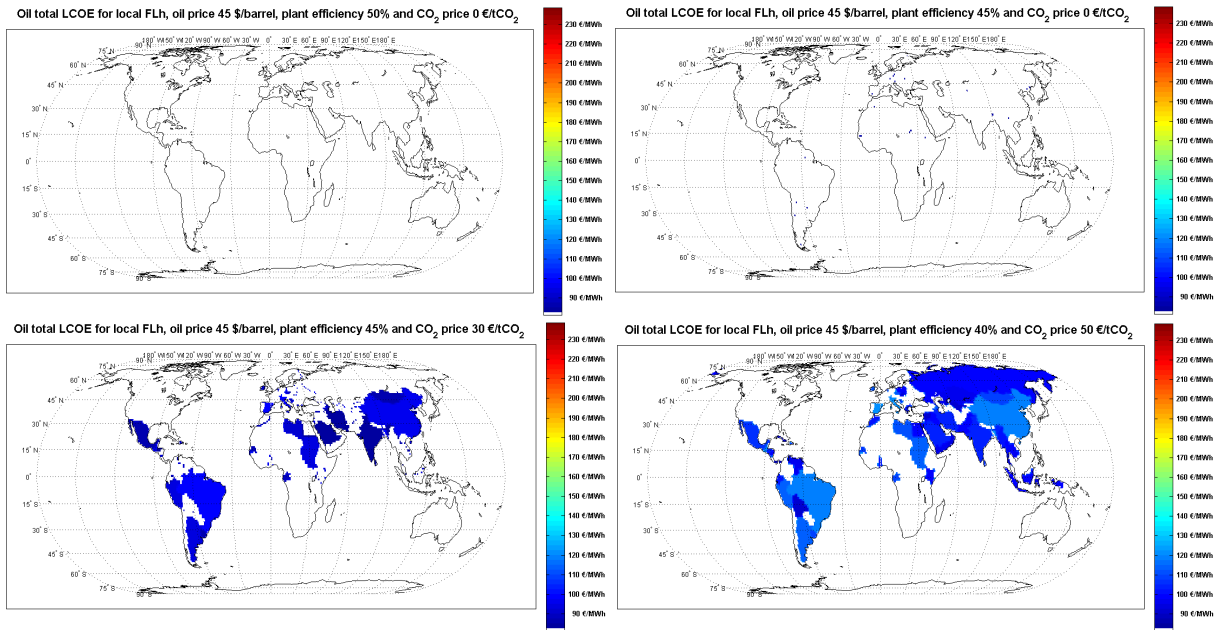


Figure 6.2-12: Oil LCOE for local FLh based on a crude oil level of 45 USD/barrel and variations on oil power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 50% and 0 €/tCO₂ (top, left), 45% and 0 €/tCO₂ (top, right), 45% and 30 €/tCO₂ (bottom, left) and 40% and 50 €/tCO₂ (bottom, right). Oil LCOE model is defined in Equations 6.2-1 and remaining parameters are according to the base case assumptions of Table 6.2-1.

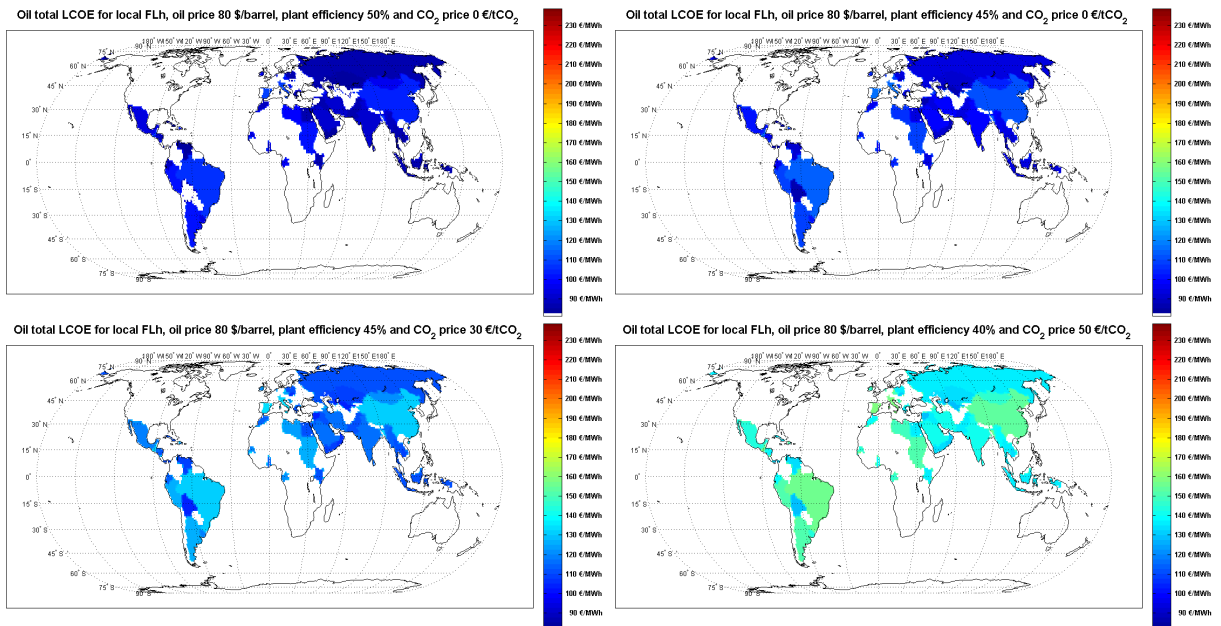


Figure 6.2-13: Oil LCOE for local FLh based on a crude oil level of 80 USD/barrel and variations on oil power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 50% and 0 €/tCO₂ (top, left), 45% and 0 €/tCO₂ (top, right), 45% and 30 €/tCO₂ (bottom, left) and 40% and 50 €/tCO₂ (bottom, right). Oil LCOE model is defined in Equations 6.2-1 and remaining parameters are according to the base case assumptions of Table 6.2-1.

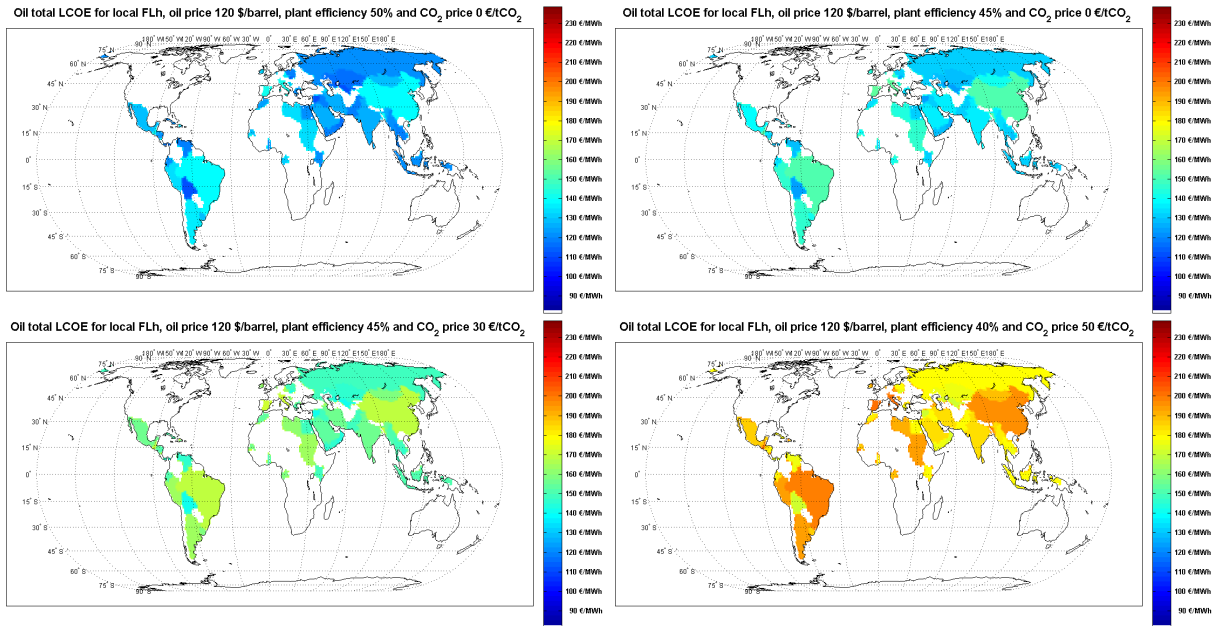


Figure 6.2-14: Oil LCOE for local FLh based on a crude oil level of 120 USD/barrel and variations on oil power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 50% and 0 €/tCO₂ (top, left), 45% and 0 €/tCO₂ (top, right), 45% and 30 €/tCO₂ (bottom, left) and 40% and 50 €/tCO₂ (bottom, right). Oil LCOE model is defined in Equations 6.2-1 and remaining parameters are according to the base case assumptions of Table 6.2-1.

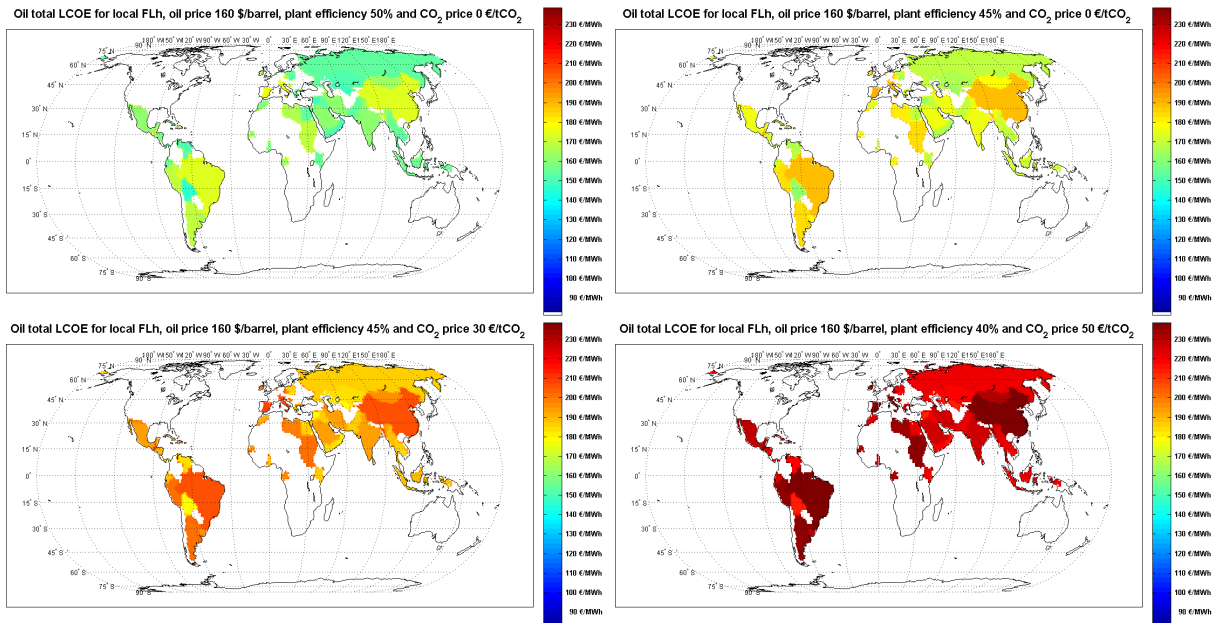


Figure 6.2-15: Oil LCOE for local FLh based on a crude oil level of 160 USD/barrel and variations on oil power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 50% and 0 €/tCO₂ (top, left), 45% and 0 €/tCO₂ (top, right), 45% and 30 €/tCO₂ (bottom, left) and 40% and 50 €/tCO₂ (bottom, right). Oil LCOE model is defined in Equations 6.2-1 and remaining parameters are according to the base case assumptions of Table 6.2-1.

Efficiency/ CO ₂ price for 4,000 and 2,000 FLh	crude oil price				
	45 USD/bl	80 USD/bl	120 USD/bl	160 USD/bl	200 USD/bl
	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]
35%/ 0 €/t _{CO2}	75.7 – 95.7	118.2 – 138.2	166.8 – 186.8	215.3 – 235.4	263.9 – 284.0
35%/ 30 €/t _{CO2}	98.3 – 118.4	140.8 – 160.9	189.4 – 209.4	238.0 – 258.0	286.5 – 306.6
35%/ 50 €/t _{CO2}	113.4 – 133.4	155.9 – 175.9	204.5 – 224.5	253.0 – 273.1	301.6 – 321.7
35%/ 70 €/t _{CO2}	128.5 – 148.5	171.0 – 191.0	219.6 – 239.6	268.1 – 288.2	316.7 – 336.8
40%/ 0 €/t _{CO2}	68.9 – 88.9	106.0 – 126.1	148.5 – 168.6	191.0 – 211.1	233.6 – 253.6
40%/ 30 €/t _{CO2}	88.7 – 108.7	125.8 – 145.9	168.3 – 188.4	210.8 – 230.9	253.4 – 273.4
40%/ 50 €/t _{CO2}	101.9 – 121.9	139.0 – 159.1	181.5 – 201.6	224.0 – 244.1	266.6 – 286.6
40%/ 70 €/t _{CO2}	115.1 – 135.1	152.2 – 172.3	194.7 – 214.8	237.2 – 257.3	279.8 – 299.8
45%/ 0 €/t _{CO2}	63.5 – 83.6	96.6 – 116.6	134.4 – 154.4	172.2 – 192.2	209.9 – 230.0
45%/ 30 €/t _{CO2}	81.1 – 101.2	114.2 – 134.2	152.0 – 172.0	189.8 – 209.8	227.5 – 247.6
45%/ 50 €/t _{CO2}	92.9 – 112.9	125.9 – 146.0	163.7 – 183.8	201.5 – 221.5	239.3 – 259.3
45%/ 70 €/t _{CO2}	104.6 – 124.7	137.7 – 157.7	175.4 – 195.5	213.2 – 233.3	251.0 – 271.0
50%/ 0 €/t _{CO2}	59.3 – 79.3	89.0 – 109.1	123.0 – 143.1	157.0 – 177.1	191.0 – 211.1
50%/ 30 €/t _{CO2}	75.1 – 95.2	104.9 – 124.9	138.9 – 158.9	172.9 – 192.9	206.9 – 226.9
50%/ 50 €/t _{CO2}	85.7 – 105.7	115.4 – 135.5	149.4 – 169.5	183.4 – 203.5	217.4 – 237.5
50%/ 70 €/t _{CO2}	96.3 – 116.3	126.0 – 146.1	160.0 – 180.1	194.0 – 214.1	228.0 – 248.1
55%/ 0 €/t _{CO2}	55.8 – 75.9	82.9 – 102.9	113.8 – 133.8	144.7 – 164.7	175.6 – 195.6
55%/ 30 €/t _{CO2}	70.2 – 90.3	97.3 – 117.3	128.2 – 148.2	159.1 – 179.1	190.0 – 210.0
55%/ 50 €/t _{CO2}	79.8 – 99.9	106.9 – 126.9	137.8 – 157.8	168.7 – 188.7	199.6 – 219.6
55%/ 70 €/t _{CO2}	89.4 – 109.5	116.5 – 136.5	147.4 – 167.4	178.3 – 198.3	209.2 – 229.2

Table 6.2-2: Oil LCOE for 2,000 to 4,000 FLh, power plant conversion efficiencies of 35%, 40%, 45%, 50% and 55%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}. Oil LCOE model is defined in Equations 6.2-1 and remaining parameters are according to the base case assumptions of Table 6.2-1.

Depending on efficiency, carbon emission cost and FLh, the oil LCOE of a crude oil price of 45 USD/barrel range between 56 and 149 €/MWh (Fig. 6.2-12 and Table 6.2-2). Low efficient oil power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 76 to 96 €/MWh for FLh between 4,000 to 2,000. Highly efficient oil power plants of 55% conversion efficiency and no CO₂ cost show LCOE of 56 to 76 €/MWh for FLh between 4,000 to 2,000.

Oil LCOE of a crude oil price of 80 USD/barrel range between 83 and 191 €/MWh (Fig. 6.2-13 and Table 6.2-2). Low efficient oil power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 118 to 138 €/MWh for FLh between 4,000 to 2,000. Highly efficient oil power plants of 55% conversion efficiency and no CO₂ cost show LCOE of 83 to 103 €/MWh for FLh between 4,000 to 2,000.

Oil LCOE of a crude oil price of 120 USD/barrel range between 114 and 240 €/MWh (Fig. 6.2-14 and Table 6.2-2). Low efficient oil power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 167 to 187 €/MWh for FLh between 4,000 to 2,000. Highly efficient oil power plants of 55% conversion efficiency and no CO₂ cost show LCOE of 114 to 134 €/MWh for FLh between 4,000 to 2,000.

Oil LCOE of a crude oil price of 160 USD/barrel range between 145 and 288 €/MWh (Fig. 6.2-15 and Table 6.2-2). Low efficient oil power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 215 to 235 €/MWh for FLh between 4,000 to 2,000. Highly efficient oil power plants of 55% conversion efficiency and no CO₂ cost show LCOE of 145 to 165 €/MWh for FLh between 4,000 to 2,000.

Oil LCOE of a crude oil price of 200 USD/barrel range between 176 and 337 €/MWh (Table 6.2-2). Low efficient oil power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 264 to 284 €/MWh for FLh between 4,000 to 2,000. Highly efficient oil power plants of 55% conversion efficiency and no CO₂ cost show LCOE of 176 to 196 €/MWh for FLh between 4,000 to 2,000.

In the year 2010 PV LCOE in sunny regions are about 100 to 120 €/MWh depending on location and assumptions (Fig. 6.2-10 and 3.2-16). Therefore, PV power plants are already lower in cost than low efficient oil power plants at crude oil prices of about 80 USD/barrel and PV power plants are always lower in LCOE than oil power plants for a crude oil price of 120 USD/barrel or more. In near future, i.e. in first half of 2010s, in sunny regions PV power plants are always lower in LCOE than oil power plants at 80 USD/barrel or more. Consequently, in sunny regions oil power plants are an excellent component for hybrid PV-Oil power plants due to drastically improved economics by upgrading existing oil power plants with PV power plants.

6.2.3 Hybrid PV-Oil Power Plant Demand Curve

In the following scenario assumptions are taken into account for oil power plants (Table 6.2-1) and for fixed optimally tilted PV power plants (Table 3.2-1). Oil power plant base case assumes a crude oil price of 80 USD/barrel and an annual escalation rate of 3% in real terms. Oil LCOE projection in the 2010s is depicted in Figure 6.2-16.

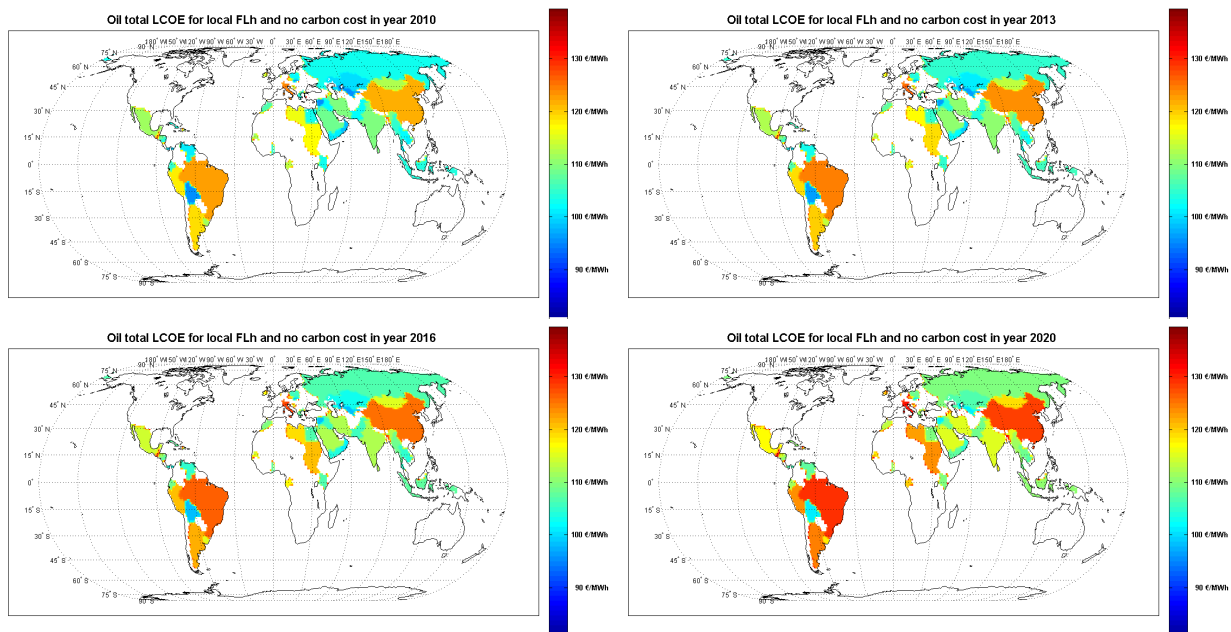


Figure 6.2-16: Oil LCOE for local FLh in the 2010s for the base case scenario. Base case scenario is defined in Table 6.2-1. Countries operating oil power plants in average of at least 2,000 FLh are included in the analysis.

Upgrading existing oil power plants by PV power plants to hybrid PV-Oil power plants is economically favourable for PV LCOE lower than oil LCOE. The precise calculation needs to include slightly higher capital cost of oil power plants by reducing their FLh in order of the PV FLh. This effect can be calculated by Equation 6.2-1a and has to be generated additionally by the PV component, i.e. lower PV LCOE, of the hybrid PV-Oil power plant. All breakeven,

i.e. parity, analyses in this sub-chapter take this effect into account. The year of PV and oil power plant parity is illustrated in Figures 6.2-17 and 6.2-18.

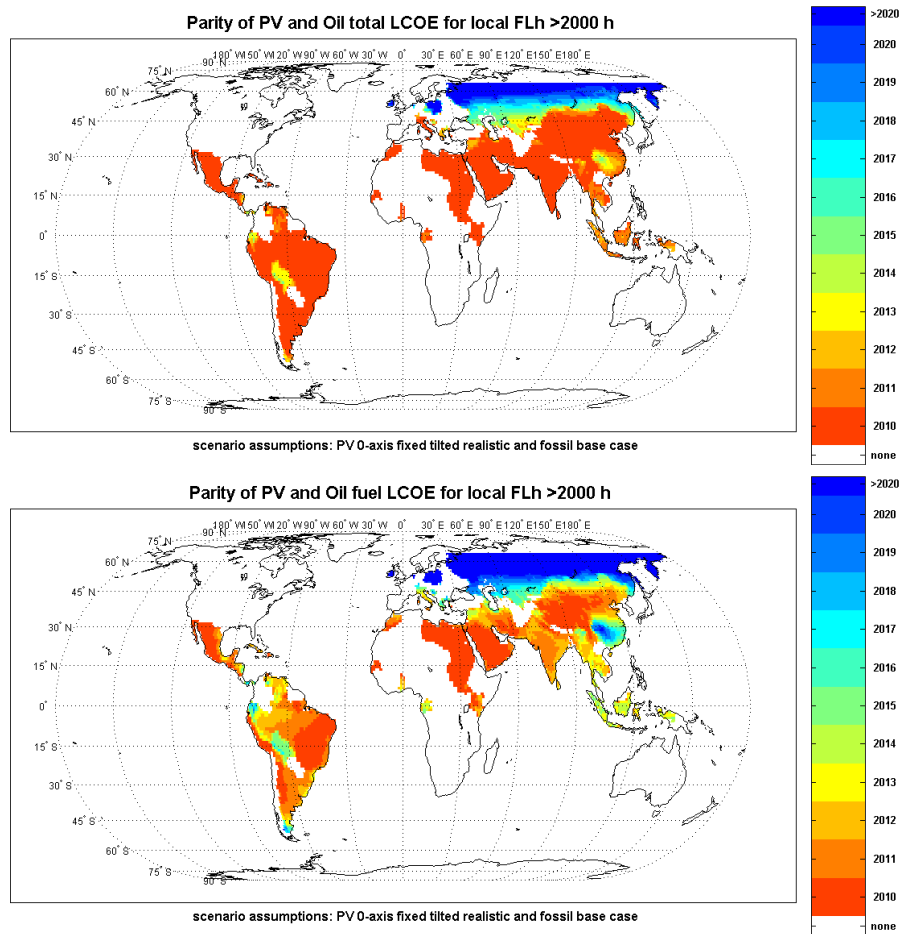
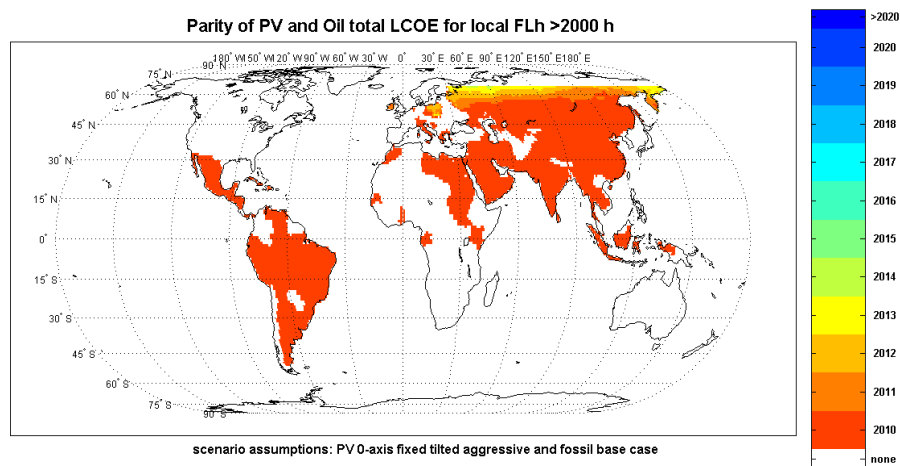


Figure 6.2-17: Parity of fixed optimally tilted PV and oil power plants for total plant LCOE (top) and fuel-only LCOE (bottom) for PV realistic and oil base case scenario assumptions. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.2-1 and Figure 6.2-16 (oil). Countries operating oil power plants in average of at least 2,000 FLh are included in the analysis.



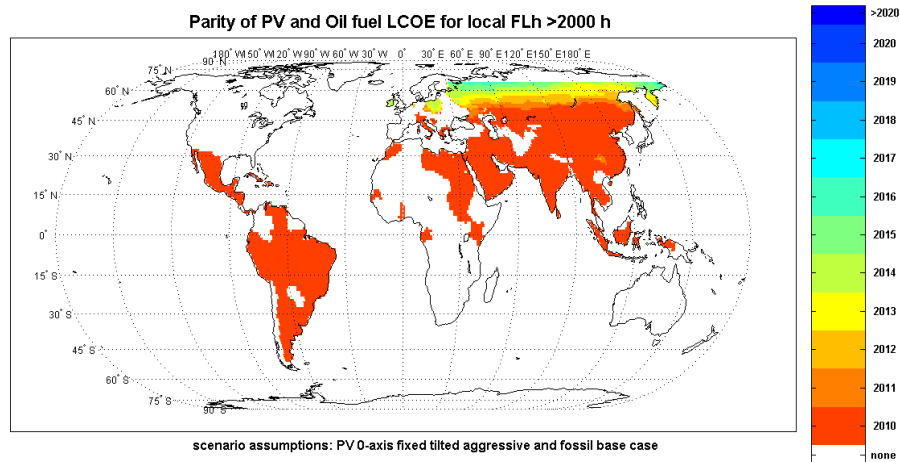


Figure 6.2-18: Parity of fixed optimally tilted PV and oil power plants for total plant LCOE (top) and fuel-only LCOE (bottom) for PV aggressive and oil base case scenario assumptions. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.2-1 and Figure 6.2-16 (oil). Countries operating oil power plants in average of at least 2,000 FLh are included in the analysis.

In nearly all sunny regions in the world, PV power plants are lower in LCOE than oil power plants already in the year 2010 (Fig. 6.2-17). In most sunny regions PV LCOE are even lower than fuel-only LCOE of oil fired power plants. For the aggressive case nearly all relevant regions in the world show lower PV LCOE than oil LCOE in 2010 even for the fuel-only LCOE restriction (Fig. 6.2-18). As discussed in sub-chapter 3.2, true PV cost might be between the realistic and aggressive scenario assumptions. Consequently, PV power plants are already fully competitive to oil power plants in nearly all regions in the world at a crude oil price level of 80 USD/barrel.

Financial benefits are depicted in Figures 6.2-19 and 6.2-20 for the most competitive conditions of PV LCOE versus fuel-only oil LCOE.

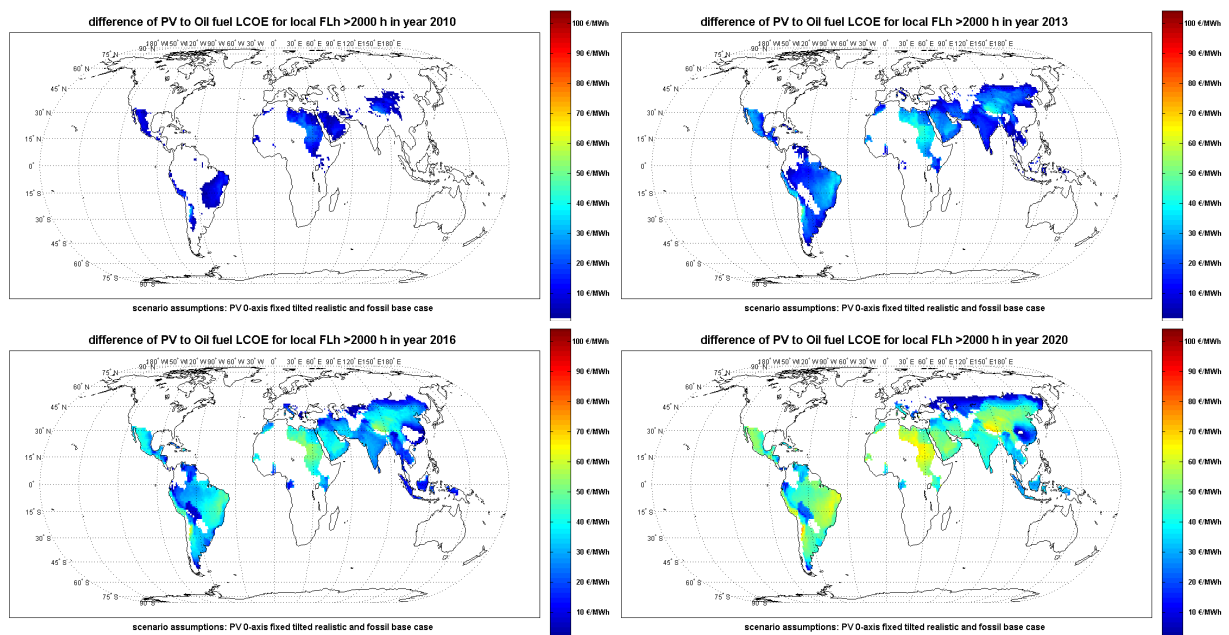


Figure 6.2-19: PV LCOE benefit in comparison to fuel-only oil LCOE for fixed optimally tilted PV realistic and oil base case scenario assumptions in the 2010s. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.2-1 and Figure 6.2-16 (oil). Countries operating oil power plants in average of at least 2,000 FLh are included in the analysis.

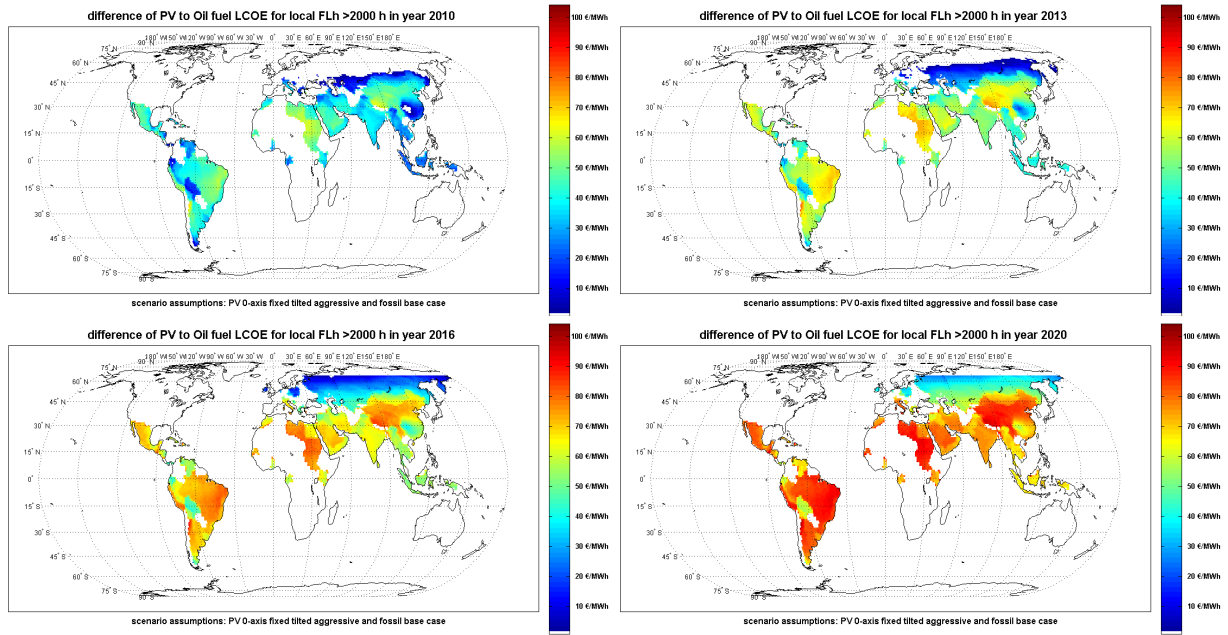


Figure 6.2-20: PV LCOE benefit in comparison to fuel-only oil LCOE for fixed optimally tilted PV aggressive and oil base case scenario assumptions in the 2010s. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.2-1 and Figure 6.2-16 (oil). Countries operating oil power plants in average of at least 2,000 FLh are included in the analysis.

The LCOE advantage of PV power plants in respect to those of oil power plants in the economically strictest case of fuel-only LCOE reveals the enormous competitiveness of PV versus oil power plants. For realistic scenario assumptions PV LCOE are lower than fuel-only oil LCOE by about 10 €/MWh (2010), 20 €/MWh (2013), 40 €/MWh (2016) and 55 €/MWh (2020) in very sunny regions (Fig. 6.2-19). For aggressive scenario assumptions PV LCOE are lower than fuel-only oil LCOE by about 40 €/MWh (2010), 60 €/MWh (2013), 70 €/MWh (2016) and 80 €/MWh (2020) in very sunny regions (Fig. 6.2-20). These results are based on a crude oil price of 80 USD/barrel in 2010 and an escalation rate of 3%, i.e. 107 USD/barrel in 2020. In case of faster crude oil escalation the benefits of PV power plants are significantly higher.

Based on fuel-parity analyses of PV versus oil power plants (Fig. 6.2-17 and 6.2-18) a global hybrid PV-Oil power plant demand curve can be derived. Regions of oil power plants operated less than 2,000 FLh are excluded from the analysis, this is the case for 338 GW of the total 558 GW oil power capacity (Table 5.1-1). All oil power plants in the world are available by their georeferenced coordinates (Fig. 6.2-2) enabling a direct comparison of PV LCOE at the respective site. For each coordinate of a 1°x1° mesh of latitude and longitude the year of PV LCOE (plus higher oil capital cost due to reduced FLh) lower than total and fuel-only oil LCOE is recorded. All the coordinates are aggregated afterwards to the country of their location. Global hybrid PV-Oil power plant demand curves for PV realistic and aggressive and oil base case scenario assumptions are plotted in Figures 6.2-21 and 6.2-22.

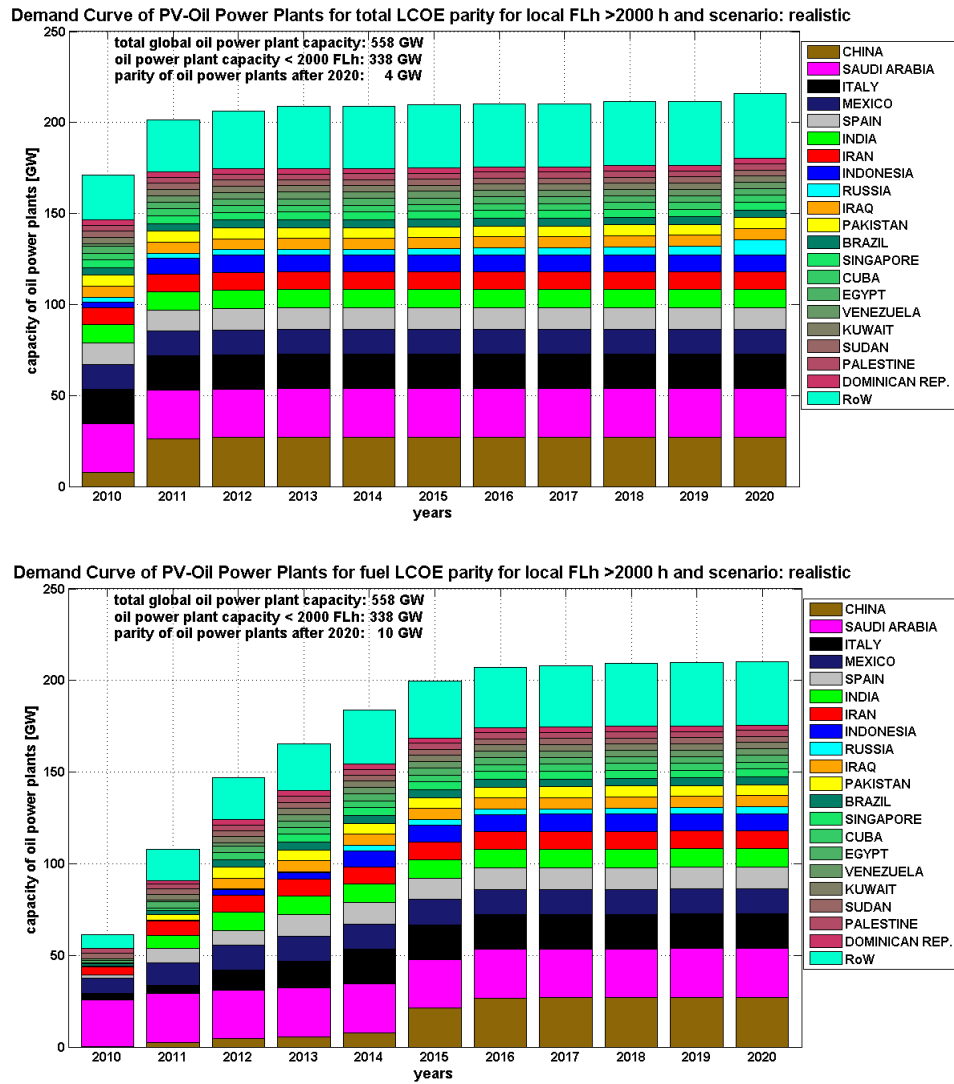
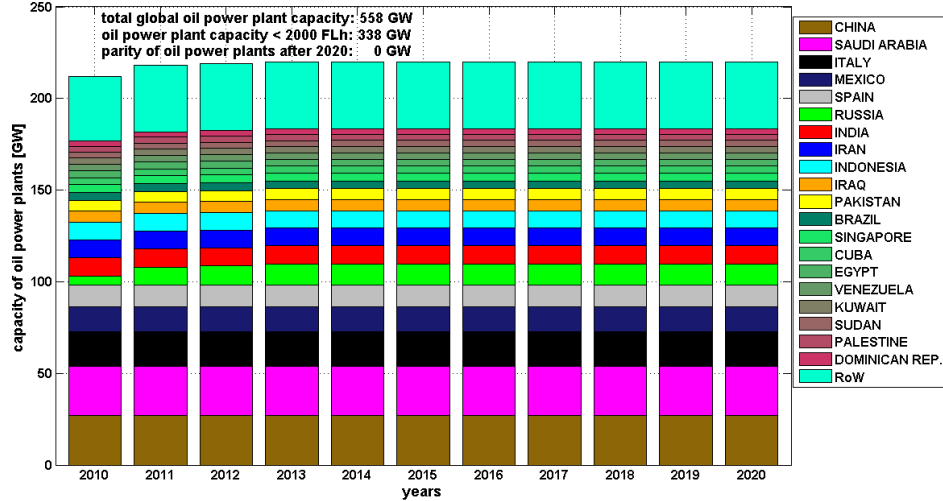


Figure 6.2-21: Global hybrid PV-Oil power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV realistic and oil base case scenario assumptions in the 2010s. Oil power plant capacity is counted only in case of PV LCOE (plus higher oil capital cost due to reduced FLh) lower than total and fuel-only oil LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.2-1 and Figure 6.2-16 (oil). Countries operating oil power plants in average of at least 2,000 FLh are included in the analysis. Data for oil power plant capacity are taken from UDI World Electric Power Plants database ¹²⁵.

¹²⁵ Platts, UDI World Electric Power Plants data base, 2009

Demand Curve of PV-Oil Power Plants for total LCOE parity for local FLh >2000 h and scenario: aggressive



Demand Curve of PV-Oil Power Plants for fuel LCOE parity for local FLh >2000 h and scenario: aggressive

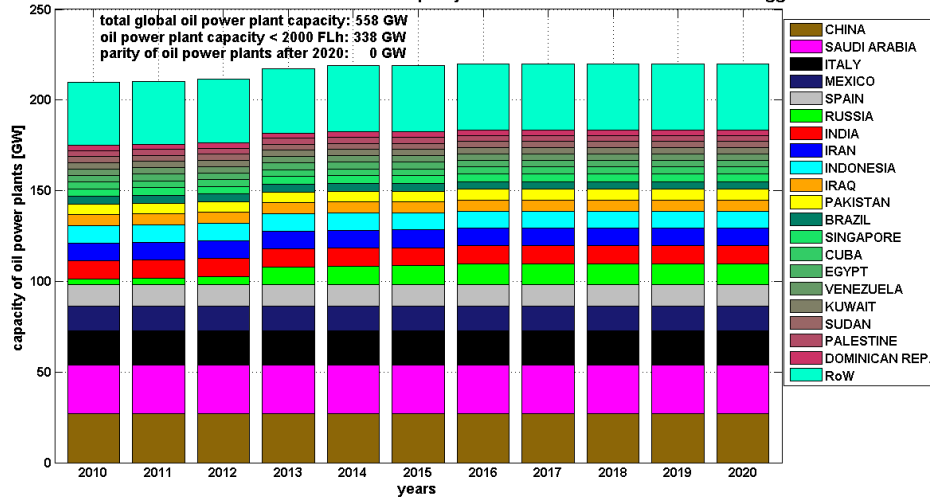


Figure 6.2-22: Global hybrid PV-Oil power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV aggressive and oil base case scenario assumptions in the 2010s. Oil power plant capacity is counted only in case of PV LCOE (plus higher oil capital cost due to reduced FLh) lower than total and fuel-only oil LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.2-1 and Figure 6.2-16 (oil). Countries operating oil power plants in average of at least 2,000 FLh are included in the analysis. Data for oil power plant capacity are taken from UDI World Electric Power Plants database ¹²⁶.

In 2010, nearly all oil power plants show higher LCOE than nearby PV power plants on a total power plant LCOE basis even for the realistic scenario assumptions of PV power plants (Fig. 6.2-21). The first large market for hybrid PV-Oil power plants is Saudi Arabia. By the end of the 2010s, the largest markets for hybrid PV-Oil power plants are China, Saudi Arabia, Italy, Mexico, Spain, India, Iran, Indonesia, Russia, Iraq and Pakistan. Depending on scenario assumptions market potential for hybrid PV-Oil power plants has been about 50 GW in 2010 and might fast rise to 200 GW by the mid of the 2010s. The maximum market potential is about 220 GW due to limited oil power plant capacity operated in average for at least 2,000 FLh.

¹²⁶ Platts, UDI World Electric Power Plants data base, 2009

The results for hybrid PV-Oil power plant economics show several characteristics for a beneficial combination. Already existing oil power plants should be operated for at least 2,000 FLh during daytime. Fuel represents the by far highest fraction of power plant LCOE, e.g. about 80% for a crude oil price of 80 USD/barrel, hence oil LCOE are highly influenced by crude oil price. The solar resource quality at local sites of existing power plants is very important for PV LCOE and thus hybrid PV-Oil power plant economics, but the crude oil price is more decisive. Oil producing countries have the identical oil LCOE due to the respective opportunity cost in case of burning oil priced lower than world market price. However, these countries would have no problems in organising the financing of large scale PV power plant investments. PV power plants might be in competition to wind power plants due to excellent wind power economics (sub-chapters 4.2 and 4.3). In case of complementary wind and solar resource availability the economics of hybrid PV-Oil power plants might be further improved by integrating wind power and establishing hybrid PV-Wind-Oil power plants. Complementary versus competitive characteristics of solar and wind resources are discussed in sub-chapter 7.3.

Summing up, results for hybrid PV-Oil power plant economics give plenty of insights for excellent competitiveness of this approach for upgrading existing oil fired power plants. Most regions in the world in which oil power plants are operated on a significant FLh level have good and excellent solar resources which lead to favourable PV power plant economics. Already in the year 2010, most oil power plants in the world could lower the LCOE by upgrading with nearby PV power plants. Financial upgrading benefit for resulting hybrid PV-Oil power plants is fast increasing as a consequence of fast PV LCOE reductions and higher than expected crude oil price escalation.

6.3 Hybrid PV-Gas Power Plant

Natural gas fired power plants are used for power supply all around the world (section 6.3.1) but depending on local conditions on a larger range of intensity. The economics of gas power generation (section 6.3.2) are the financial basis for a successful hybridization of PV power plants and gas fired power plants. This builds the fundament for the derivation of a global demand curve for hybrid PV-Gas power plants in the 2010s (section 6.3.3). In contrast to end-user prices driven grid-parity, the most decisive economic criteria in the power plant sector is the fuel-parity, i.e. competitive PV power generation cost in reference to total and fuel-only power generation cost of conventional power plants. The already discussed preconditions for a successful hybridization (sub-chapter 6.1) of PV and gas power plants are expanded and analysed in this sub-chapter in a special focus on the economics.

6.3.1 Global Overview on Natural Gas Power Capacity

The present and future relevance of a power technology can be assessed by its resource availability (sub-chapter 1.3), the installed power capacity, utilization of the available power capacity and the local power supply contribution. These dimensions will be presented and discussed in the following for gas fired power plants. The distribution of global natural gas reserves is depicted in Figure 6.3-1.

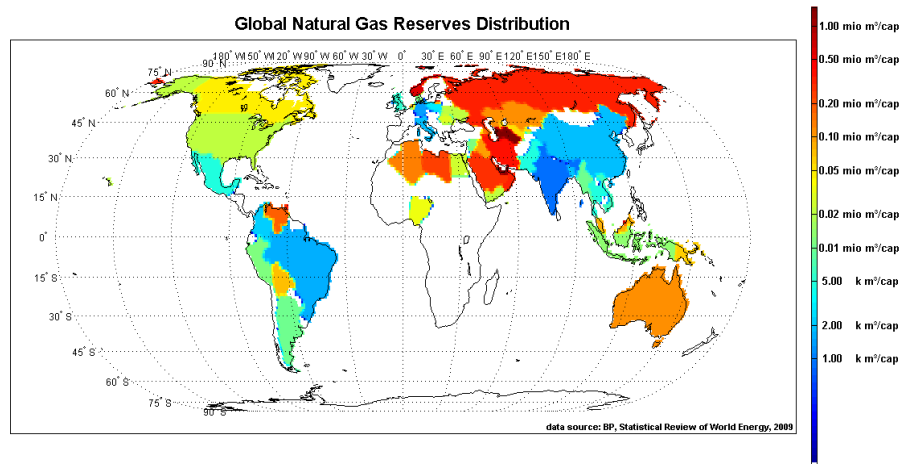
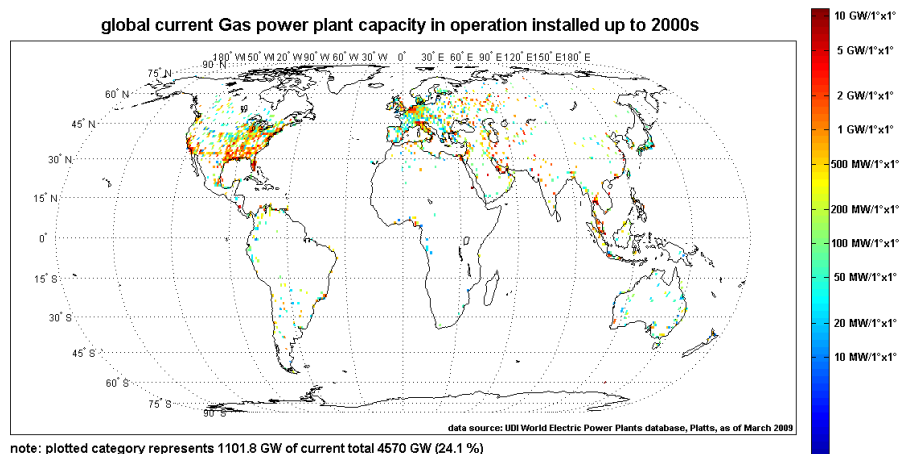


Figure 6.3-1: Distribution of global natural gas reserves. Data are taken from BP ¹²⁷.

Total global installed gas power capacity was 1,230 GW by end of 2008 and generated electricity was 4,303 TWh in the year 2008, translating to 3,500 full load hours.¹²⁸

It is necessary to know the coordinates of the gas power plants for further analysis. Due to that the UDI World Electric Power Plants database ¹²⁹ has been enhanced by coordinates of all 145,000 power plants in the world.¹³⁰ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. However, a crosscheck reveals a capacity of about 1,102 GW of gas power plants in the database versus 1,230 GW denominated in the IEA dataset. The deviation of about 130 GW might be caused by fuel shifts between oil and natural gas (section 6.2.1).

In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration has been taken in these cases. The result of the georeferenced global power plant capacity being in operation is depicted in Figure 6.3-2.



¹²⁷ BP, Statistical Review of World Energy, 2009

¹²⁸ IEA, World Energy Outlook 2010, 2010

¹²⁹ Platts, UDI World Electric Power Plants data base, 2009

¹³⁰ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

Figure 6.3-2: Global gas power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. Data are plotted in a $1^\circ \times 1^\circ$ mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database¹³¹ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced gas power plant data (Fig. 6.3-2) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current natural gas fired power plant capacity (Fig. 6.3-3). About 405 GW out of 1,102 GW included in the database are located in areas of more than 1,800 kWh/m²/y irradiation on fixed optimally tilted module surfaces, i.e. 37% of global gas power installed base is already installed in regions of very good solar resource quality. Gas power plants operated during daytime match in an excellent way to the feed-in profile of PV power plants and can be operated very flexibly (section 6.1.2 and 3.4.2.2), hence detailed analysis on the economics of hybrid PV-Gas power plants is performed and discussed in sections 6.3.2 and 6.3.3.

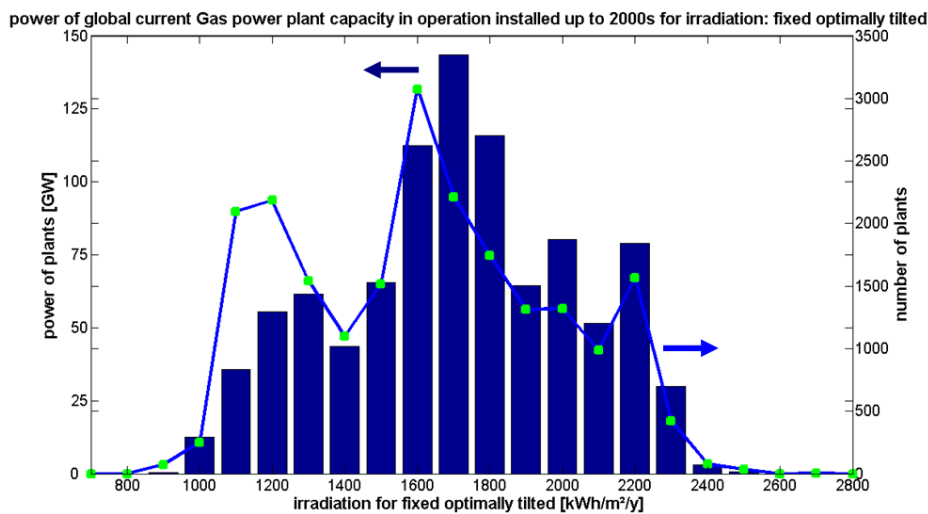


Figure 6.3-3: Global gas fired power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 6.3-2) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 6.3-4 and shows that most power plants are in the power class of 1 - 10 MW or even smaller in size. However, their contribution to global power capacity is negligible. Almost 25% of global gas power plant capacity consists of power plants of 10 - 100 MW in size and 62% in the power class of 100 - 1000 MW.

¹³¹ Platts, UDI World Electric Power Plants data base, 2009

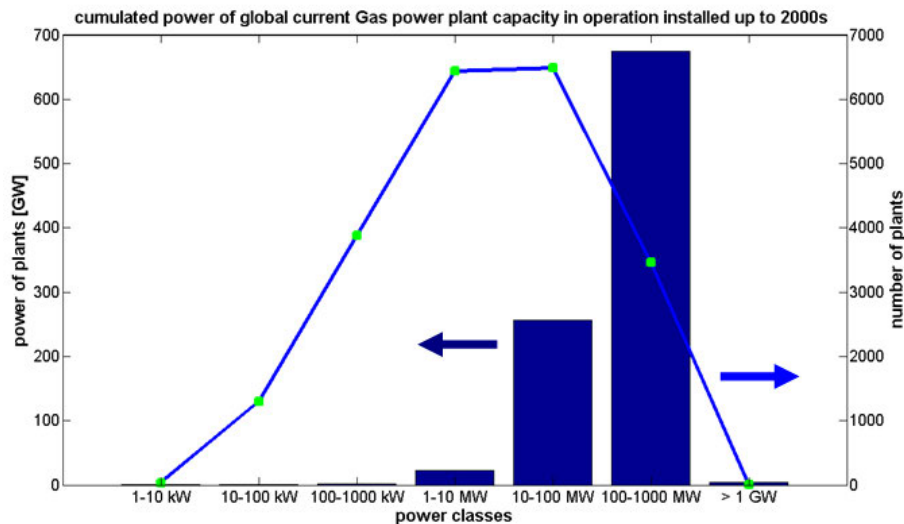


Figure 6.3-4: Global gas power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent power plant capacity. Data are taken from UDI World Electric Power Plants database ¹³².

Contribution of gas power to global electricity supply is significant and accounts for about 22%. Global average total electricity generation per capita is about 3.0 MWh_{el} but 5 – 10 MWh_{el} in industrialised countries (sub-chapter 5.1). Leading gas electricity per capita countries in the world are the United Arab Emirates and Qatar achieving 14 and 10 MWh_{el} per capita (Fig. 6.3-5). Several other countries reach a high level of gas power supply per capita, as well.

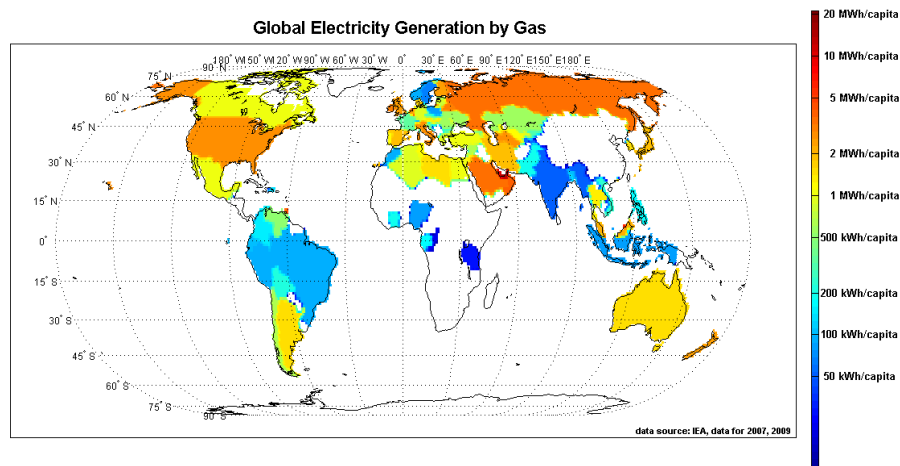


Figure 6.3-5: Global electricity generation by gas per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency ¹³³ and United Nations ¹³⁴.

Global installed gas power plant capacity per country is illustrated in Figure 6.3-6. Leading countries by cumulated gas power capacity are the US, Russia, Italy, Iran and UK by end of 2008. However, full load hours of the US gas power plants are rather low at about 2,000 (Fig. 6.3-7).

¹³² Platts, UDI World Electric Power Plants data base, 2009

¹³³ IEA, Key World Energy Statistics 2009, 2009

¹³⁴ UN, World Population Prospects: The 2008 Revision Highlights, 2009

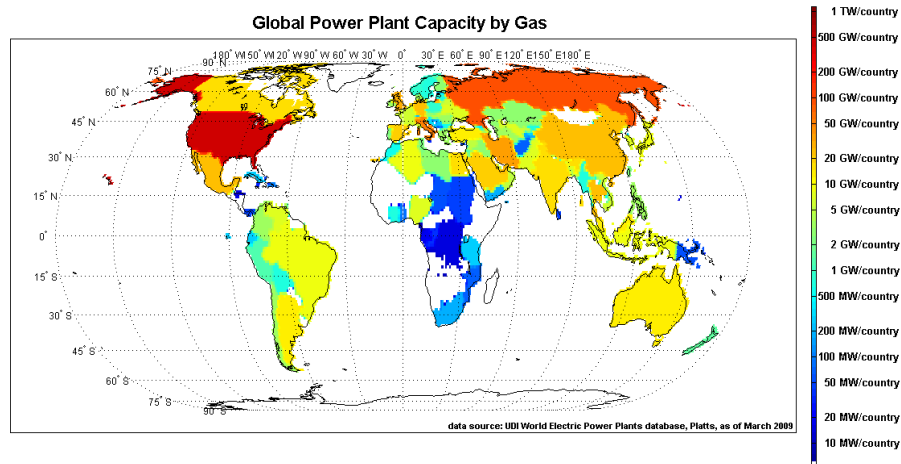


Figure 6.3-6: Global gas power plant capacity per country by early 2009. Only power plants in operation are regarded. Data are taken from UDI World Electric Power Plants database ¹³⁵.

The structure of power plant capacity can be illustrated on a per country basis for average annual full load hours (Fig. 6.3-7) and relevance of respective domestic overall electricity generation (Fig. 6.3-8). Gas power can be used in different operation modes, i.e. baseload, intermediate and peaking power supply. There are several countries in the world achieving a gas power supply contribution of more than 50% at a high absolute installed power capacity, e.g. Italy, Iran, Thailand, the United Arab Emirates, Egypt, the Netherlands, Malaysia and Argentina. Full load hours of gas power plants are dependent on the operation mode. Combination of PV and gas power is a real option and is discussed later in this sub-chapter.

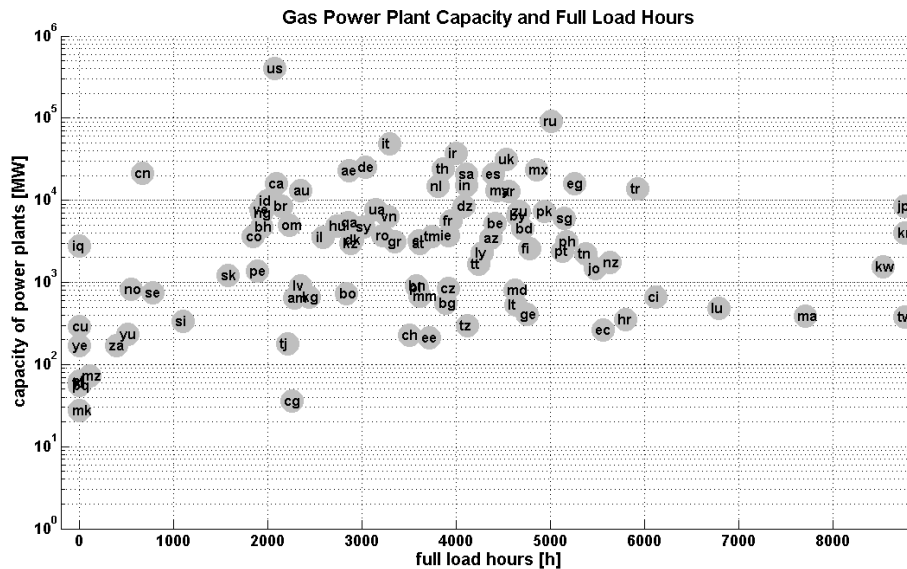


Figure 6.3-7: Gas power plant capacity in dependence on full load hours per country. Each dot represents the absolute gas power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ¹³⁶ and International Energy Agency ¹³⁷.

¹³⁵ Platts, UDI World Electric Power Plants data base, 2009

¹³⁶ Platts, UDI World Electric Power Plants data base, 2009

¹³⁷ IEA, Key World Energy Statistics 2009, 2009

Global Power Plant Full Load hours by Gas

data source: IEA, data for 2007, 2009, UDI World Electric Power Plants database, Plants, as of March 2009

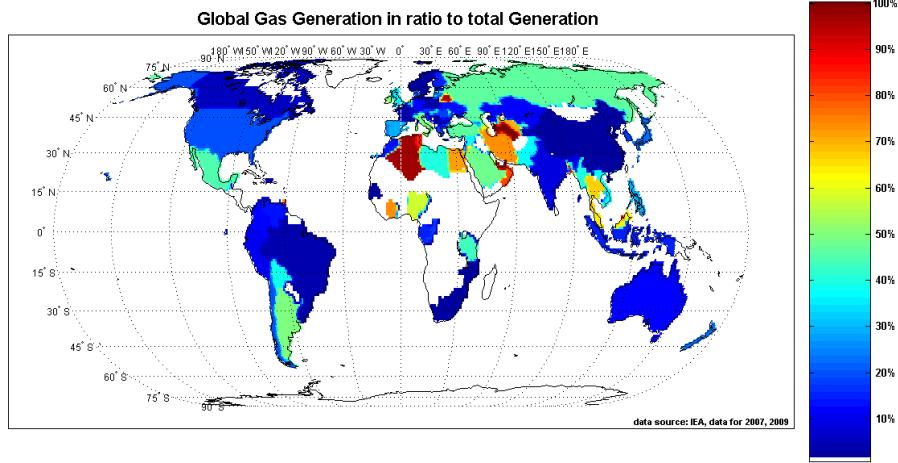


Figure 6.3-9: Global distribution of gas power plant full load hours (top) and the ratio to total domestic electricity generation (bottom). Data are taken from UDI World Electric Power Plants database ¹⁴⁰ and International Energy Agency ¹⁴¹.

Summing up, global gas power plant capacity of 1,230 GW is in average 3,500 full load hours in operation and generate annually about 4,300 TWh of electricity, representing 26% of total global installed power capacity and 22% of global generated electricity. Gas power plants operated during daytime match in an excellent way to the feed-in profile of PV power plants and can be operated very flexibly. In the following section, hybrid PV-Gas plants are discussed in more detail.

6.3.2 Natural Gas Power Economics

A cost model for gas fired power plants enables the calculation of gas power levelized cost of electricity (LCOE) for all coordinates by applying average local full load hours (FLh) shown in Figure 6.3-9. These gas FLh contain all relevant data on local gas power plant operation patterns and can be used as an indicator for combining PV and gas power plants to a hybrid PV-Gas power plant. Besides typical capital expenditures (Capex) and operational expenditures (Opex) major current and future cost positions are expenditures for fuel and related carbon emissions. Both fuel and carbon emission expenditures are directly related to the power conversion efficiency of the gas power plant. Such derived gas LCOE makes it possible to compare gas LCOE to LCOE of other renewable and conventional power plant technologies.

Methodology of calculating gas power LCOE is nearly identical to that of oil power plants (Eqs. 6.2-1) and based on that of PV (section 3.2.1 and Eqs. 3.2-1). Adjustments are needed for specific differences of gas and oil power plants, summarized in Equations 6.3-1:

$$LCOE = \frac{Capex \cdot crf + Opex_{fix}}{FLh_{gas,el}} + Opex_{var} + \frac{fuel_{gas}}{PE_{th,gas} \cdot \eta_{gas,el}} + \frac{carbon \cdot GHG_{gas}}{\eta_{gas,el}} \quad (\text{Eq. 6.3-1a})$$

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (\text{Eq. 6.3-1b})$$

¹⁴⁰ Platts, UDI World Electric Power Plants data base, 2009

¹⁴¹ IEA, Key World Energy Statistics 2009, 2009

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \quad (\text{Eq. 6.3-1c})$$

$$fuel_{gas} = fuel_{crudeoil} \cdot cf_{gas} \quad (\text{Eq. 6.3-1d})$$

$$fuel_{crudeoil} = fuel_{crudeoil,2010} \cdot (1 + r_{crudeoil})^{y-2010} \quad (\text{Eq. 6.3-1e})$$

$$\eta_{gas,el} = \eta_{gas,el,2010} + (y - 2010) \cdot r_{\eta,gas} \quad (\text{Eq. 6.3-1f})$$

$$carbon = carbon_{2010} \cdot (1 + r_{carbon})^{y-2010} \quad (\text{Eq. 6.3-1g})$$

Equation 6.3-1: Levelized cost of electricity (LCOE) for gas power plants. Abbreviations stand for: capital expenditures (*Capex*), annuity factor (*crf*), annual operation and maintenance expenditures (*Opex*), annual fixed Opex (*Opex_{fix}*), variable Opex (*Opex_{var}*), annual full load hours of gas power plants (*FLh_{gas,el}*), fuel cost for gas fired power plants (*fuel_{gas}*), thermal energy conversion factor (*PE_{th,gas}*), primary to electric energy conversion efficiency of gas fired power plants (*η_{gas,el}*), carbon emission cost (*carbon*), carbon emission intensity per thermal energy of gas fired power plants (*GHG_{gas}*), weighted average cost of capital (*WACC*), lifetime of gas power plants (*N*), equity (*E*), debt (*D*), return on equity (*k_E*), cost of debt (*k_D*), fuel cost of crude oil (*fuel_{crude oil}*), fuel cost of crude oil in the year 2010 (*fuel_{crude oil,2010}*), annual escalation rate of crude oil price (*r_{crude oil}*), year (*y*), ratio of gas to crude oil price as coupling factor (*cf_{gas}*), primary to electric energy conversion efficiency of gas fired power plants in the year 2010 (*η_{gas,el,2010}*), annual increase of primary to electric energy conversion efficiency of gas fired power plants (*r_{η,gas}*), specific greenhouse gas emission cost (*carbon*), specific greenhouse gas emission cost in the year 2010 (*carbon₂₀₁₀*) and annual escalation rate of greenhouse gas emission cost (*r_{carbon}*).

The scenario assumptions for calculating LCOE of gas power plants are summarized in Table 6.3-1. Major LCOE component of gas power plants are the fuel cost which are indirectly coupled to the crude oil price due to the specific thermal energy of gas (section 6.1.4) and its fluctuations and tendency for long-term escalation. Applied base case scenario assumes a moderate crude oil price of 80 USD/barrel. This core assumption might be too conservative, in particular due to a further assumed annual crude oil escalation rate of 3% in real terms. The price coupling of natural gas to crude oil is assumed to be 0.8 in the base case scenario according to the long-term trend. A separate low cost case is applied for analysing the impact potential of a lower price coupling, set in that case to 0.7.

Parameters	units	scenario base case	scenario low cost case
Capex_Gas	[€/kW]	750	750
fin_RoE	[%]	10.0%	10.0%
fin_interest	[%]	6.0%	6.0%
fin_WACC	[%]	6.80%	6.80%
fin_equityRatio	[%]	20%	20%
exchange_rate	[USD/€]	1.40	1.40
plant_lifetime	[y]	30	30
plant_Opex_fix	[€/kW/y]	15	15
plant_Opex_var	[€/MWh _{el}]	1	1
plant_turbine_efficiency_2010	[%]	50%	50%
plant_turbine_efficiency_2020	[%]	55%	55%
plant_turbine_efficiency_increase	[%/y]	0.5%	0.5%
coupling_factor_gas-to-crude oil	[-]	0.80	0.70
fuel_price_crude oil_2010	[USD/barrel]	80.0	80.0
escalation_rate_crude oil_price	[%/y]	3%	3%
carbon_price_2010	[€/t _{CO2}]	0.0	0.0
escalation_rate_carbon_price	[%/y]	0%	0%

thermal energy conversion gas	[MWh _{th} /barrel]	1.68063	1.68063
greenhouse gas intensity gas	[tCO ₂ /MWh _{th}]	0.202	0.202

Table 6.3-1: Scenario assumptions for gas power plant economics. The base case scenario covers a business-as-usual approach, whereas the assumptions on the crude oil price and its escalation as the most relevant cost factor might be too conservative. Price coupling of natural gas to crude oil fluctuates over time and is reflected in the low cost case scenario. Numbers mentioned are for gas power plants of multi-100 MW. The methodology is identical to that of oil power plants (Table 6.2-1) comparable to that of PV, STEG and wind power LCOE calculation (Tables 3.2-1, 4.1-1 and 4.2-1). General parameters are set identical as far as possible or at least comparable, in particular for the financial parameters, although fossil WACC should be higher than that of renewable energy technologies due to a higher price risk profile (section 3.2.1) ¹⁴². Abbreviations stand for: capital expenditures (Capex), return on equity (RoE), weighted average cost of capital (WACC), operational expenditures (Opex), annual fixed Opex (Opex_{fix}) and variable Opex (Opex_{var}). Data are taken from various sources like European Climate Foundation ¹⁴³, Greenpeace ¹⁴⁴, Pehnt et al. ¹⁴⁵, Shah and Greenblatt ¹⁴⁶, Delucchi and Jacobson ¹⁴⁷, BMU ¹⁴⁸, IEA ^{149,150} and IPCC ¹⁵¹.

Gas power plant LCOE structure is illustrated in Figure 6.3-10 and is mainly driven by scenario assumptions of the base case definition for gas power plants (Table 6.3-1). Parameter settings are varied for crude oil price, greenhouse gas emission cost, energy conversion efficiency and full load hours. These scenario variations are compared to expected PV LCOE structure in 2010 and 2020 in sunny regions (based on Table 3.2-1).

Parameter setting of ‘set 2’ is representative for LCOE structure of gas power plants in late 2010. Total gas LCOE of 7.4 €/kWh are composed by capital cost of about 20% (1.5 €/kWh), Opex of about 5% (0.5 €/kWh) and fuel cost of 75% (5.4 €/kWh) based on a crude oil price of 80 USD/barrel and a price coupling of natural gas to crude oil of about 0.8. Such a cost structure is highly vulnerable to crude oil price fluctuations. Therefore, mid- to long-term price escalations are unfavourable for gas power plant economics. On the contrary, LCOE structure of PV power plants is dominated by capital cost being fixed by the investment decision and stable during the entire investment period. Moreover, low PV Opex enable excellent economics after the investment period for power plants being still in operation.

¹⁴² Awerbuch S., Portfolio-based electricity generation planning: policy implications for renewables and energy security, 2006

¹⁴³ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

¹⁴⁴ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

¹⁴⁵ Pehnt M. et al., Das Steinkohle-Kraftwerk Hamburg Moorburg und seine Alternativen, 2007

¹⁴⁶ Shah V. and Greenblatt J., Solar Energy Handbook: The Third Growth Phase of the Solar Era, 2010

¹⁴⁷ Delucchi M.A. and Jacobson M.Z., Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies, 2011

¹⁴⁸ BMU, Leitstudie 2010 – Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global, 2010

¹⁴⁹ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008

¹⁵⁰ IEA, Projected Costs of Generating Electricity 2010 Edition, 2010

¹⁵¹ Bolin B. (ed.), Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3), 1996

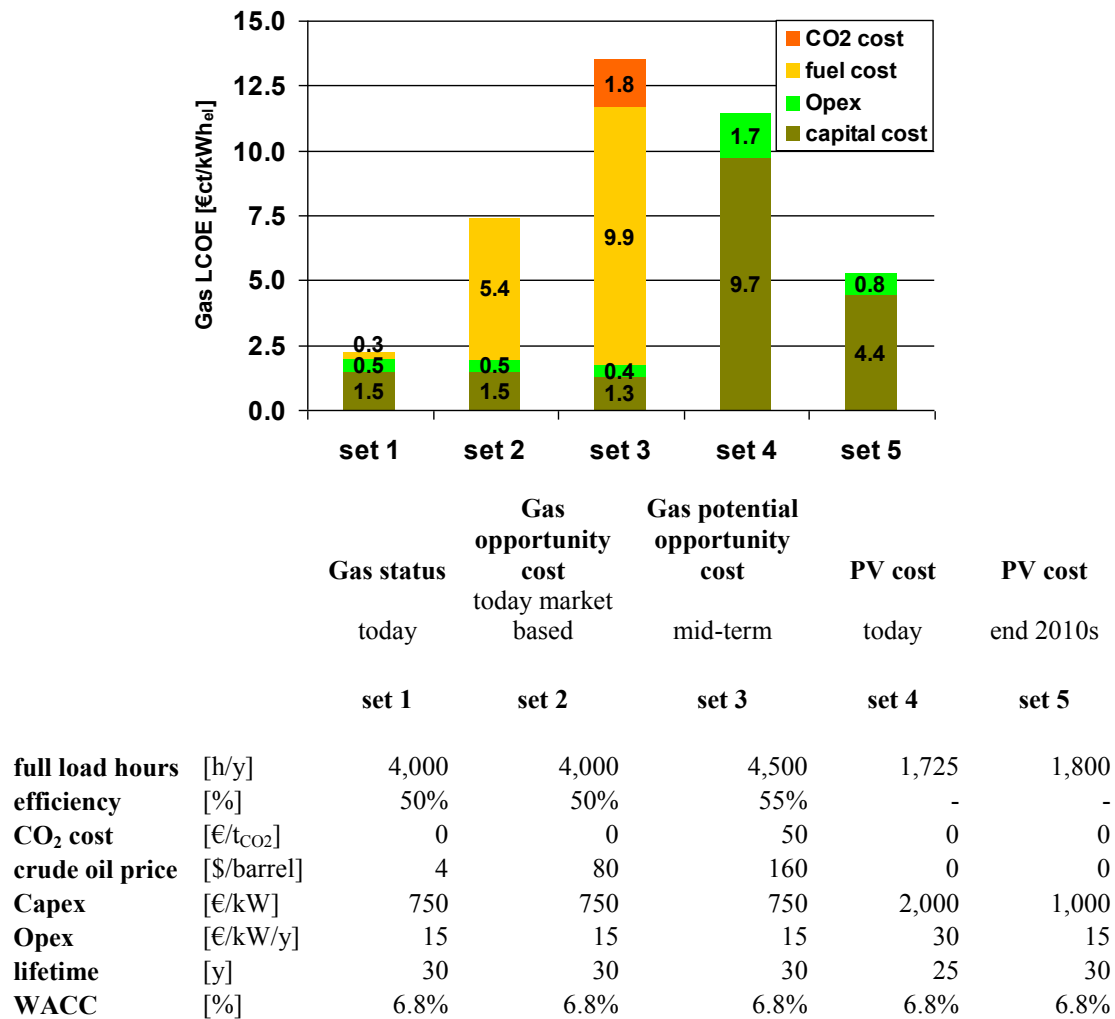


Figure 6.3-10: LCOE structure of gas fired and PV power plants (top) based on major driving forces (bottom). Major variations for gas fired power plants are the crude oil price, the power conversion efficiency and greenhouse gas emission cost and for PV power plants the Capex. Other parameters are set according to the base case scenario defined in Table 6.3-1.

Full gas extraction cost in gas rich MENA countries are equivalent to about 4 USD/barrel (Table 6.3-2) but can add up to 55 USD/barrel for costly offshore gas production and long pipeline transport (Table 6.3-2), whereas the base case scenario is set to 80 USD/barrel and mid-term 160 USD/barrel. The world market gas and oil prices represent the real current value of natural gas and crude oil, i.e. in case of burning gas and oil for less is identical to an energy subsidy and need to be accounted as opportunity cost, since it could be sold for the world market price. Greenhouse gas emissions, i.e. mainly CO₂, need to be priced for covering the enormous social cost of climate change (sub-chapter 1.2). Not charged CO₂ emissions are a subsidy due to social cost not covered by the electricity price.

gas field type		transport pipeline				total pipeline		
		production	short	long	LNG	short	long	LNG
conventional field	[USD/MBtu]	0.7	2.5	5.5	3.5	3.2	6.2	4.2
conventional field	[USD/barrel]	4.0	14.3	31.5	20.1	18.3	35.6	24.1
offshore field	[USD/MBtu]	4.0	2.5	5.5	3.5	6.5	9.5	7.5
offshore field	[USD/barrel]	22.9	14.3	31.5	20.1	37.3	54.5	43.0

Table 6.3-2: Total cost of natural gas in dependence on gas field type related production cost and transport cost constraints. Data are taken from International Energy Agency ¹⁵².

Key indicator for combining PV and gas fired power plants to hybrid PV-Gas power plants are the full load hours (FLh) of gas power plants. 2,000 FLh of gas power plants are assumed to be a necessary threshold for beneficial hybridization. Gas power plants only in operation under special peak load conditions of one season or after sunset cannot be used for hybrid operation. Some countries use such peakers for stabilizing their electricity grids, e.g. China, Norway, Sweden, Columbia, Venezuela, Peru and South Africa. Figure 6.3-11 illustrates the countries in the world operating gas power plants of in average at least 2,000 FLh per year.

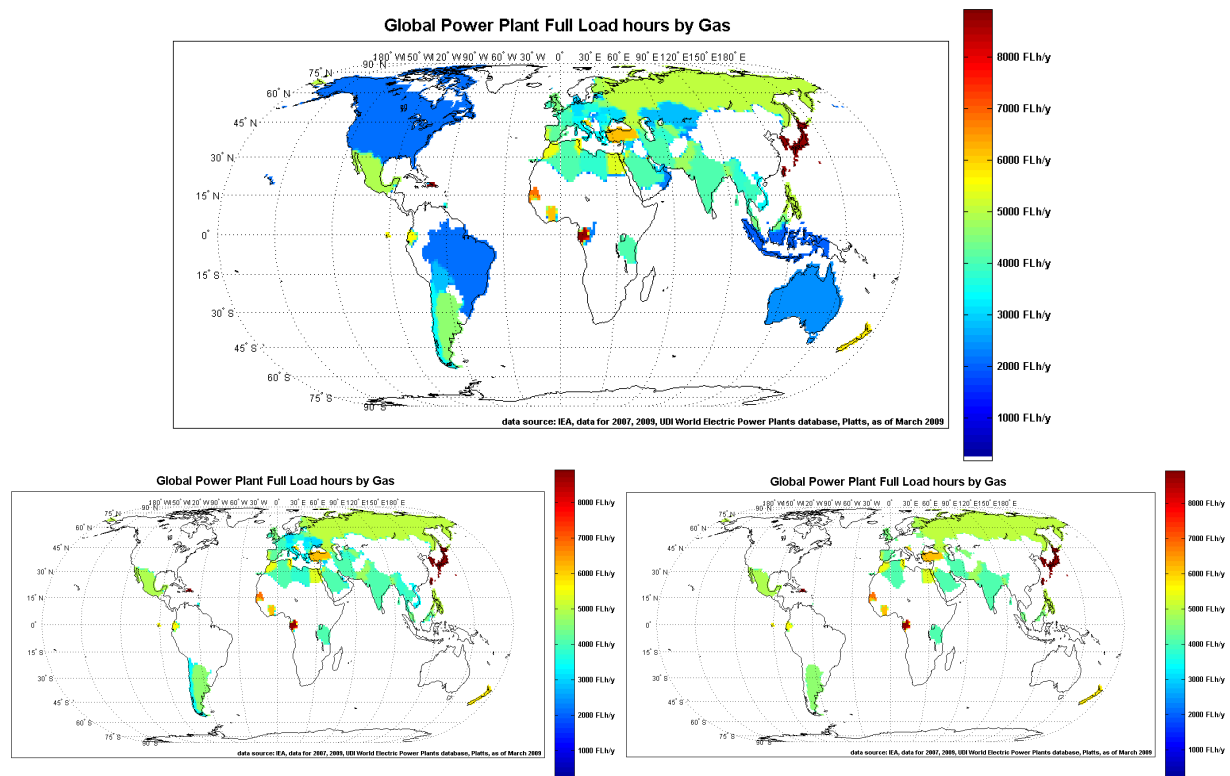


Figure 6.3-11: Global average gas power plant full load hours of at least 2,000 FLh (top), 3,000 FLh (bottom, left) and 4,000 FLh (bottom, right). Further visualization of gas power plant FLh can be found in Figures 6.3-7 and 6.3-9. Data are taken from UDI World Electric Power Plants database ¹⁵³ and International Energy Agency ¹⁵⁴.

Several countries in the world achieve a relative high contribution of gas power supply to overall electricity supply in combination with at least 2,000 FLh and based on significant power

¹⁵² IEA, World Energy Outlook 2009, 2009, p. 389-531

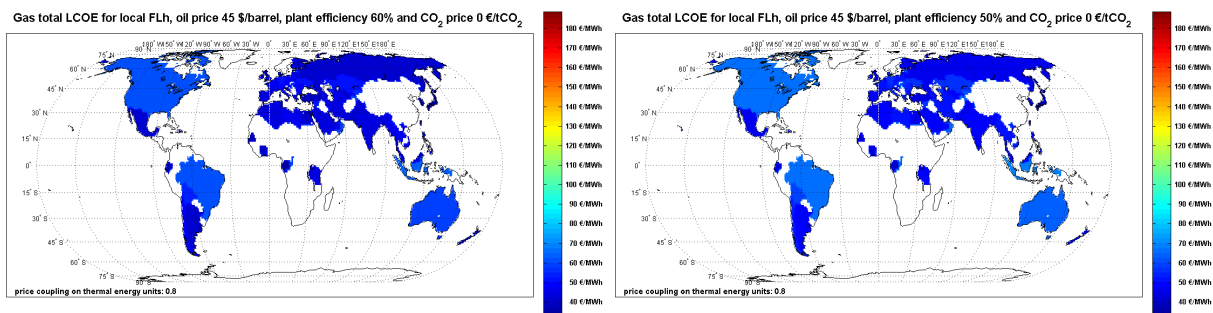
¹⁵³ Platts, UDI World Electric Power Plants data base, 2009

¹⁵⁴ IEA, Key World Energy Statistics 2009, 2009

capacities, e.g. the US, Mexico, Argentina, Spain, Italy, UK, the Netherlands, Germany, Russia, Algeria, Egypt, the United Arab Emirates, Saudi Arabia, Iran, Thailand and Malaysia (Fig. 5.1-13, 6.3-7, 6.3-8 and 6.3-11). In the following, only regions are considered in which the gas power plants are characterized by in average at least 2,000 FLh per year.

Base case scenario assumptions summarized in Table 6.3-1 are used for assessing gas power plant economics. However, in the following a broader parameter variation is taken into account for a better understanding of the range of gas LCOE. Precondition for all variations is a minimum average level of 2,000 FLh. Calculations are based on crude oil prices of 45, 80, 120 and 160 USD/barrel, respectively, and a natural gas to crude oil price coupling of 0.8. With all these price regimes a variation in power plant energy conversion efficiency is applied for values of 40%, 50% and 60%, respectively. Moreover, CO₂ emission cost are taken into account for the range of 0, 30 and 50 €/t_{CO2}, respectively. Within one crude oil price domain the least LCOE are achieved for highest efficiency (60%) and lowest carbon emission cost (0 €/t_{CO2}) and the highest LCOE are reached for lowest efficiency (40%) and highest carbon emission cost (50 €/t_{CO2}). The crude oil price level has the highest impact on LCOE, therefore variations in efficiency and carbon emission cost can be considered as first order effects on the LCOE. Assumed parameter range for the power conversion efficiency is optimistic, since global average of gas power plant energy conversion efficiency is 34%, based on a fuel consumption of 12,520 MWh_{th} (1,015 Mtoe) and resulting 4,300 TWh_{el} feed-in the grid.¹⁵⁵ Greenhouse gas emission cost of 0 €/t_{CO2} assumes a failure in global climate change diplomacy, which is possible but would result in a collapse of our global human society (sub-chapter 1.2), and cost of 50 €/t_{CO2} is still below social cost of 70 €/t_{CO2} or even more. Thus both power plant efficiency and carbon emission cost are optimistic and real cost might be significantly higher in the years to come. Crude oil price assumptions of 45 to 160 USD/barrel might be too optimistic, as well. Price spiked in 2008 on 147 USD/barrel and might reach a long-term level of 200 USD/barrel for an oil and natural gas constraint potentially near future (sub-chapter 1.3 and section 6.1.4).

Gas LCOE for a crude oil price of 45, 80, 120 and 160 USD/barrel are shown in Figures 6.3-12 to 6.3-15. Each oil price level is further differentiated by efficiency and carbon emission price for the cases of efficiency and carbon emission price of 60% and 0 €/t_{CO2}, 50% and 0 €/t_{CO2}, 50% and 30 €/t_{CO2} and 40% and 50 €/t_{CO2}. The parameter variation results in a gas LCOE range for each crude oil price level and takes into account the local average FLh.



¹⁵⁵ IEA, World Energy Outlook 2010, 2010

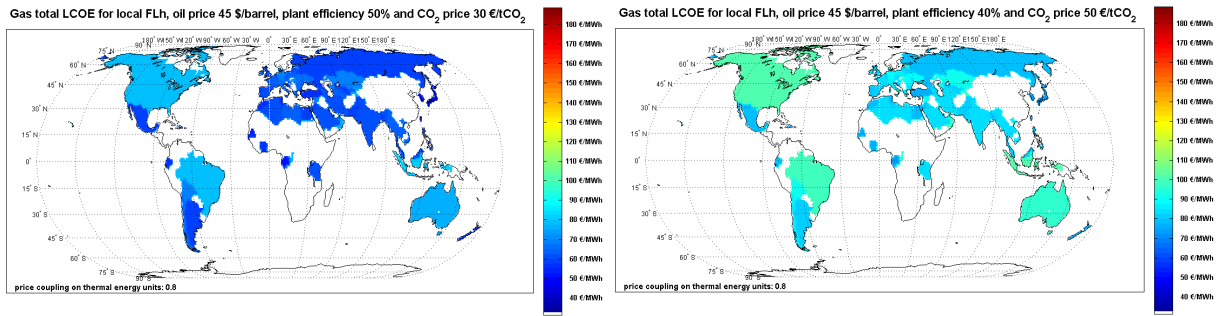


Figure 6.3-12: Gas LCOE for local FLh based on a crude oil level of 45 USD/barrel, natural gas to crude oil price coupling of 0.8, variations on gas power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 60% and 0 €/tCO₂ (top, left), 50% and 0 €/tCO₂ (top, right), 50% and 30 €/tCO₂ (bottom, left) and 40% and 50 €/tCO₂ (bottom, right). Gas LCOE model is defined in Equations 6.3-1 and remaining parameters are according to the base case assumptions of Table 6.3-1.

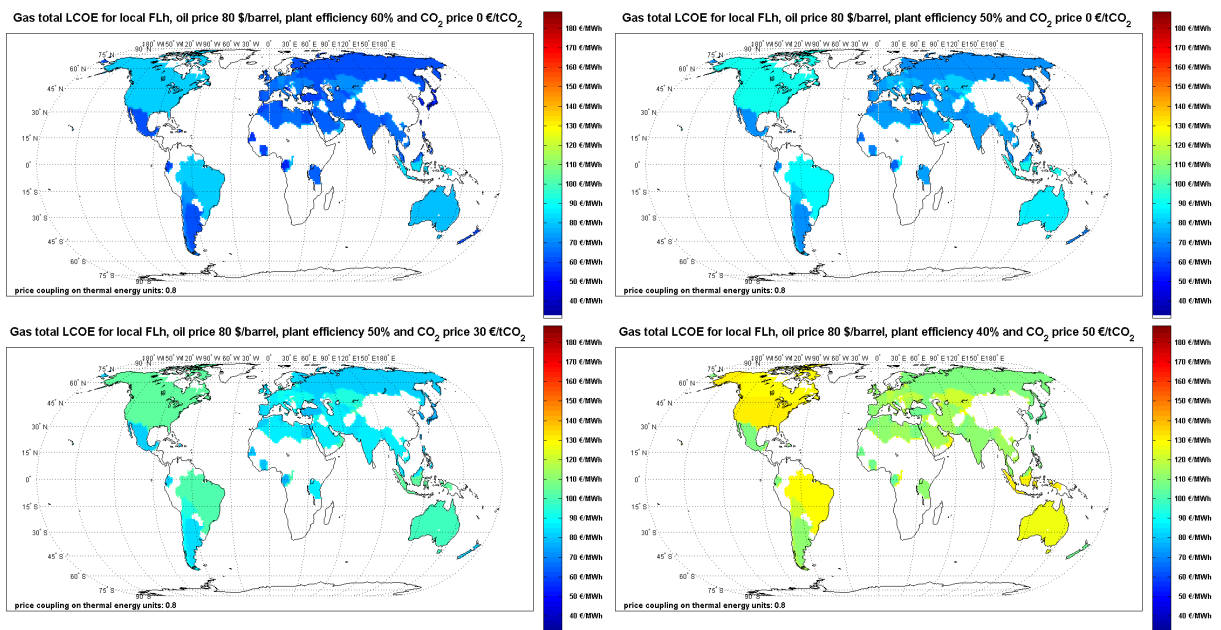
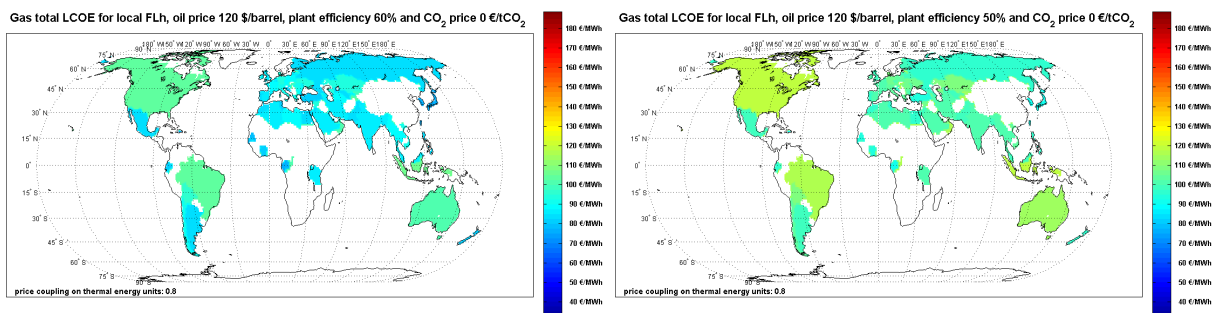


Figure 6.3-13: Gas LCOE for local FLh based on a crude oil level of 80 USD/barrel, natural gas to crude oil price coupling of 0.8, variations on gas power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 60% and 0 €/tCO₂ (top, left), 50% and 0 €/tCO₂ (top, right), 50% and 30 €/tCO₂ (bottom, left) and 40% and 50 €/tCO₂ (bottom, right). Gas LCOE model is defined in Equations 6.3-1 and remaining parameters are according to the base case assumptions of Table 6.3-1.



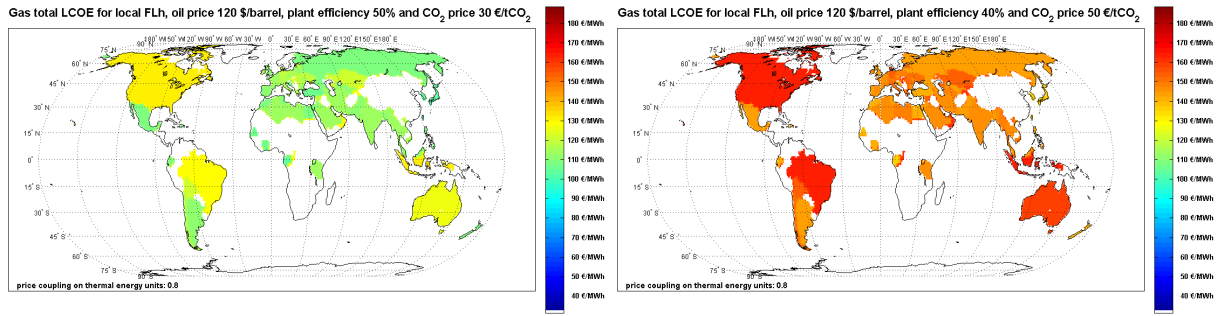


Figure 6.3-14: Gas LCOE for local FLh based on a crude oil level of 120 USD/barrel, natural gas to crude oil price coupling of 0.8, variations on gas power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 60% and 0 €/t_{CO2} (top, left), 50% and 0 €/t_{CO2} (top, right), 50% and 30 €/t_{CO2} (bottom, left) and 40% and 50 €/t_{CO2} (bottom, right). Gas LCOE model is defined in Equations 6.3-1 and remaining parameters are according to the base case assumptions of Table 6.3-1.

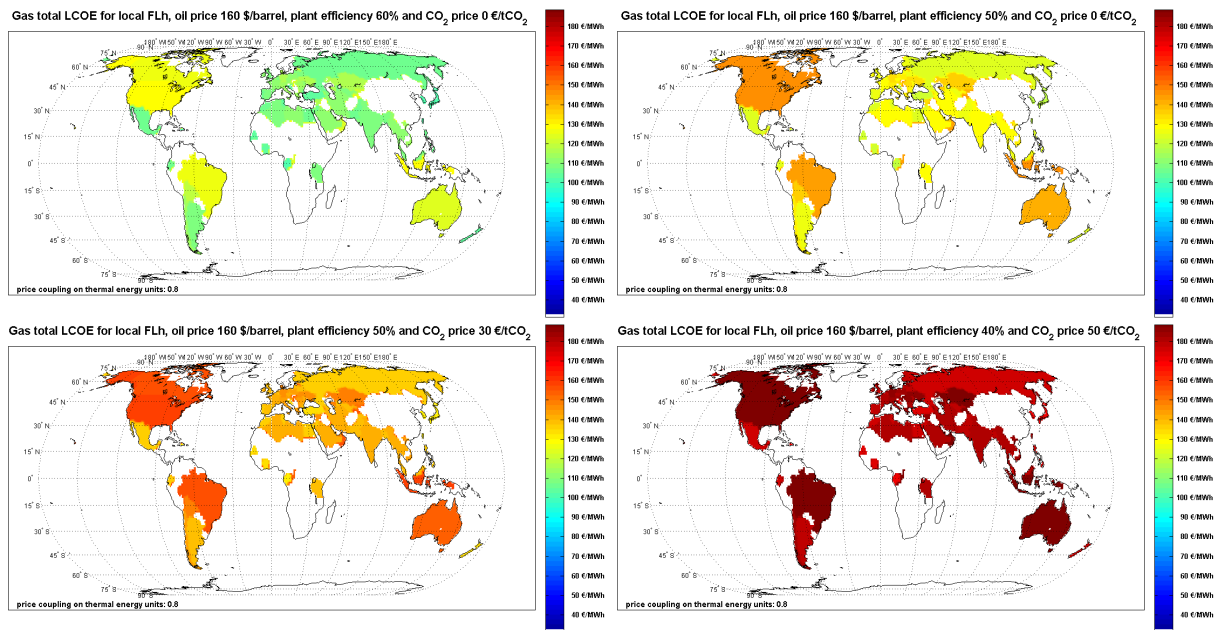


Figure 6.3-15: Gas LCOE for local FLh based on a crude oil level of 160 USD/barrel, natural gas to crude oil price coupling of 0.8, variations on gas power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 60% and 0 €/t_{CO2} (top, left), 50% and 0 €/t_{CO2} (top, right), 50% and 30 €/t_{CO2} (bottom, left) and 40% and 50 €/t_{CO2} (bottom, right). Gas LCOE model is defined in Equations 6.3-1 and remaining parameters are according to the base case assumptions of Table 6.3-1.

Efficiency/ CO ₂ price for 4,000 and 2,000 FLh gas to oil coupling 0.8	crude oil price				
	45 USD/bl	80 USD/bl	120 USD/bl	160 USD/bl	200 USD/bl
	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]
40%/ 0 €/t _{CO2}	57.8 – 76.4	87.6 – 106.1	121.6 – 140.1	155.6 – 174.1	189.6 – 208.1
40%/ 30 €/t _{CO2}	73.0 – 91.5	102.7 – 121.3	136.7 – 155.3	170.7 – 189.3	204.7 – 223.3
40%/ 50 €/t _{CO2}	83.1 – 101.6	112.8 – 131.4	146.8 – 165.4	180.8 – 199.4	214.8 – 233.4
40%/ 70 €/t _{CO2}	93.2 – 111.7	122.0 – 141.5	156.9 – 175.5	190.9 – 209.5	224.9 – 243.5
50%/ 0 €/t _{CO2}	50.2 – 68.7	74.0 – 92.5	101.2 – 119.7	128.4 – 146.9	155.6 – 174.1
50%/ 30 €/t _{CO2}	62.3 – 80.8	86.1 – 104.6	113.3 – 131.8	140.5 – 159.0	167.7 – 186.2
50%/ 50 €/t _{CO2}	70.4 – 88.9	94.2 – 112.7	121.4 – 139.9	148.6 – 167.1	175.8 – 194.3
50%/ 70 €/t _{CO2}	78.4 – 97.0	102.2 – 120.8	129.4 – 148.0	156.6 – 175.2	183.8 – 202.4
60%/ 0 €/t _{CO2}	45.1 – 63.6	64.9 – 83.4	87.6 – 106.1	110.2 – 128.8	132.9 – 151.5
60%/ 30 €/t _{CO2}	55.2 – 73.7	75.0 – 93.5	97.7 – 116.2	120.3 – 138.9	143.0 – 161.5
60%/ 50 €/t _{CO2}	61.9 – 80.4	81.7 – 100.3	104.4 – 122.9	127.1 – 145.6	149.7 – 168.3
60%/ 70 €/t _{CO2}	68.6 – 87.2	88.5 – 107.0	111.1 – 129.7	133.8 – 152.3	156.5 – 175.0

Table 6.3-3: Gas LCOE for 2,000 to 4,000 FLh, power plant conversion efficiencies of 40%, 50% and 60%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, natural gas to crude oil price coupling of 0.8 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}. Gas LCOE model is defined in Equations 6.3-1 and remaining parameters are according to the base case assumptions of Table 6.3-1. Natural gas prices being equivalent to crude oil prices of 45, 80, 120, 160 and 200 USD/barrel are 6.3 USD/MBtu (238 USD/kNm³, 6.0 USD/GJ), 11.2 USD/MBtu (422 USD/kNm³, 10.6 USD/GJ), 16.7 USD/MBtu (634 USD/kNm³, 15.9 USD/GJ), 22.3 USD/MBtu (845 USD/kNm³, 21.2 USD/GJ), 27.9 USD/MBtu (1,056 USD/kNm³, 26.4 USD/GJ), respectively, based on a natural gas to crude oil price coupling of 0.8 on thermal energy units.

Efficiency/ CO ₂ price for 4,000 and 2,000 FLh gas to oil coupling 0.7	crude oil price				
	45 USD/bl	80 USD/bl	120 USD/bl	160 USD/bl	200 USD/bl
	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]
40%/ 0 €/t _{CO2}	53.0 – 71.6	79.1 – 97.6	108.8 – 127.4	138.6 – 157.1	168.3 – 186.9
40%/ 30 €/t _{CO2}	68.2 – 86.7	94.2 – 112.8	124.0 – 142.5	153.7 – 172.3	183.5 – 202.0
40%/ 50 €/t _{CO2}	78.3 – 96.8	104.3 – 122.9	134.1 – 152.6	163.8 – 182.4	193.6 – 212.1
40%/ 70 €/t _{CO2}	88.4 – 106.9	114.4 – 133.0	144.2 – 162.7	173.9 – 192.5	203.7 – 222.2
50%/ 0 €/t _{CO2}	46.3 – 64.9	67.2 – 85.7	91.0 – 109.5	114.8 – 133.3	138.6 – 157.1
50%/ 30 €/t _{CO2}	58.5 – 77.0	79.3 – 97.8	103.1 – 121.6	126.9 – 145.4	150.7 – 169.2
50%/ 50 €/t _{CO2}	66.5 – 85.1	87.4 – 105.9	111.2 – 129.7	135.0 – 153.5	158.8 – 177.3
50%/ 70 €/t _{CO2}	74.6 – 93.2	95.4 – 114.0	119.2 – 137.8	143.0 – 161.6	166.8 – 185.4
60%/ 0 €/t _{CO2}	41.9 – 60.4	59.2 – 77.8	79.1 – 97.6	98.9 – 117.5	118.7 – 137.3
60%/ 30 €/t _{CO2}	52.0 – 70.5	69.3 – 87.9	89.2 – 107.7	109.0 – 127.5	128.8 – 147.4
60%/ 50 €/t _{CO2}	58.7 – 77.3	76.1 – 94.6	95.9 – 114.4	115.7 – 134.3	135.6 – 154.1
60%/ 70 €/t _{CO2}	65.4 – 84.0	82.8 – 101.3	102.6 – 121.2	122.5 – 141.0	142.3 – 160.8

Table 6.3-4: Gas LCOE for 2,000 to 4,000 FLh, power plant conversion efficiencies of 40%, 50% and 60%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, natural gas to crude oil price coupling of 0.7 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}. Gas LCOE model is defined in Equations 6.3-1 and remaining parameters are according to the base case assumptions of Table 6.3-1. Natural gas prices being equivalent to crude oil prices of 45, 80, 120, 160 and 200 USD/barrel are USD/5.5 MBtu (208 USD/kNm³, 5.2 USD/GJ), 9.8 USD/MBtu (370 USD/kNm³, 9.3 USD/GJ), 14.6 USD/MBtu (554 USD/kNm³, 13.9 USD/GJ), 19.5 USD/MBtu (739 USD/kNm³, 18.5 USD/GJ), 24.4 USD/MBtu (924 USD/kNm³, 23.1 USD/GJ), respectively, based on a natural gas to crude oil price coupling of 0.7 on thermal energy units.

Depending on efficiency, carbon emission cost and FLh, the gas LCOE of a crude oil price of 45 USD/barrel and a price coupling of 0.8 range between 45 and 112 €/MWh and for a price coupling of 0.7 the span is about 7% - 5% lower between 42 and 107 €/MWh (Fig. 6.3-12 and Tables 6.3-3 and 6.3-4). Low efficient gas power plants of 40% conversion efficiency and no CO₂ cost show LCOE of 58 to 76 €/MWh (53 to 72 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000. Highly efficient gas power plants of 60% conversion efficiency and no CO₂ cost show LCOE of 45 to 64 €/MWh (42 to 60 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000.

Gas LCOE of a crude oil price of 80 USD/barrel and a price coupling of 0.8 range between 65 and 142 €/MWh and for a price coupling of 0.7 the span is about 9% - 6% lower between 59 and 133 €/MWh (Fig. 6.3-13 and Tables 6.3-3 and 6.3-4). Low efficient gas power plants of 40% conversion efficiency and no CO₂ cost show LCOE of 88 to 106 €/MWh (79 to 98 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000. Highly efficient gas power plants of 60% conversion efficiency and no CO₂ cost show LCOE of 65 to 83 €/MWh (59 to 78 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000.

Gas LCOE of a crude oil price of 120 USD/barrel and a price coupling of 0.8 range between 88 and 176 €/MWh and for a price coupling of 0.7 the span is about 10% - 7% lower between 79 and 163 €/MWh (Fig. 6.3-14 and Tables 6.3-3 and 6.3-4). Low efficient gas power plants

of 40% conversion efficiency and no CO₂ cost show LCOE of 122 to 140 €/MWh (109 to 127 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000. Highly efficient gas power plants of 60% conversion efficiency and no CO₂ cost show LCOE of 88 to 106 €/MWh (79 to 98 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000.

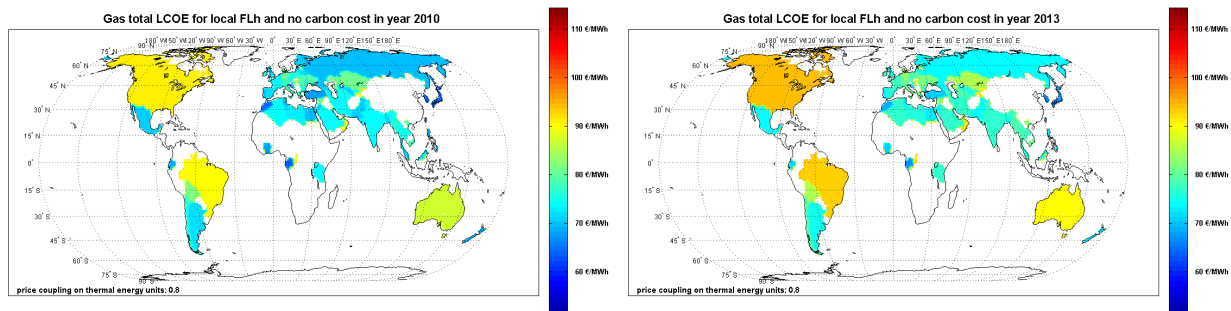
Gas LCOE of a crude oil price of 160 USD/barrel and a price coupling of 0.8 range between 110 and 210 €/MWh and for a price coupling of 0.7 the span is about 10% - 8% lower between 99 and 193 €/MWh (Fig. 6.3-15 and Tables 6.3-3 and 6.3-4). Low efficient gas power plants of 40% conversion efficiency and no CO₂ cost show LCOE of 156 to 174 €/MWh (139 to 157 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000. Highly efficient gas power plants of 60% conversion efficiency and no CO₂ cost show LCOE of 110 to 129 €/MWh (99 to 118 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000.

Gas LCOE of a crude oil price of 200 USD/barrel and a price coupling of 0.8 range between 133 and 244 €/MWh and for a price coupling of 0.7 the span is about 11% - 9% lower between 119 and 222 €/MWh (Tables 6.3-3 and 6.3-4). Low efficient gas power plants of 40% conversion efficiency and no CO₂ cost show LCOE of 190 to 208 €/MWh (168 to 187 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000. Highly efficient gas power plants of 60% conversion efficiency and no CO₂ cost show LCOE of 133 to 152 €/MWh (119 to 137 €/MWh for a price coupling of 0.7) for FLh between 4,000 to 2,000.

In the year 2010 PV LCOE in sunny regions are about 100 to 120 €/MWh depending on location and assumptions (Fig. 6.3-10 and 3.2-16). Therefore, PV power plants are lower in cost than low efficient gas power plants at crude oil prices of about 120 USD/barrel and a price coupling of 0.8 and PV power plants are always lower in LCOE than gas power plants for crude oil price of 160 USD/barrel or more. In near future, i.e. in first half of 2010s, in sunny regions PV power plants are always lower in LCOE than gas power plants at 120 USD/barrel or more. Consequently, in sunny regions gas power plants are an excellent component for hybrid PV-Gas power plants due to drastically improved economics by upgrading existing gas power plants with PV power plants.

6.3.3 Hybrid PV-Gas Power Plant Demand Curve

In the following scenario assumptions are taken into account for gas power plants (Table 6.3-1) and for fixed optimally tilted PV power plants (Table 3.2-1). Gas power plant base case assumes a crude oil price of 80 USD/barrel, a natural gas to crude oil price coupling of 0.8 and an annual escalation rate of 3% in real terms. Gas LCOE projection in the 2010s is depicted in Figure 6.3-16.



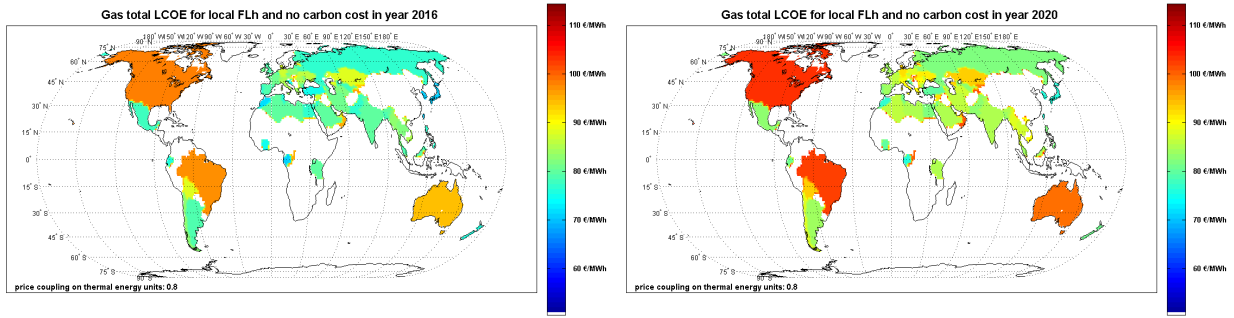


Figure 6.3-16: Gas LCOE for local FLh in the 2010s for the base case scenario. Base case scenario is defined in Table 6.3-1. Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis.

Upgrading existing gas power plants by PV power plants to hybrid PV-Gas power plants is economically favourable for PV LCOE lower than gas LCOE. The precise calculation needs to include slightly higher capital cost of gas power plants by reducing their FLh in order of the PV FLh. This effect can be calculated by Equation 6.3-1a and has to be generated additionally by the PV component, i.e. lower PV LCOE, of the hybrid PV-Gas power plant. All breakeven, i.e. parity, analyses in this sub-chapter take this effect into account. The year of PV and gas power plant parity is illustrated in Figures 6.3-17 and 6.3-18.

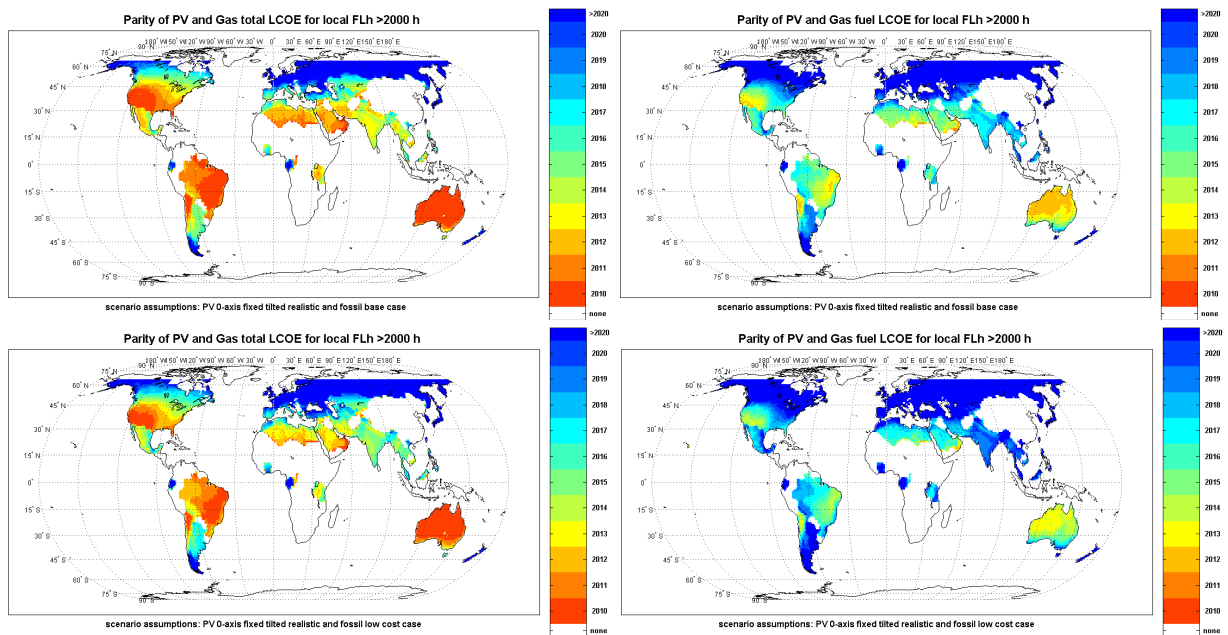
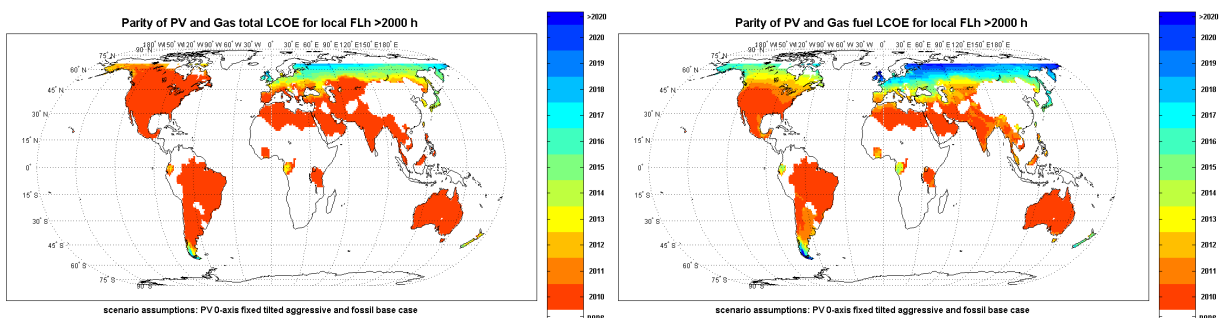


Figure 6.3-17: Parity of fixed optimally tilted PV and gas power plants for total plant LCOE (left) and fuel-only LCOE (right) for PV realistic and gas base case (top) and low cost (bottom) scenario assumptions. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.3-1 and Figure 6.3-16 (gas). Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis.



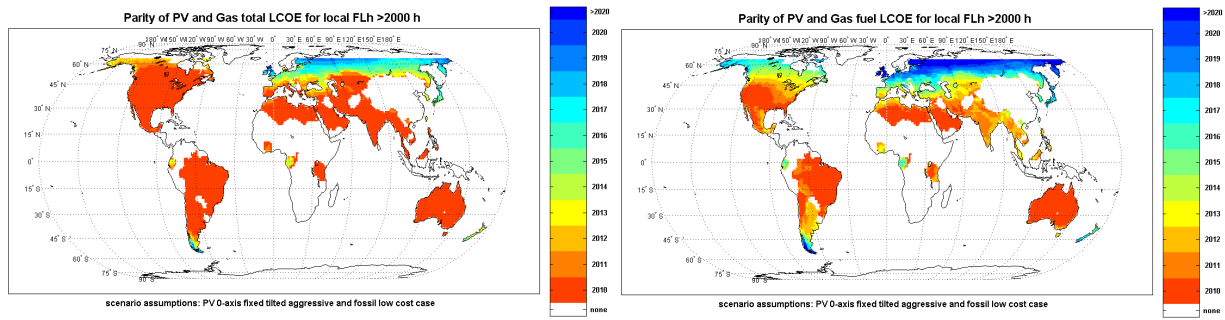


Figure 6.3-18: Parity of fixed optimally tilted PV and gas power plants for total plant LCOE (left) and fuel-only LCOE (right) for PV aggressive and gas base case (top) and low cost (bottom) scenario assumptions. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.3-1 and Figure 6.3-16 (gas). Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis.

In nearly all sunny regions in the world, PV power plants are lower in LCOE than gas power plants on total plant basis and for realistic scenario (PV) and base case (gas) conditions already in the year 2010 (Fig. 6.3-17). PV LCOE compared to fuel-only LCOE of gas fired power plants begin their breakeven in the first half of the 2010s in the very sunny regions, however the adequate economic reference is the total plant basis and the fuel-only level is the economically strictest reference. Consequence of lower natural gas prices, i.e. looser price coupling to crude oil, would be a delayed economic breakthrough of hybrid PV-Gas power plants. PV LCOE start to be lower than those of gas power plants on a total plant basis in the very sunny regions in the world in the year 2010 and reach the regions of moderate solar resources in the end of the decade. For the aggressive case nearly all relevant regions in the world show lower PV LCOE than gas LCOE in 2010 even for the fuel-only LCOE restriction in very sunny regions (Fig. 6.3-18) for the fossil base case conditions. As discussed in sub-chapter 3.2, true PV cost might be between the realistic and aggressive scenario assumptions. Consequently, PV power plants are already competitive to gas power plants in the sunny regions in the world at a crude oil price level of 80 USD/barrel.

Financial benefits are depicted in Figures 6.3-19 and 6.3-20 for the most competitive conditions of PV LCOE versus fuel-only gas LCOE.

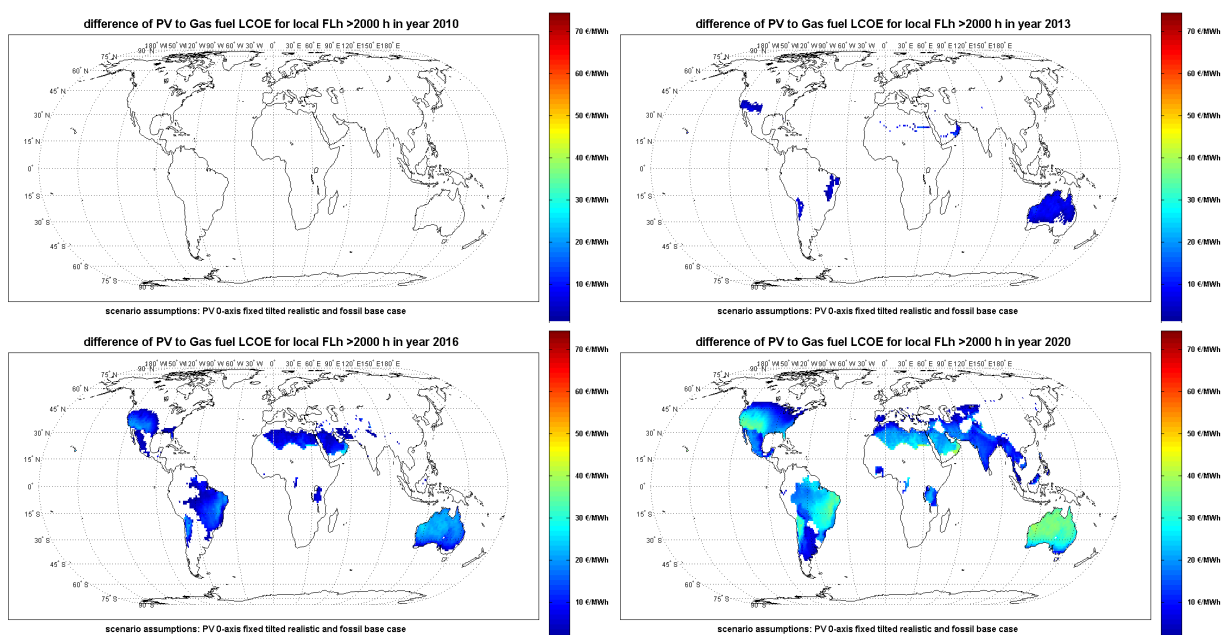


Figure 6.3-19: PV LCOE benefit in comparison to fuel-only gas LCOE for fixed optimally tilted PV realistic and gas base case scenario assumptions in the 2010s. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.3-1 and Figure 6.3-16 (gas). Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis.

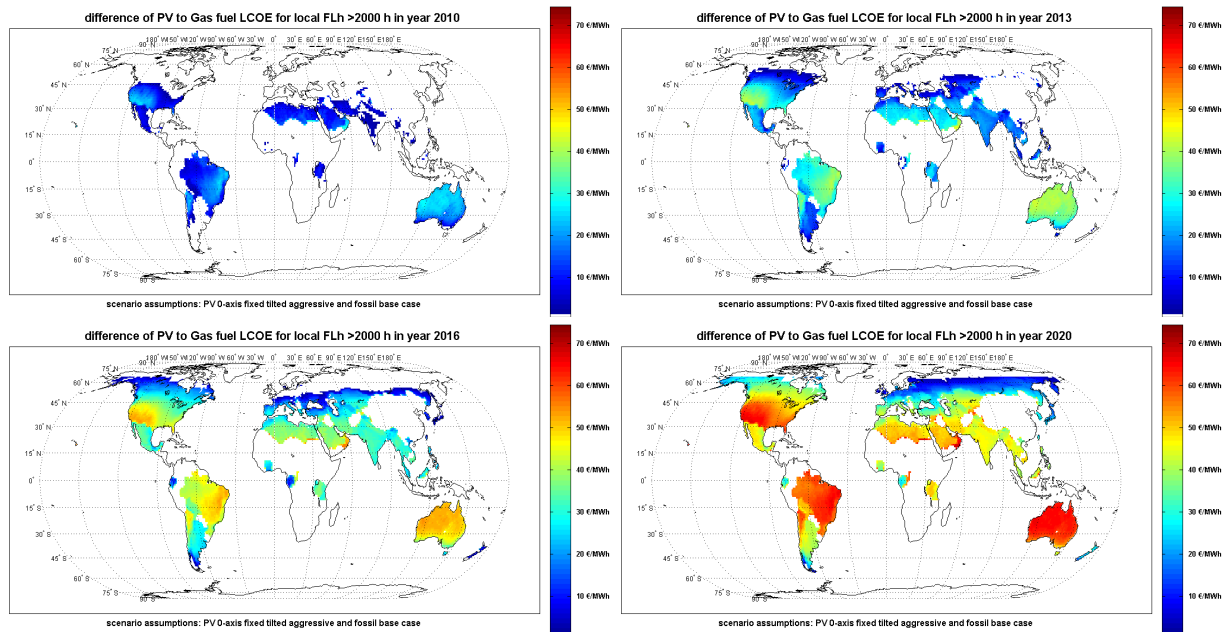


Figure 6.3-20: PV LCOE benefit in comparison to fuel-only gas LCOE for fixed optimally tilted PV aggressive and gas base case scenario assumptions in the 2010s. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.3-1 and Figure 6.3-16 (gas). Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis.

The LCOE advantage of PV power plants in respect to those of gas power plants in the economically strictest case of fuel-only LCOE reveals the high competitiveness of PV versus gas power plants. For realistic (PV) and base case (gas) scenario assumptions PV LCOE are lower than fuel-only gas LCOE by mid of the 2010s in the very sunny regions, although this is already the case in 2010 for total plant LCOE (Fig. 6.3-19 and 6.3-17). By the end of the decade PV LCOE are lower than fuel-only LCOE of gas power plants by about 10 to 40 €/MWh in very sunny regions. For aggressive (PV) and base case (gas) scenario assumptions PV LCOE are lower than fuel-only gas LCOE by about 15 €/MWh (2010), 30 €/MWh (2013), 40 €/MWh (2016) and 55 €/MWh (2020) in very sunny regions (Fig. 6.3-20). These results are based on a crude oil price of 80 USD/barrel in 2010 and an escalation rate of 3%, i.e. 107 USD/barrel in 2020. In case of faster crude oil escalation the benefits of PV power plants are significantly higher.

Based on fuel-parity analyses of PV versus gas power plants (Fig. 6.3-17 and 6.3-18) a global hybrid PV-Gas power plant demand curve can be derived. Regions of gas power plants operated less than 2,000 FLh are excluded from the analysis, this is the case for about 100 GW of the total 1,100 GW gas power capacity (Table 5.1-1). All gas power plants in the world are available by their georeferenced coordinates (Fig. 6.3-2) enabling a direct comparison of PV LCOE at the respective site. For each coordinate of a 1°x1° mesh of latitude and longitude the year of PV LCOE (plus higher gas capital cost due to reduced FLh) lower than total and fuel-only gas LCOE is recorded. All the coordinates are aggregated afterwards to the country of their location. Global hybrid PV-Gas power plant demand curves for PV realistic and aggressive and gas base case scenario assumptions are plotted in Figures

6.3-21 and 6.3-22 and respective gas low cost scenario assumptions are summarized in Figure 6.3-23.

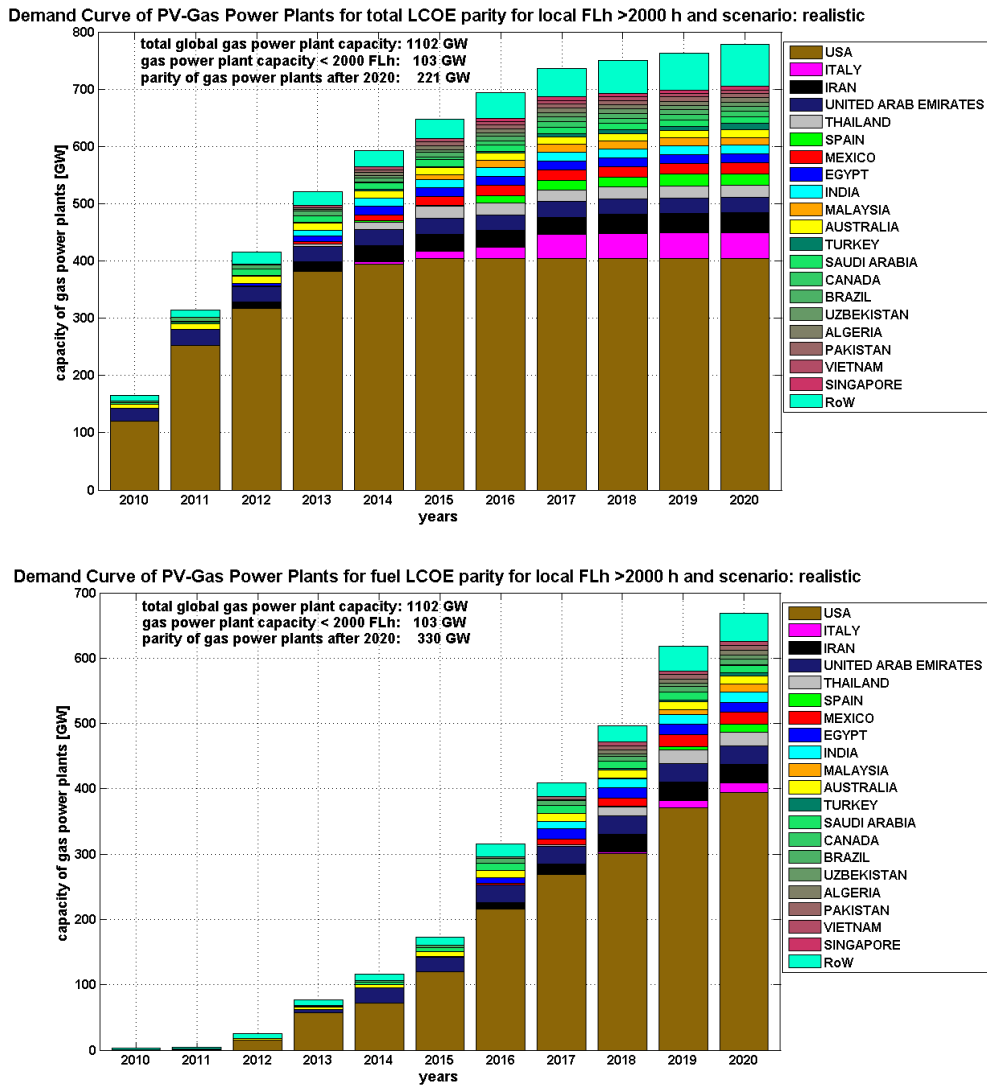


Figure 6.3-21: Global hybrid PV-Gas power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV realistic and gas base case scenario assumptions in the 2010s. Gas power plant capacity is counted only in case of PV LCOE (plus higher gas capital cost due to reduced FLh) lower than total and fuel-only gas LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.3-1 and Figure 6.3-16 (gas). Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis. Data for gas power plant capacity are taken from UDI World Electric Power Plants database ¹⁵⁶.

¹⁵⁶ Platts, UDI World Electric Power Plants data base, 2009

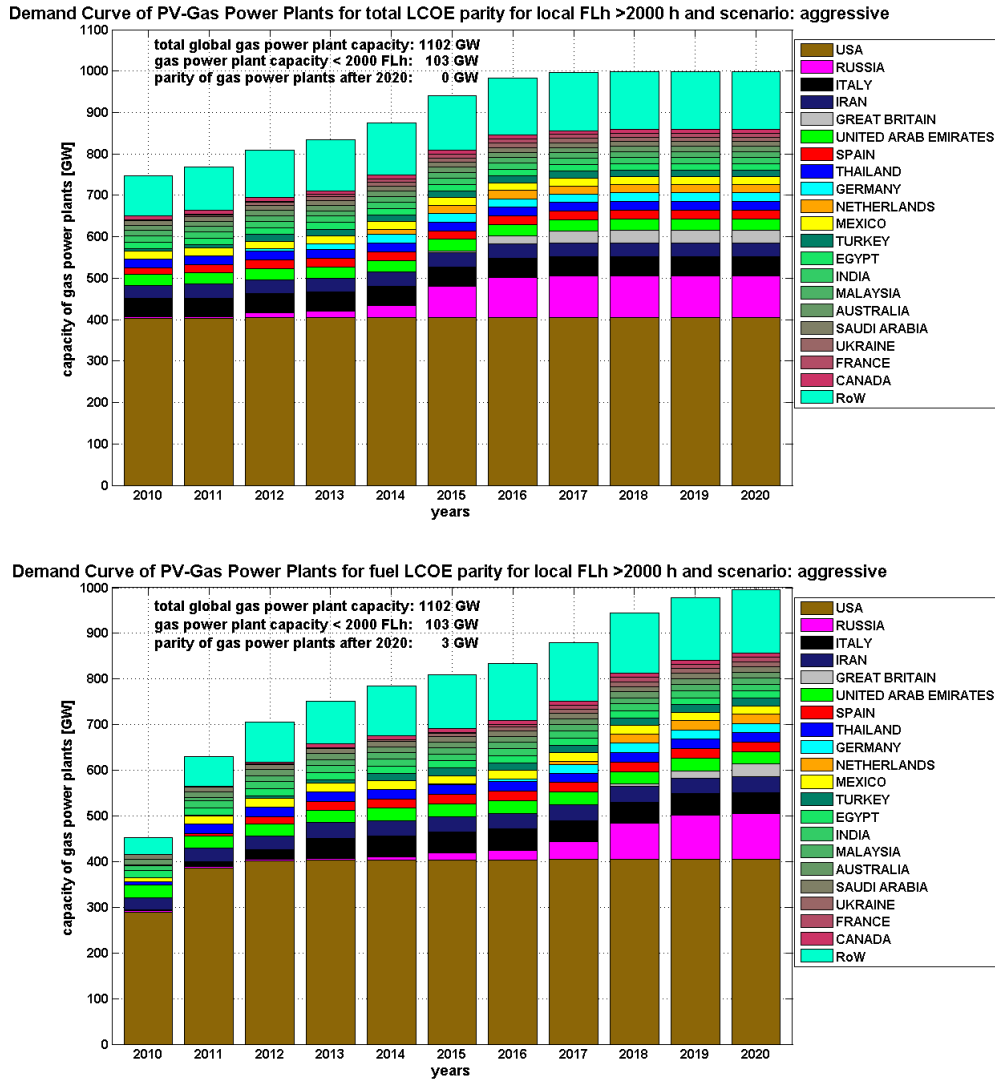
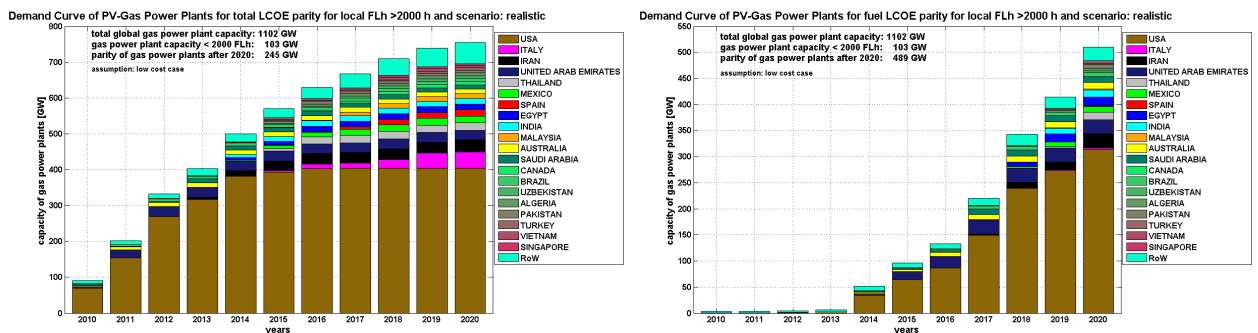


Figure 6.3-22: Global hybrid PV-Gas power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV aggressive and gas base case scenario assumptions in the 2010s. Gas power plant capacity is counted only in case of PV LCOE (plus higher gas capital cost due to reduced FLh) lower than total and fuel-only gas LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.3-1 and Figure 6.3-16 (gas). Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis. Data for gas power plant capacity are taken from UDI World Electric Power Plants database¹⁵⁷.



¹⁵⁷ Platts, UDI World Electric Power Plants data base, 2009

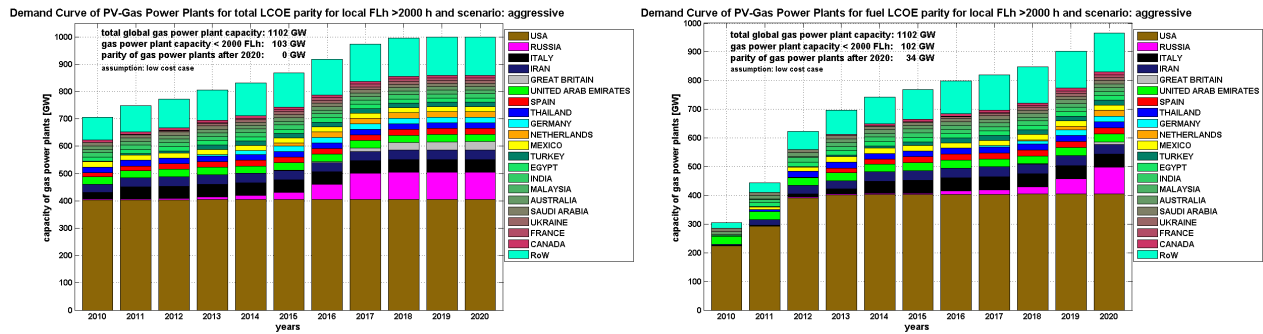


Figure 6.3-23: Global hybrid PV-Gas power plant demand curve in the 2010s on total (left) and fuel-only (right) LCOE parity for fixed optimally tilted PV in the realistic (top) and aggressive (bottom) and gas low cost case scenario assumptions in the 2010s. Gas power plant capacity is counted only in case of PV LCOE (plus higher gas capital cost due to reduced FLh) lower than total and fuel-only gas LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.3-1 (gas). Countries operating gas power plants in average of at least 2,000 FLh are included in the analysis. Data for gas power plant capacity are taken from UDI World Electric Power Plants database ¹⁵⁸.

In 2010, first gas power plants in very sunny regions show higher LCOE than nearby PV power plants on a total power plant LCOE basis even for the realistic scenario assumptions of PV power plants (Fig. 6.3-21). The by far largest market for hybrid PV-Gas power plants is the US. By the end of the 2010s, the largest markets for hybrid PV-Gas power plants are the US, Italy, Iran, the United Arab Emirates, Thailand, Spain, Mexico, Egypt, India, Malaysia, Australia and Turkey. In the aggressive scenario, i.e. fast PV cost reduction dynamic, four further major markets are beyond economic breakeven: Russia, UK, Germany and the Netherlands. Even countries of moderate solar resource conditions show favourable economics by end of the 2010s for hybrid PV-Gas power plants. Noteworthy, this analytically derived natural gas fuel-parity of PV power plants in Germany has been also found by Wenzel and Nitsch for the end of the 2010s. ¹⁵⁹

Depending on scenario assumptions market potential for hybrid PV-Gas power plants has been more than 150 GW in 2010 and might fast rise to 750 GW by the end of the 2010s. The maximum market potential is about 1,000 GW due to limited gas power plant capacity operated in average for at least 2,000 FLh.

The results for hybrid PV-Gas power plant economics show several characteristics for a beneficial combination. Already existing gas power plants should be operated for at least 2,000 FLh during daytime. Fuel represents the by far highest fraction of power plant LCOE, e.g. about 75% for a crude oil price of 80 USD/barrel, hence gas LCOE are highly influenced by crude oil price. The solar resource quality at local sites of existing power plants is very important for PV LCOE and thus hybrid PV-Gas power plant economics, but the crude oil price is more decisive. Gas producing countries have the identical gas LCOE due to the respective opportunity cost in case of burning gas priced lower than world market price. However, these countries would have no problems in organising the financing of large scale PV power plant investments. PV power plants might be in competition to wind power plants due to excellent wind power economics (sub-chapters 4.2 and 4.3). In case of complementary wind and solar resource availability the economics of hybrid PV-Gas power plants might be

¹⁵⁸ Platts, UDI World Electric Power Plants data base, 2009

¹⁵⁹ Wenzel B. and Nitsch J., Langfristszenarien und Strategien für den Ausbau der Erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global, 2010, p. 38

further improved by integrating wind power and establishing hybrid PV-Wind-Gas power plants. Complementary versus competitive characteristics of solar and wind resources are discussed in sub-chapter 7.3.

Summing up, results for hybrid PV-Gas power plant economics give plenty of insights for excellent competitiveness of this approach for upgrading existing gas fired power plants. Many regions in the world in which gas power plants are operated on a significant FLh level have good and excellent solar resources which lead to favourable PV power plant economics. Already in the year 2010, several gas power plants in the world could lower the LCOE by upgrading with nearby PV power plants. Financial upgrading benefit for resulting hybrid PV-Gas power plants is fast increasing as a consequence of fast PV LCOE reductions and higher than expected crude oil price escalation and collateral natural gas price adaption.

6.4 Hybrid PV-Coal Power Plant

Coal fired power plants are used for power supply all around the world (section 6.4.1) but depending on local conditions on a larger range of intensity. The economics of coal power generation (section 6.4.2) are the financial basis for a successful hybridization of PV power plants and coal fired power plants. This builds the fundament for the derivation of a global demand curve for hybrid PV-Coal power plants in the 2010s (section 6.4.3). In contrast to end-user prices driven grid-parity, the most decisive economic criteria in the power plant sector is the fuel-parity, i.e. competitive PV power generation cost in reference to total and fuel-only power generation cost of conventional power plants. The already discussed preconditions for a successful hybridization (sub-chapter 6.1) of PV and coal power plants, in particular for IGCC plants, are expanded and analysed in this sub-chapter in a special focus on the economics.

6.4.1 Global Overview on Coal Power Capacity

The present and future relevance of a power technology can be assessed by its resource availability (sub-chapter 1.3), the installed power capacity, utilization of the available power capacity and the local power supply contribution. These dimensions will be presented and discussed in the following for coal fired power plants. The distribution of coal reserves is depicted in Figure 6.4-1.

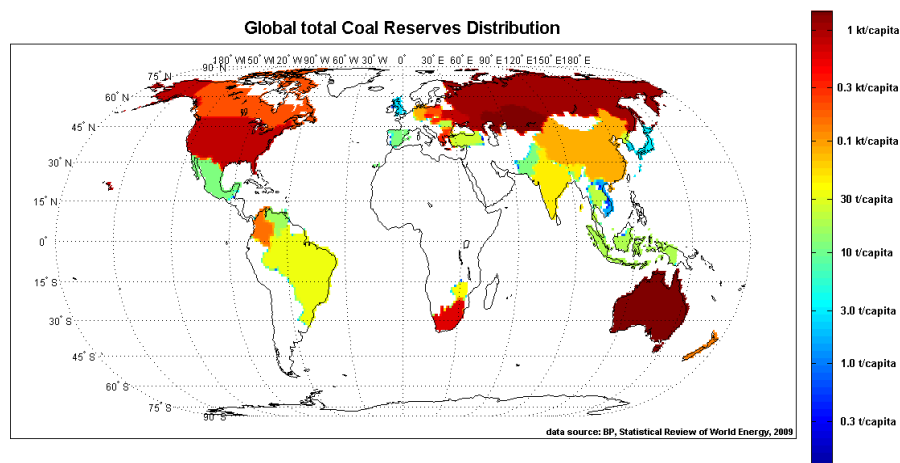


Figure 6.4-1: Distribution of coal reserves. Data are taken from BP ¹⁶⁰.

Total global installed coal power capacity was 1,514 GW by end of 2008 and generated electricity was 8,273 TWh in the year 2008, translating to 5,460 full load hours.¹⁶¹

It is necessary to know the coordinates of the coal power plants for further analysis. Due to that the UDI World Electric Power Plants database ¹⁶² has been enhanced by coordinates of all 145,000 power plants in the world.¹⁶³ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. However, a crosscheck reveals a capacity of about 1,466 GW of coal power plants in the database versus 1,514 GW denominated in the IEA dataset. The deviation of about 50 GW might be caused by different dates on commissioning and decommissioning of capacities.

In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration has been taken in these cases. The result of the georeferenced global power plant capacity being in operation is depicted in Figure 6.4-2.

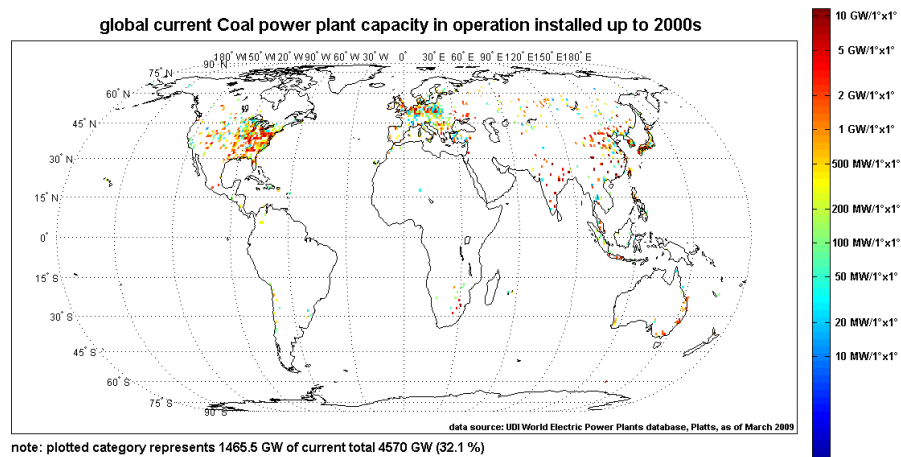


Figure 6.4-2: Global coal power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. Data are plotted in a 1°x1° mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database ¹⁶⁴ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced coal power plant data (Fig. 6.4-2) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current coal fired power plant capacity (Fig. 6.4-3). About 520 GW out of 1,466 GW included in the database are located in areas of more than 1,800 kWh/m²/y irradiation on fixed optimally tilted module surfaces, i.e. 36% of global coal power installed base is installed in regions of very good solar resource quality. Coal power plants operated during daytime match in an excellent way to the feed-in profile of PV power plants and should be adaptable to power profile of PV plants, hence detailed analysis on the economics of hybrid PV-Coal power plants is performed and discussed in sections 6.4.2 and 6.4.3.

¹⁶⁰ BP, Statistical Review of World Energy, 2009

¹⁶¹ IEA, World Energy Outlook 2010, 2010

¹⁶² Platts, UDI World Electric Power Plants data base, 2009

¹⁶³ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

¹⁶⁴ Platts, UDI World Electric Power Plants data base, 2009

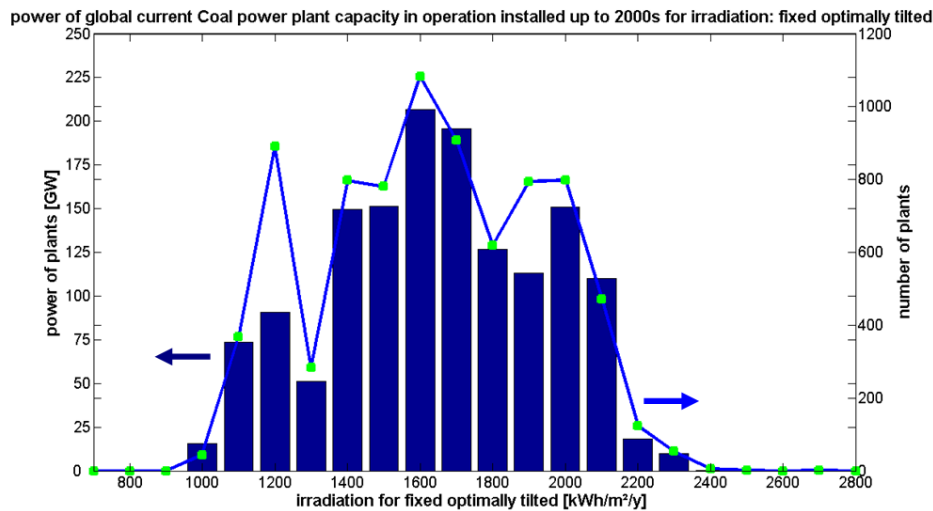


Figure 6.4-3: Global coal fired power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 6.4-2) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 6.4-4 and shows that most power plants are in the power class of 100 - 1000 MW representing about 89% of global coal power plant capacity.

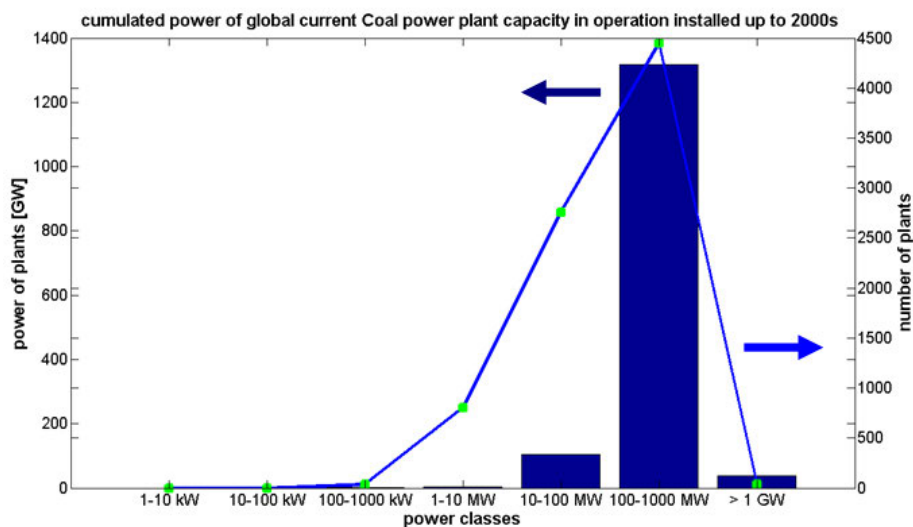


Figure 6.4-4: Global coal power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent power plant capacity. Data are taken from UDI World Electric Power Plants database ¹⁶⁵.

Contribution of coal power to global electricity supply is significant and accounts for about 41%. Global average total electricity generation per capita is about 3.0 MWh_{el} but 5 – 10 MWh_{el} in industrialised countries (sub-chapter 5.1). Leading coal electricity per capita

¹⁶⁵ Platts, UDI World Electric Power Plants data base, 2009

countries in the world are Australia and the US achieving 9.2 and 6.7 MWh_{el} per capita (Fig. 6.4-5). Several other countries reach a high level of coal power supply per capita, as well.

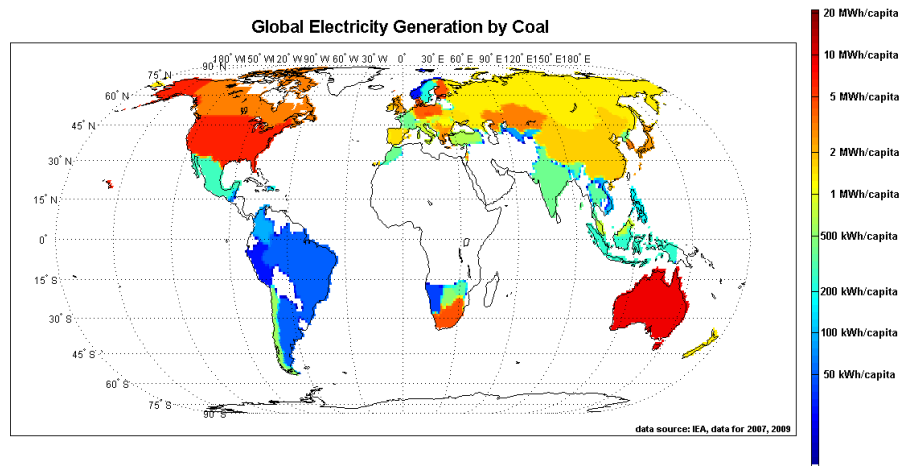


Figure 6.4-5: Global electricity generation by coal per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency¹⁶⁶ and United Nations¹⁶⁷.

Global installed coal power plant capacity per country is illustrated in Figure 6.4-6. Leading countries by cumulated coal power capacity are China, the US, India and Germany by end of 2008.

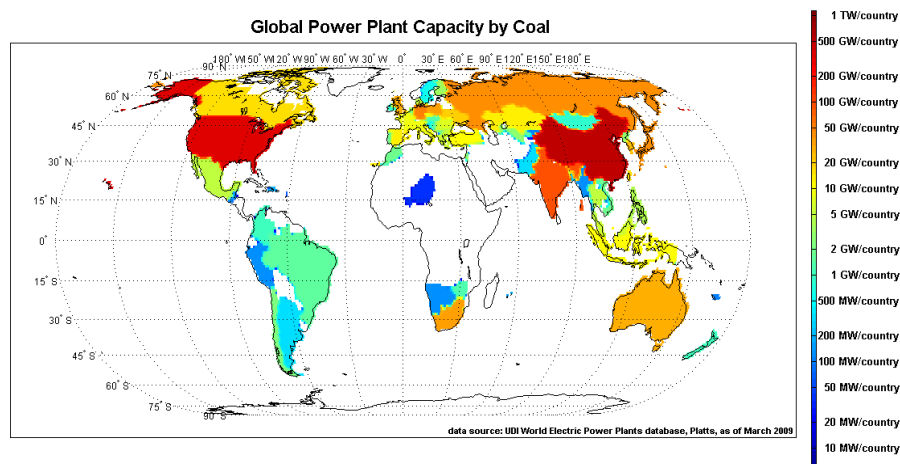


Figure 6.4-6: Global coal power plant capacity per country by early 2009. Only power plants in operation are regarded. Data are taken from UDI World Electric Power Plants database¹⁶⁸.

The structure of power plant capacity can be illustrated on a per country basis for average annual full load hours (Fig. 6.4-7) and relevance of respective domestic overall electricity generation (Fig. 6.4-8). Coal power plants are operated in two major modes, i.e. baseload and intermediate power supply. There are several countries in the world achieving a coal power supply contribution of more than 50% at a high absolute installed power capacity, e.g. China, the US, India, South Africa, Poland and Australia. Full load hours of coal power plants are dependent on the operation mode, whereas most coal power plants are operated between

¹⁶⁶ IEA, Key World Energy Statistics 2009, 2009

¹⁶⁷ UN, World Population Prospects: The 2008 Revision Highlights, 2009

¹⁶⁸ Platts, UDI World Electric Power Plants data base, 2009

3,000 – 7,000 full load hours. Combination of PV and coal power is a real option and is discussed later in this sub-chapter.

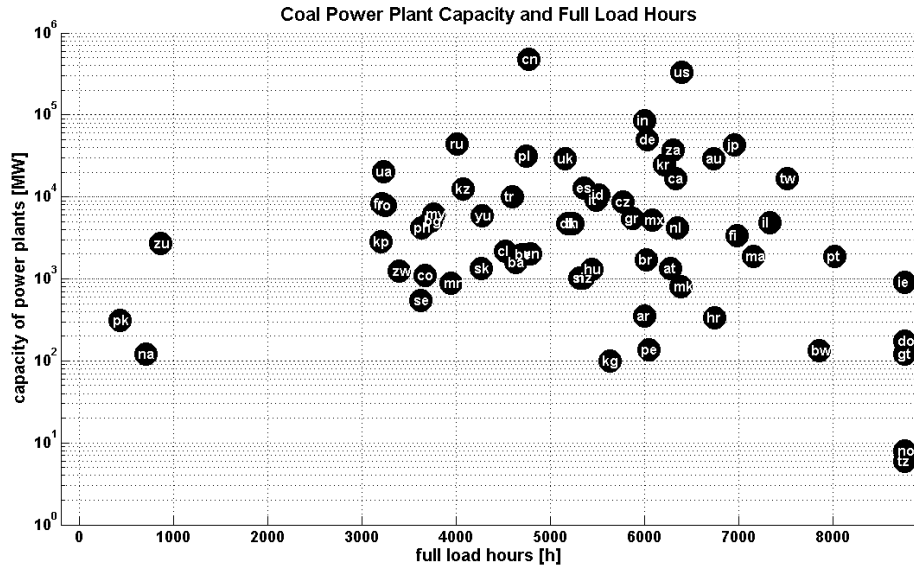


Figure 6.4-7: Coal power plant capacity in dependence on full load hours per country. Each dot represents the absolute coal power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database¹⁶⁹ and International Energy Agency¹⁷⁰.

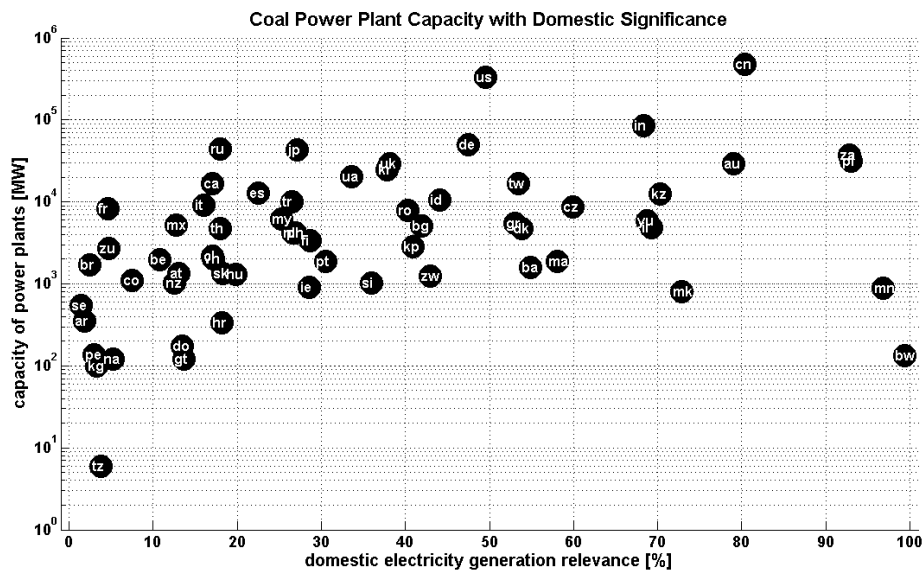


Figure 6.4-8: Coal power plant capacity in dependence on domestic electricity generation relevance per country. Each dot represents the absolute and relative coal power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database¹⁷¹ and International Energy Agency¹⁷².

Global distribution of full load hours and ratio to total domestic electricity generation is depicted in Figure 6.4-9 for visualising purposes. Identical information is given in Figures

¹⁶⁹ Platts, UDI World Electric Power Plants data base, 2009

¹⁷⁰ IEA, Key World Energy Statistics 2009, 2009

¹⁷¹ Platts, UDI World Electric Power Plants data base, 2009

¹⁷² IEA, Key World Energy Statistics 2009, 2009

6.4-7 and 6.4-8, but for subjective perception and for an analysis coordinate wise this kind of illustration is very helpful.

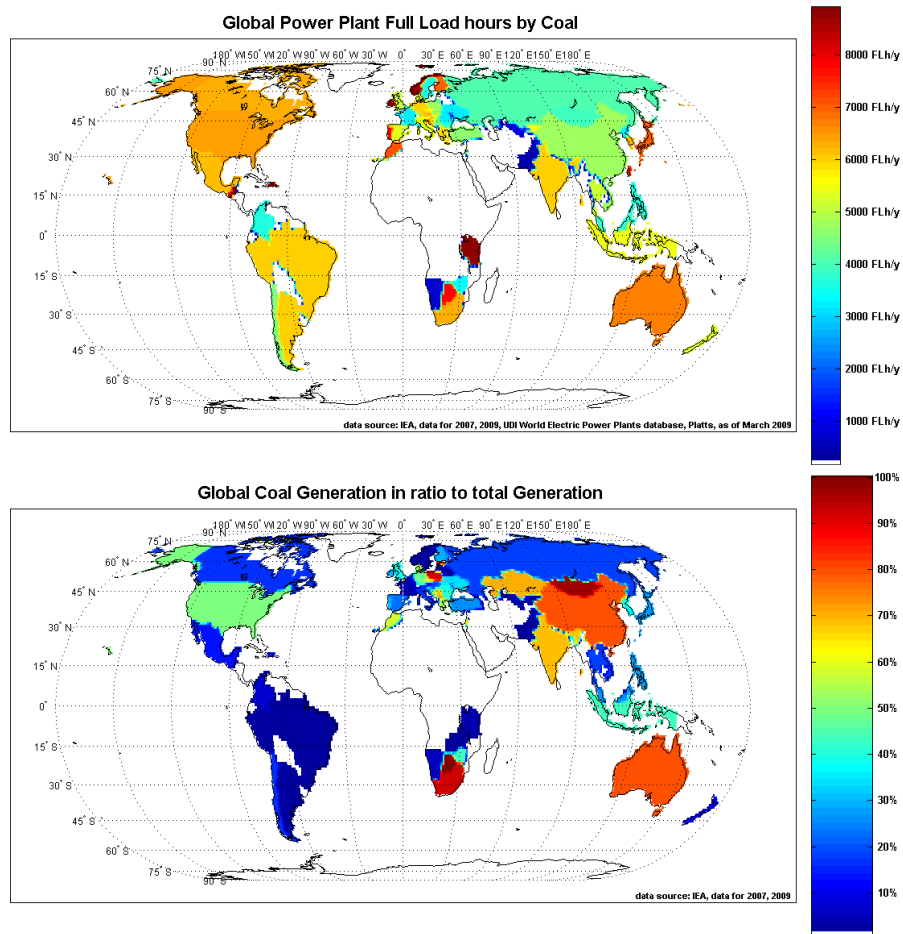


Figure 6.4-9: Global distribution of coal power plant full load hours (top) and the ratio to total domestic electricity generation (bottom). Data are taken from UDI World Electric Power Plants database ¹⁷³ and International Energy Agency ¹⁷⁴.

Summing up, global coal power plant capacity of 1,510 GW is in average 5,460 full load hours in operation and generate annually about 8,270 TWh of electricity, representing 32% of total global installed power capacity and 41% of global generated electricity. Coal power plants operated during daytime match in an excellent way to the feed-in profile of PV power plants and should be adaptable to the power profile of PV plants. In the following section, hybrid PV-Coal plants are discussed in more detail.

6.4.2 Coal Power Economics

A cost model for coal fired power plants enables the calculation of coal power levelized cost of electricity (LCOE) for all coordinates by applying average local full load hours (FLh) shown in Figure 6.4-9. These coal FLh contain all relevant data on local coal power plant operation patterns and can be used as an indicator for combining PV and coal power plants to a hybrid PV-Coal power plant. Besides typical capital expenditures (Capex) and operational expenditures (Opex) major current and future cost positions are expenditures for fuel and

¹⁷³ Platts, UDI World Electric Power Plants data base, 2009

¹⁷⁴ IEA, Key World Energy Statistics 2009, 2009

related carbon emissions. Both fuel and carbon emission expenditures are directly related to the power conversion efficiency of the coal power plant. Such derived coal LCOE make it possible to compare coal LCOE to LCOE of other renewable and conventional power plant technologies.

Methodology of calculating coal power LCOE is nearly identical to that of oil and gas power plants (Eqs. 6.2-1 and 6.3-1) and based on that of PV (section 3.2.1 and Eqs. 3.2-1). Adjustments are needed for specific differences of coal, gas and oil power plants, summarized in Equations 6.4-1:

$$LCOE = \frac{Capex \cdot crf + Opex_{fix}}{FLh_{coal,el}} + Opex_{var} + \frac{fuel_{coal}}{PE_{th,coal} \cdot \eta_{coal,el}} + \frac{carbon \cdot GHG_{coal}}{\eta_{coal,el}} \quad (\text{Eq. 6.4-1a})$$

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (\text{Eq. 6.4-1b})$$

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \quad (\text{Eq. 6.4-1c})$$

$$fuel_{coal} = fuel_{crudeoil} \cdot cf_{coal} \quad (\text{Eq. 6.4-1d})$$

$$fuel_{crudeoil} = fuel_{crudeoil,2010} \cdot (1 + r_{crudeoil})^{y-2010} \quad (\text{Eq. 6.4-1e})$$

$$\eta_{coal,el} = \eta_{coal,el,2010} + (y - 2010) \cdot r_{\eta,coal} \quad (\text{Eq. 6.4-1f})$$

$$carbon = carbon_{2010} \cdot (1 + r_{carbon})^{y-2010} \quad (\text{Eq. 6.4-1g})$$

Equation 6.4-1: Levelized cost of electricity (LCOE) for coal power plants. Abbreviations stand for: capital expenditures (*Capex*), annuity factor (*crf*), annual operation and maintenance expenditures (*Opex*), annual fixed Opex (*Opex_{fix}*), variable Opex (*Opex_{var}*), annual full load hours of coal power plants (*FLh_{coal,el}*), fuel cost for coal fired power plants (*fuel_{coal}*), thermal energy conversion factor (*PE_{th,coal}*), primary to electric energy conversion efficiency of coal fired power plants (*η_{coal,el}*), carbon emission cost (*carbon*), carbon emission intensity per thermal energy of coal fired power plants (*GHG_{coal}*), weighted average cost of capital (*WACC*), lifetime of coal power plants (*N*), equity (*E*), debt (*D*), return on equity (*k_E*), cost of debt (*k_D*), fuel cost of crude oil (*fuel_{crudeoil}*), fuel cost of crude oil in the year 2010 (*fuel_{crudeoil,2010}*), annual escalation rate of crude oil price (*r_{crudeoil}*), year (*y*), ratio of coal to crude oil price as coupling factor (*cf_{coal}*), primary to electric energy conversion efficiency of coal fired power plants in the year 2010 (*η_{coal,el,2010}*), annual increase of primary to electric energy conversion efficiency of coal fired power plants (*r_{η,coal}*), specific greenhouse gas emission cost (*carbon*), specific greenhouse gas emission cost in the year 2010 (*carbon₂₀₁₀*) and annual escalation rate of greenhouse gas emission cost (*r_{carbon}*).

The scenario assumptions for calculating LCOE of coal power plants are summarized in Table 6.4-1. Significant LCOE component of coal power plants are the fuel cost which are indirectly coupled to the crude oil price due to the specific thermal energy of coal (section 6.1.4) and its fluctuations and tendency for long-term escalation. Applied base case scenario assumes a moderate crude oil price of 80 USD/barrel. This core assumption might be too conservative, in particular due to a further assumed annual crude oil escalation rate of 3% in real terms. The price coupling of anthracite (hard) coal to crude oil is assumed to be 0.3 in the base case scenario according to the long-term trend. A separate low cost case is applied for analysing the impact potential of a lower price coupling, set in that case to 0.2.

Parameters	unit	scenario base case	scenario low cost case
Capex_Coal	[€/kW]	1,500	1,500
fin_RoE	[%]	10.0%	10.0%
fin_interest	[%]	6.0%	6.0%
fin_WACC	[%]	6.80%	6.80%
fin_equityRatio	[%]	20%	20%
exchange_rate	[USD/€]	1.40	1.40
plant_lifetime	[y]	40	40
plant_Opex_fix	[€/kW/y]	20	20
plant_Opex_var	[€/MWh _{el}]	1	1
plant_turbine_efficiency_2010	[%]	35%	35%
plant_turbine_efficiency_2020	[%]	45%	45%
plant_turbine_efficiency_increase	[%/y]	1.0%	1.0%
coupling_factor_coal-to-crude oil	[-]	0.30	0.20
fuel_price_crude oil_2010	[USD/barrel]	80.0	80.0
escalation_rate_crude oil_price	[%/y]	3%	3%
carbon_price_2010	[€/t _{CO2}]	0.0	0.0
escalation_rate_carbon_price	[%/y]	0%	0%
thermal energy conversion oil	[MWh _{th} /barrel]	1.68063	1.68063
thermal energy conversion coal	[MWh _{th} /t _{coal}]	8.214	8.214
greenhouse gas intensity coal	[t _{CO2} /MWh _{th}]	0.354	0.354

Table 6.4-1: Scenario assumptions for coal power plant economics. The base case scenario covers a business-as-usual approach, whereas the assumptions on the crude oil price and its escalation as the most relevant cost factor might be too conservative. Price coupling of coal to crude oil fluctuates over time and is reflected in the low cost case scenario. Numbers mentioned are for coal power plants of multi-100 MW. The methodology is identical to that of oil and gas power plants (Tables 6.2-1 and 6.3-1) comparable to that of PV, STEG and wind power LCOE calculation (Tables 3.2-1, 4.1-1 and 4.2-1). General parameters are set identical as far as possible or at least comparable, in particular for the financial parameters, although fossil WACC should be higher than that of renewable energy technologies due to a higher price risk profile (section 3.2.1) ¹⁷⁵. Abbreviations stand for: capital expenditures (Capex), return on equity (RoE), weighted average cost of capital (WACC), operational expenditures (Opex), annual fixed Opex (Opex_{fix}) and variable Opex (Opex_{var}). Data are taken from various sources like European Climate Foundation ¹⁷⁶, Greenpeace ¹⁷⁷, Pehnt et al. ¹⁷⁸, BMU ¹⁷⁹, IEA ^{180,181} and IPCC ¹⁸².

Coal power plant LCOE structure is illustrated in Figure 6.4-10 and is mainly driven by scenario assumptions of the base case definition for coal power plants (Table 6.4-1). Parameter settings are varied for crude oil price, greenhouse gas emission cost, energy conversion efficiency and full load hours. These scenario variations are compared to expected PV LCOE structure in 2010 and 2020 in sunny regions (based on Table 3.2-1).

¹⁷⁵ Awerbuch S., Portfolio-based electricity generation planning: policy implications for renewables and energy security, 2006

¹⁷⁶ ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

¹⁷⁷ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

¹⁷⁸ Pehnt M. et al., Das Steinkohle-Kraftwerk Hamburg Moorburg und seine Alternativen, 2007

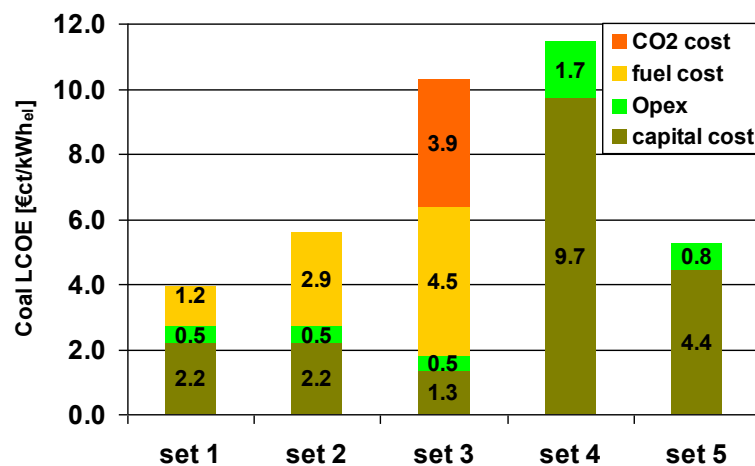
¹⁷⁹ BMU, Leitstudie 2010 – Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global, 2010

¹⁸⁰ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008

¹⁸¹ IEA, Projected Costs of Generating Electricity 2010 Edition, 2010

¹⁸² Bolin B. (ed.), Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3), 1996

Parameter setting of ‘set 2’ is representative for LCOE structure of coal power plants in late 2010. Total coal LCOE of 5.6 €/kWh are composed by capital cost of about 40% (2.2 €/kWh), Opex of about 10% (0.5 €/kWh) and fuel cost of 50% (2.9 €/kWh) based on a crude oil price of 80 USD/barrel and a price coupling of coal to crude oil of about 0.3. Such a cost structure is highly vulnerable to crude oil price fluctuations. Therefore, mid- to long-term price escalations are unfavourable for coal power plant economics. On the contrary, LCOE structure of PV power plants is dominated by capital cost being fixed by the investment decision and stable during the entire investment period. Moreover, low PV Opex enable excellent economics after the investment period for power plants being still in operation.



	Coal status	Coal opportunity cost	Coal potential opportunity cost	PV cost	PV cost
	today	today market based	mid-term	today	end 2010s
	set 1	set 2	set 3	set 4	set 5
full load hours [h/y]	5,000	5,000	5,000	1,725	1,800
efficiency [%]	35%	35%	45%	-	-
CO ₂ cost [€/t _{CO2}]	0	0	50	0	0
crude oil price [\$ /barrel]	10	80	160	0	0
Capex [€/kW]	1,500	1,500	1,500	2,000	1,000
Opex [€/kW/y]	20	20	20	30	15
lifetime [y]	40	40	40	25	30
WACC [%]	6.8%	6.8%	6.8%	6.8%	6.8%

Figure 6.4-10: LCOE structure of coal fired and PV power plants (top) based on major driving forces (bottom). Major variations for coal fired power plants are the crude oil price, the power conversion efficiency and greenhouse gas emission cost and for PV power plants the Capex. Coal mining cash cost in the major coal regions in the world is about 50 USD/t¹⁸³, which translates to 10 USD/barrel on thermal energy units on basis of a price coupling factor of 1 but to 33 and 50 USD/barrel on a price coupling factor of 0.3 and 0.2, respectively. Other parameters are set according to the base case scenario defined in Table 6.4-1.

Coal mining cash cost in major coal producing countries are equivalent to about 10 USD/barrel on basis of a price coupling factor of 1 (equivalent to 33 and 50 USD/barrel and a price coupling factor of 0.3 and 0.2, respectively), whereas the base case scenario is set to 80

¹⁸³ IEA, World Energy Outlook 2010, 2010, p. 213

USD/barrel and mid-term 160 USD/barrel. The world market coal prices represent the real current value of coal, i.e. in case of burning coal for less is identical to an energy subsidy and need to be accounted as opportunity cost, since it could be sold for the world market price. Greenhouse gas emissions, i.e. mainly CO₂, need to be priced for covering the enormous social cost of climate change (sub-chapter 1.2). Not charged CO₂ emissions are a subsidy due to social cost not covered by the electricity price.

Key indicator for combining PV and coal fired power plants to hybrid PV-Coal power plants are the full load hours (FLh) of coal power plants. 2,000 FLh of coal power plants are assumed to be a necessary threshold for beneficial hybridization. Typically, coal power plants are in operation 3,000 to 7,000 FLh (Fig. 6.4-7). Figure 6.4-11 illustrates the countries in the world operating coal power plants of in average at least 2,000 FLh per year.

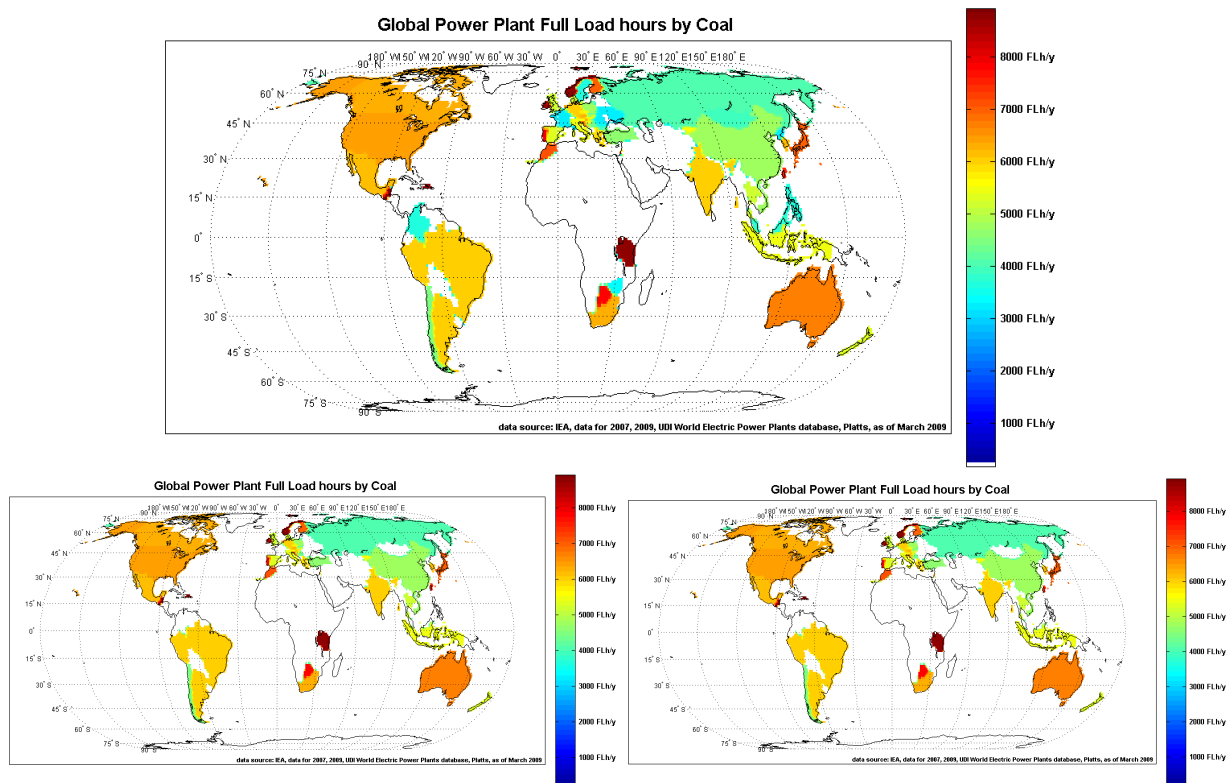


Figure 6.4-11: Global average coal power plant full load hours of at least 2,000 FLh (top), 3,000 FLh (bottom, left) and 4,000 FLh (bottom, right). Further visualization of coal power plant FLh can be found in Figure 6.4-7 and 6.4-9. Data are taken from UDI World Electric Power Plants database¹⁸⁴ and International Energy Agency¹⁸⁵.

Several countries in the world achieve a relative high contribution of coal power supply to overall electricity supply in combination with at least 2,000 FLh and based on significant power capacities, e.g. Canada, the US, Spain, UK, Germany, Poland, Ukraine, Turkey, Kazakhstan, Russia, China, India, Korea, Japan, Taiwan, Indonesia, Australia and South Africa (Fig. 5.1-13, 6.4-7, 6.4-8 and 6.4-11). In the following, only regions are considered in which coal power plants are characterized by in average at least 2,000 FLh per year.

Base case scenario assumptions summarized in Table 6.4-1 are used for assessing coal power plant economics. However, in the following a broader parameter variation is taken into account

¹⁸⁴ Platts, UDI World Electric Power Plants data base, 2009

¹⁸⁵ IEA, Key World Energy Statistics 2009, 2009

for a better understanding of the range of coal LCOE. Precondition for all variations is a minimum average level of 2,000 FLh. Calculations are based on crude oil prices of 45, 80, 120 and 160 USD/barrel, respectively, and a coal to crude oil price coupling of 0.3. With all these price regimes a variation in power plant energy conversion efficiency is applied for values of 35%, 40% and 45%, respectively. Moreover, CO₂ emission cost are taken into account for the range of 0, 30 and 50 €/tCO₂, respectively. Within one crude oil price domain the least LCOE are achieved for highest efficiency (45%) and lowest carbon emission cost (0 €/tCO₂) and the highest LCOE are reached for lowest efficiency (35%) and highest carbon emission cost (50 €/tCO₂). The crude oil price level has the highest impact on LCOE, therefore variations in efficiency and carbon emission cost can be considered as first order effects on the LCOE. Assumed parameter range for the power conversion efficiency is optimistic, since global average of coal power plant energy conversion efficiency is 31%, based on a fuel consumption of 26,720 MWh_{th} (2,170 Mtoe) and resulting 8,270 TWh_{el} feed-in the grid.¹⁸⁶ Greenhouse gas emission cost of 0 €/tCO₂ assumes a failure in global climate change diplomacy, which is possible but would result in a collapse of our global human society (sub-chapter 1.2), and cost of 50 €/tCO₂ is still below social cost of 70 €/tCO₂ or even more. Thus both power plant efficiency and carbon emission cost are optimistic and real cost might be significantly higher in the years to come. Crude oil price assumptions of 45 to 160 USD/barrel might be too optimistic, as well. Price spiked in 2008 on 147 USD/barrel and might reach a long-term level of 200 USD/barrel for an oil and natural gas constraint potentially near future (sub-chapter 1.3 and section 6.1.4).

Coal LCOE for a crude oil price of 45, 80, 120 and 160 USD/barrel are shown in Figures 6.4-12 to 6.3-15. Each oil price level is further differentiated by efficiency and carbon emission price for the cases of efficiency and carbon emission price of 45% and 0 €/tCO₂, 40% and 0 €/tCO₂, 40% and 30 €/tCO₂ and 35% and 50 €/tCO₂. The parameter variation results in a coal LCOE range for each crude oil price level and takes into account the local average FLh.

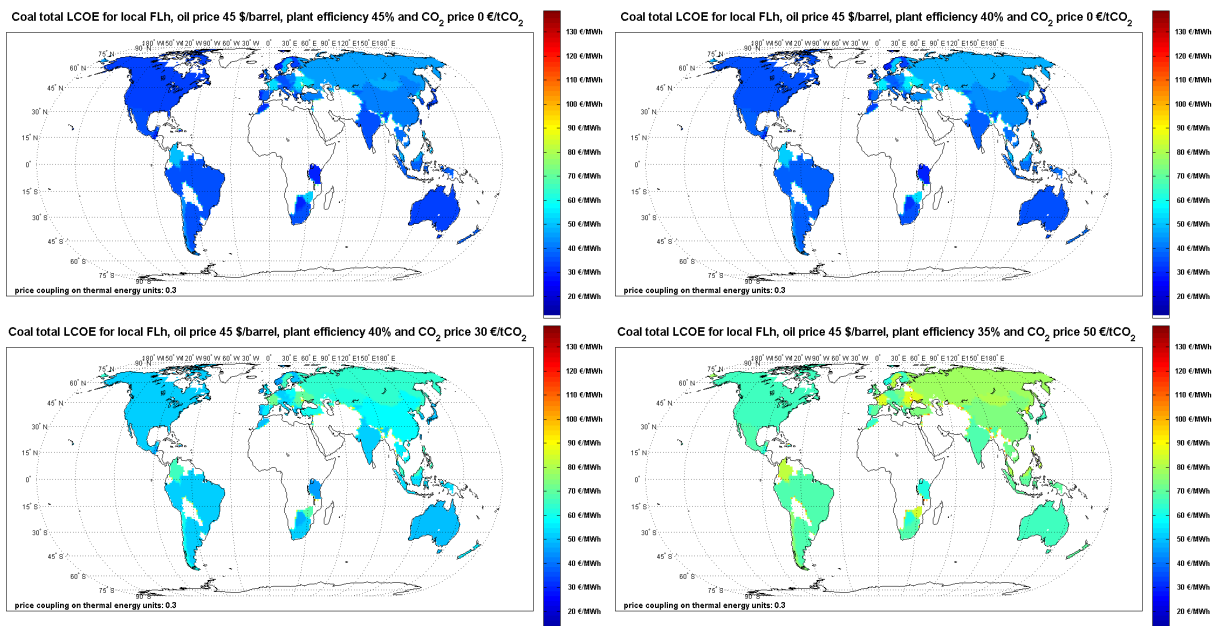


Figure 6.4-12: Coal LCOE for local FLh based on a crude oil level of 45 USD/barrel, coal to crude oil price coupling of 0.3, variations on coal power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 45% and 0 €/tCO₂ (top, left), 40% and 0 €/tCO₂ (top, right), 40% and 30 €/tCO₂ (bottom, left) and 35% and 50 €/tCO₂ (bottom, right). Coal LCOE model is defined in Equations 6.4-1 and remaining parameters are according to the base case assumptions of Table 6.4-1.

¹⁸⁶ IEA, World Energy Outlook 2010, 2010

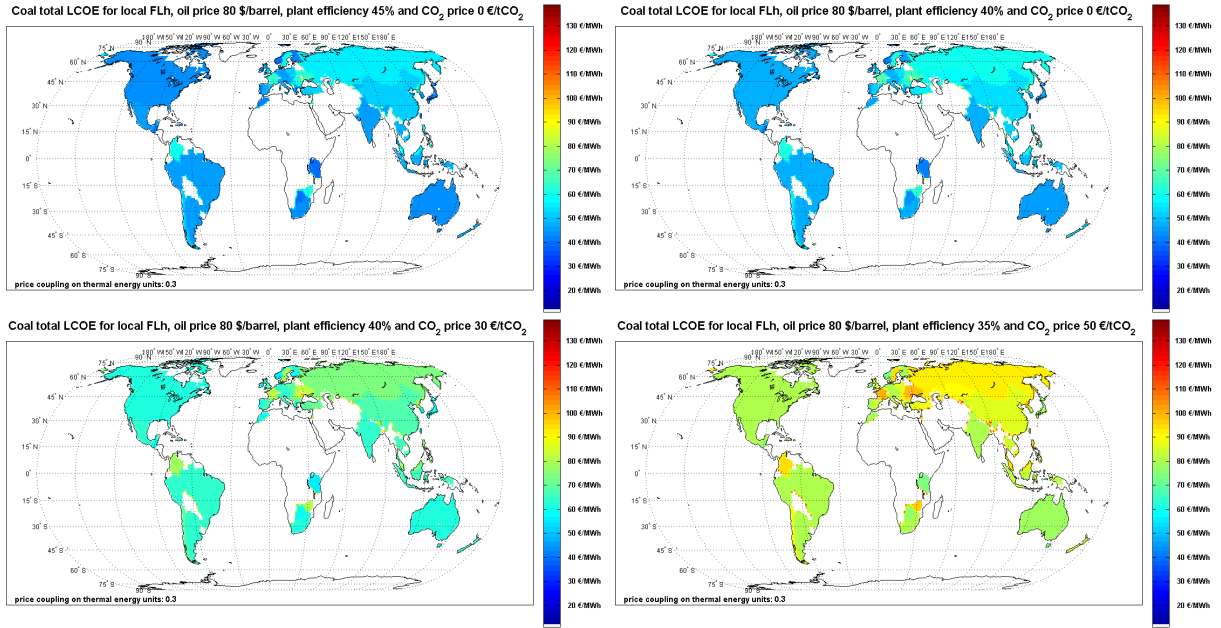


Figure 6.4-13: Coal LCOE for local FLh based on a crude oil level of 80 USD/barrel, coal to crude oil price coupling of 0.3, variations on coal power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 45% and 0 €/tCO₂ (top, left), 40% and 0 €/tCO₂ (top, right), 40% and 30 €/tCO₂ (bottom, left) and 35% and 50 €/tCO₂ (bottom, right). Coal LCOE model is defined in Equations 6.4-1 and remaining parameters are according to the base case assumptions of Table 6.4-1.

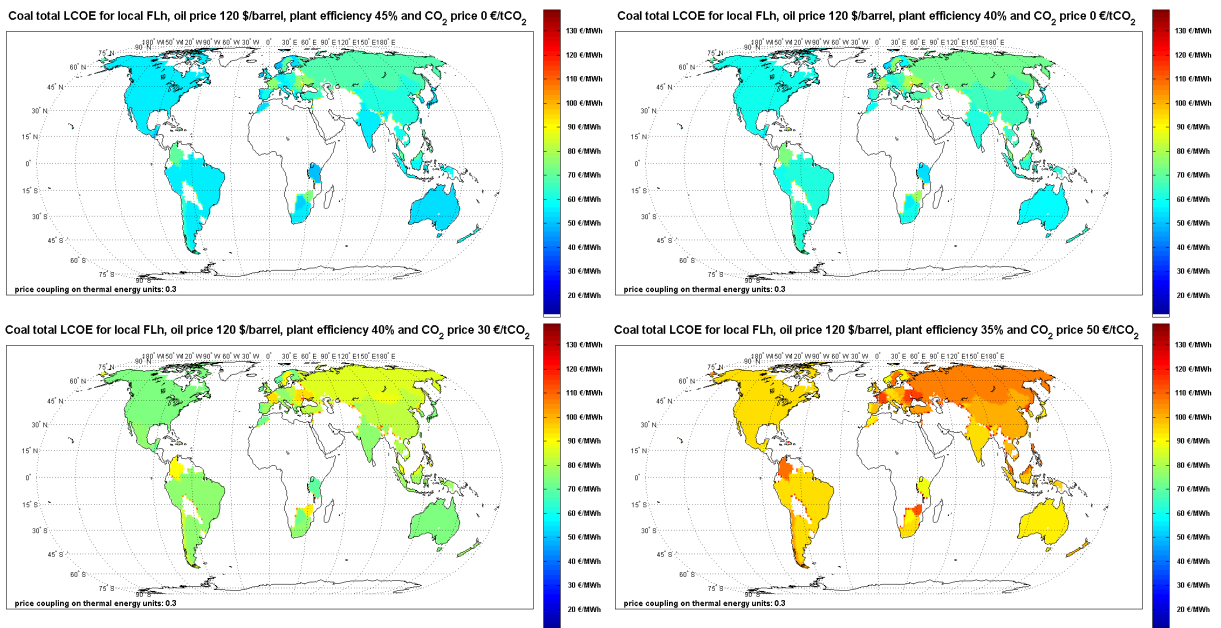


Figure 6.4-14: Coal LCOE for local FLh based on a crude oil level of 120 USD/barrel, coal to crude oil price coupling of 0.3, variations on coal power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 45% and 0 €/tCO₂ (top, left), 40% and 0 €/tCO₂ (top, right), 40% and 30 €/tCO₂ (bottom, left) and 35% and 50 €/tCO₂ (bottom, right). Coal LCOE model is defined in Equations 6.4-1 and remaining parameters are according to the base case assumptions of Table 6.4-1.

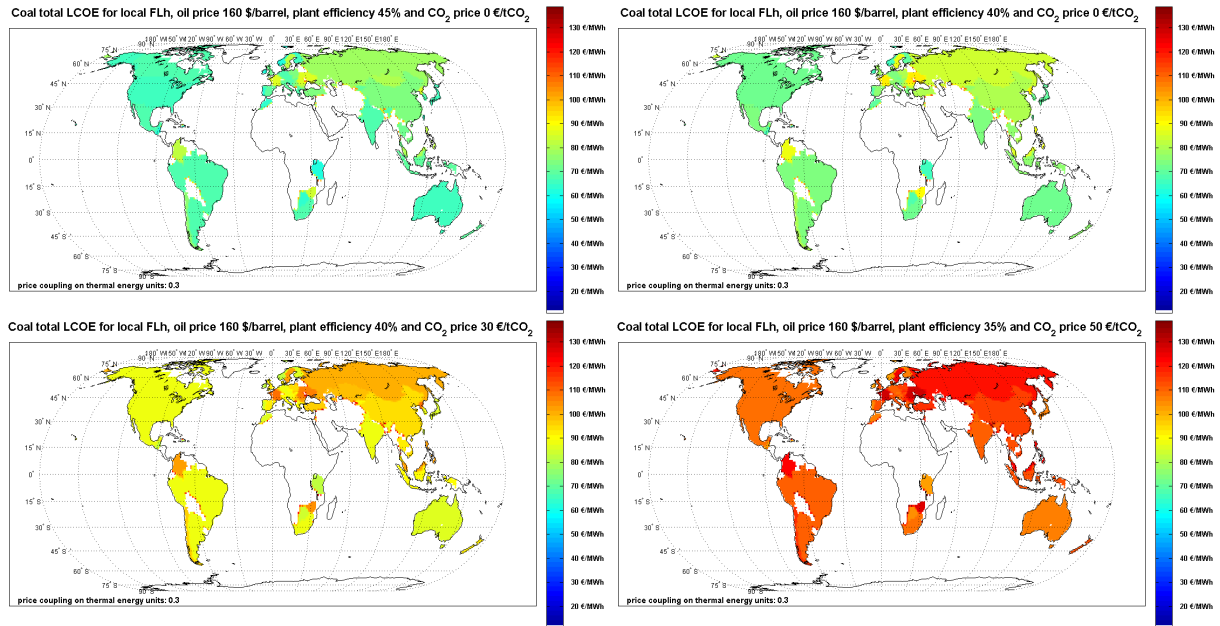


Figure 6.4-15: Coal LCOE for local FLh based on a crude oil level of 160 USD/barrel, coal to crude oil price coupling of 0.3, variations on coal power plant efficiency and carbon emission cost. Efficiency and carbon emission price are set to 45% and 0 €/t_{CO2} (top, left), 40% and 0 €/t_{CO2} (top, right), 40% and 30 €/t_{CO2} (bottom, left) and 35% and 50 €/t_{CO2} (bottom, right). Coal LCOE model is defined in Equations. 6.4-1 and remaining parameters are according to the base case assumptions of Table 6.4-1.

Efficiency/ CO ₂ price for 6,000 and 3,000 FLh coal to oil coupling 0.3	crude oil price				
	45 USD/bl [€/MWh _{el}]	80 USD/bl [€/MWh _{el}]	120 USD/bl [€/MWh _{el}]	160 USD/bl [€/MWh _{el}]	200 USD/bl [€/MWh _{el}]
35%/ 0 €/t _{CO2}	39.0 – 60.7	51.8 – 73.4	66.4 – 88.0	80.9 – 102.6	95.5 – 117.2
35%/ 30 €/t _{CO2}	69.4 – 91.0	82.1 – 103.8	96.7 – 118.4	111.3 – 132.9	125.9 – 147.5
35%/ 50 €/t _{CO2}	89.6 – 111.3	102.4 – 124.0	116.9 – 138.6	131.5 – 153.2	146.1 – 167.7
35%/ 70 €/t _{CO2}	109.8 – 131.5	122.6 – 144.2	137.2 – 158.8	151.7 – 173.4	166.3 – 188.0
40%/ 0 €/t _{CO2}	37.0 – 58.6	48.2 – 69.8	60.9 – 82.8	73.7 – 95.3	86.4 – 108.1
40%/ 30 €/t _{CO2}	63.5 – 85.2	74.7 – 96.4	87.5 – 109.1	100.2 – 121.9	113.0 – 134.6
40%/ 50 €/t _{CO2}	81.2 – 102.9	92.4 – 114.1	105.2 – 126.8	117.9 – 139.6	130.7 – 152.3
40%/ 70 €/t _{CO2}	98.9 – 120.6	110.1 – 131.8	122.9 – 144.5	135.6 – 157.3	148.4 – 170.0
45%/ 0 €/t _{CO2}	35.4 – 57.1	45.3 – 67.0	56.7 – 78.3	68.0 – 89.6	79.3 – 101.0
45%/ 30 €/t _{CO2}	59.0 – 80.7	68.9 – 90.6	80.3 – 101.9	91.6 – 113.2	102.9 – 124.6
45%/ 50 €/t _{CO2}	74.7 – 96.4	84.7 – 106.3	96.0 – 117.6	107.3 – 129.0	118.7 – 140.3
45%/ 70 €/t _{CO2}	90.5 – 112.1	100.4 – 122.0	111.7 – 133.4	123.1 – 144.7	134.4 – 156.0

Table 6.4-2: Coal LCOE for 3,000 to 6,000 FLh, power plant conversion efficiencies of 35%, 40% and 45%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, coal to crude oil price coupling of 0.3 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}. Coal LCOE model is defined in Equations 6.4-1 and remaining parameters are according to the base case assumptions of Table 6.4-1. Hard coal prices being equivalent to crude oil prices of 45, 80, 120, 160 and 200 USD/barrel are 66, 117, 176, 235 and 293 USD/t_{HardCoal}, respectively, based on a coal to crude oil price coupling of 0.3 on thermal energy units, whereas 66 USD/t_{HardCoal} is slightly above the least cost global coal mining cash cost of about 50 USD/t_{HardCoal}¹⁸⁷, i.e. hardly available on the world market.

¹⁸⁷ IEA, World Energy Outlook 2010, 2010, p. 213

Efficiency/ CO ₂ price for 6,000 and 3,000 FLh coal to oil coupling 0.2	crude oil price				
	45 USD/bl	80 USD/bl	120 USD/bl	160 USD/bl	200 USD/bl
	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]	[€/MWh _{el}]
35%/ 0 €/t _{CO2}	33.6 – 55.2	42.1 – 63.7	51.8 – 73.4	61.5 – 83.2	71.2 – 92.9
35%/ 30 €/t _{CO2}	63.9 – 85.6	72.4 – 94.1	82.1 – 103.8	91.9 – 113.5	101.6 – 123.2
35%/ 50 €/t _{CO2}	84.2 – 105.8	92.7 – 114.3	102.4 – 124.0	112.1 – 133.7	121.8 – 143.4
35%/ 70 €/t _{CO2}	104.4 – 126.0	112.9 – 134.5	122.6 – 144.2	132.3 – 154.0	142.0 – 163.7
40%/ 0 €/t _{CO2}	32.2 – 53.9	39.7 – 61.3	48.2 – 69.8	56.7 – 78.3	65.2 – 86.8
40%/ 30 €/t _{CO2}	58.8 – 80.4	66.2 – 87.9	74.7 – 96.4	83.2 – 104.9	91.7 – 113.4
40%/ 50 €/t _{CO2}	76.5 – 98.1	83.9 – 105.6	92.4 – 114.1	100.9 – 122.6	109.4 – 131.1
40%/ 70 €/t _{CO2}	94.2 – 115.8	101.6 – 123.3	110.1 – 131.8	118.6 – 140.3	127.1 – 148.8
45%/ 0 €/t _{CO2}	31.2 – 52.8	37.8 – 59.4	45.3 – 67.0	52.9 – 74.5	60.4 – 82.1
45%/ 30 €/t _{CO2}	54.8 – 76.4	61.4 – 83.0	68.9 – 90.6	76.5 – 98.1	84.0 – 105.7
45%/ 50 €/t _{CO2}	70.5 – 92.1	77.1 – 98.7	84.7 – 106.3	92.2 – 113.9	99.8 – 121.4
45%/ 70 €/t _{CO2}	86.2 – 107.9	92.8 – 114.5	100.4 – 122.0	107.9 – 129.6	115.5 – 137.1

Table 6.4-3: Coal LCOE for 3,000 to 6,000 FLh, power plant conversion efficiencies of 35%, 40% and 45%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, coal to crude oil price coupling of 0.2 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}. Coal LCOE model is defined in Equations 6.4-1 and remaining parameters are according to the base case assumptions of Table 6.4-1. Hard coal prices being equivalent to crude oil prices of 45, 80, 120, 160 and 200 USD/barrel are 44, 78, 117, 156 and 196 USD/t_{HardCoal}, respectively, based on a coal to crude oil price coupling of 0.2 on thermal energy units, whereas 44 USD/t_{HardCoal}¹⁸⁸ is below the least cost global coal mining cash cost of about 50 USD/t_{HardCoal}¹⁸⁸, i.e. not available on the world market.

Depending on efficiency, carbon emission cost and FLh, the coal LCOE of a crude oil price of 45 USD/barrel and a price coupling of 0.3 range between 35 and 132 €/MWh and for a price coupling of 0.2 the span is about 11% - 5% lower between 31 and 126 €/MWh (Fig. 6.4-12 and Tables 6.4-2 and 6.4-3). Low efficient coal power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 39 to 61 €/MWh (34 to 55 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000. Highly efficient coal power plants of 45% conversion efficiency and no CO₂ cost show LCOE of 35 to 57 €/MWh (31 to 53 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000.

Coal LCOE of a crude oil price of 80 USD/barrel and a price coupling of 0.3 range between 45 and 144 €/MWh and for a price coupling of 0.2 the span is about 16% - 7% lower between 38 and 135 €/MWh (Fig. 6.4-13 and Tables 6.4-2 and 6.4-3). Low efficient coal power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 52 to 73 €/MWh (42 to 64 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000. Highly efficient coal power plants of 45% conversion efficiency and no CO₂ cost show LCOE of 45 to 67 €/MWh (38 to 59 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000.

Coal LCOE of a crude oil price of 120 USD/barrel and a price coupling of 0.3 range between 57 and 159 €/MWh and for a price coupling of 0.2 the span is about 21% - 9% lower between 45 and 144 €/MWh (Fig. 6.4-14 and Tables 6.4-2 and 6.4-3). Low efficient coal power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 66 to 88 €/MWh (52 to 73 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000. Highly efficient coal power plants of 45% conversion efficiency and no CO₂ cost show LCOE of 57 to 78 €/MWh (45 to 67 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000.

Coal LCOE of a crude oil price of 160 USD/barrel and a price coupling of 0.3 range between 68 and 173 €/MWh and for a price coupling of 0.2 the span is about 22% - 11% lower between 53 and 154 €/MWh (Fig. 6.4-15 and Tables 6.4-2 and 6.4-3). Low efficient coal

¹⁸⁸ IEA, World Energy Outlook 2010, 2010, p. 213

power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 81 to 103 €/MWh (62 to 83 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000. Highly efficient coal power plants of 45% conversion efficiency and no CO₂ cost show LCOE of 68 to 90 €/MWh (53 to 75 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000.

Coal LCOE of a crude oil price of 200 USD/barrel and a price coupling of 0.3 range between 79 and 188 €/MWh and for a price coupling of 0.2 the span is about 24% - 13% lower between 60 and 164 €/MWh (Tables 6.4-2 and 6.4-3). Low efficient coal power plants of 35% conversion efficiency and no CO₂ cost show LCOE of 96 to 117 €/MWh (71 to 93 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000. Highly efficient coal power plants of 45% conversion efficiency and no CO₂ cost show LCOE of 79 to 101 €/MWh (60 to 82 €/MWh for a price coupling of 0.2) for FLh between 6,000 to 3,000.

In the year 2010 PV LCOE in sunny regions are about 100 to 120 €/MWh depending on location and assumptions (Fig. 6.4-10 and 3.2-16). Therefore, PV power plants are lower in cost than low efficient coal power plants at crude oil prices of about 200 USD/barrel, a price coupling of 0.3 and no CO₂ emission cost. In near future, i.e. in mid of 2010s, in sunny regions PV power plants become competitive to coal power plants at prices of 120 to 160 USD/barrel or more. Consequently, in sunny regions coal power plants become a good component for hybrid PV-Coal power plants due to drastically improved economics by upgrading existing coal power plants with PV power plants.

6.4.3 Hybrid PV-Coal Power Plant Demand Curve

In the following scenario assumptions are taken into account for coal power plants (Table 6.4-1) and for fixed optimally tilted PV power plants (Table 3.2-1). Coal power plant base case assumes a crude oil price of 80 USD/barrel, a hard (anthracite) coal to crude oil price coupling of 0.3 and an annual escalation rate of 3% in real terms. Coal LCOE projection in the 2010s is depicted in Figure 6.4-16.

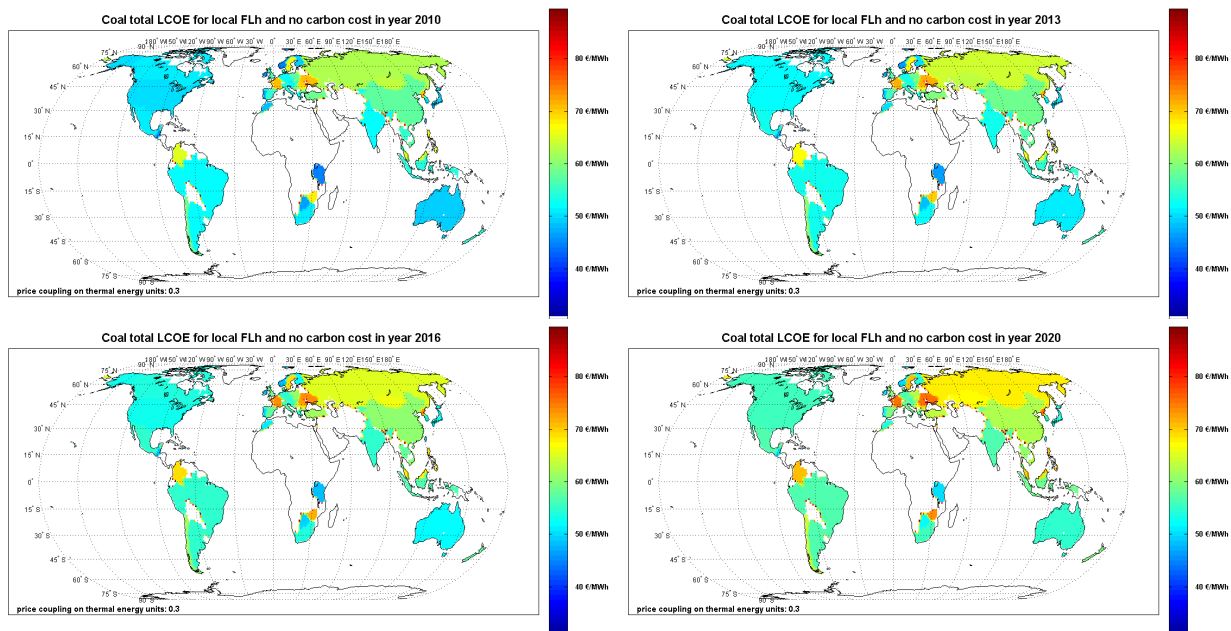


Figure 6.4-16: Coal LCOE for local FLh in the 2010s for the base case scenario. Base case scenario is defined in Table 6.4-1. Countries operating coal power plants in average of at least 2,000 FLh are included in the analysis.

The hybridization of PV and coal fired power plants is slightly less simple than in the case of oil and gas fired power plants (section 6.1.2). In many countries hard coal power plants are started-up and shut down once a day as a consequence of intermediate load operation, thus these power plants should be able for hybridization. This might be not the case for lignite fired baseload power plants. However, the recently developed integrated gasification combined cycle (IGCC) power plant can be fuelled with any type of fossil fuel and can be also operated in a very flexible way, hence also as a hybrid PV-IGCC power plant based on any type of coal firing (section 6.1.2).

Upgrading existing coal power plants by PV power plants to hybrid PV-Coal power plants is economically favourable for PV LCOE lower than coal LCOE. The precise calculation needs to include moderately higher capital cost of coal power plants by reducing their FLh in order of the PV FLh. This effect can be calculated by Equation 6.4-1a and has to be generated additionally by the PV component, i.e. lower PV LCOE, of the hybrid PV-Coal power plant. All breakeven, i.e. parity, analyses in this sub-chapter take this effect into account. The year of PV and coal power plant parity is illustrated in Figures 6.4-17 and 6.4-18.

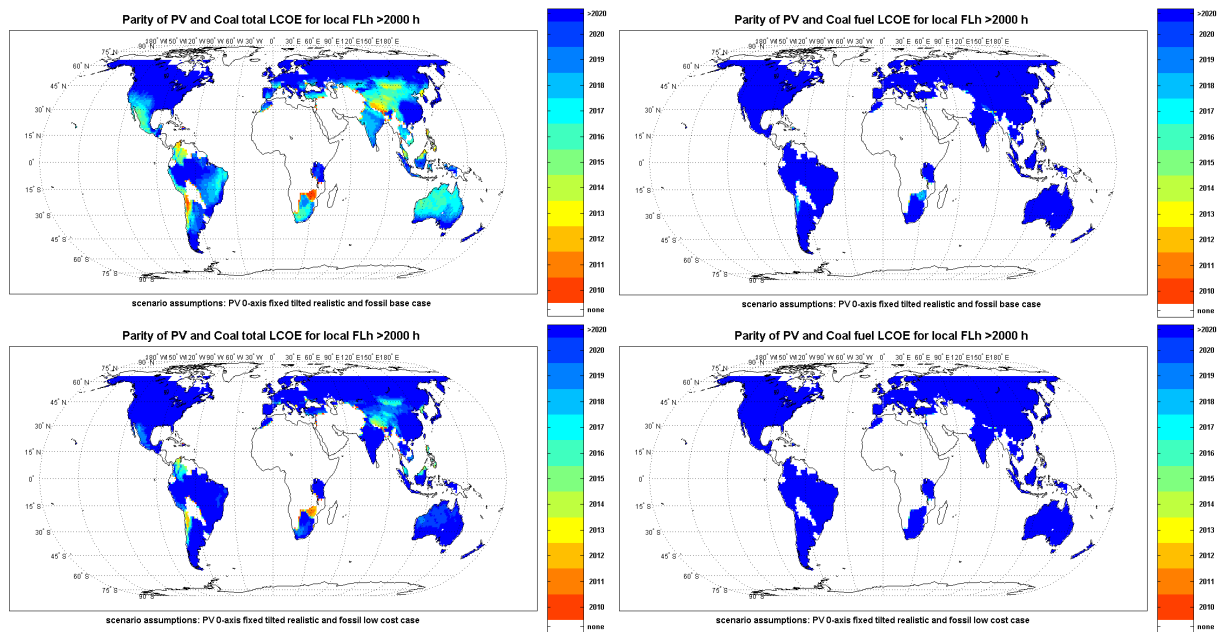
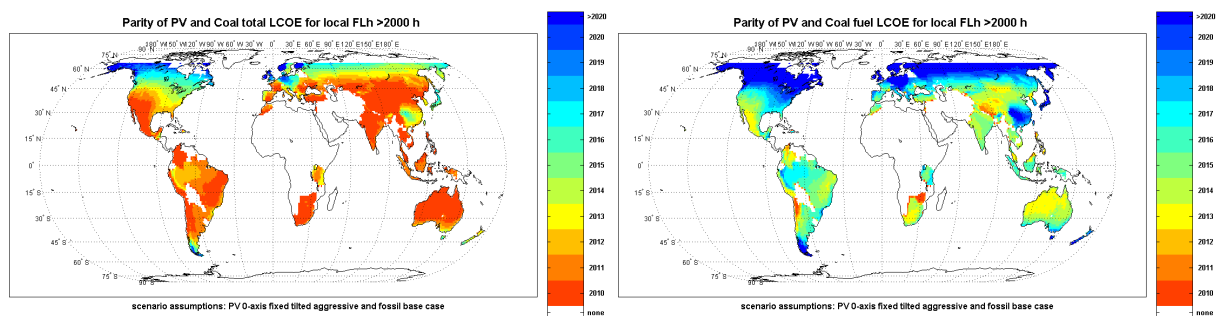


Figure 6.4-17: Parity of fixed optimally tilted PV and coal power plants for total plant LCOE (left) and fuel-only LCOE (right) for PV realistic and coal base case (top) and low cost (bottom) scenario assumptions. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.4-1 and Figure 6.4-16 (coal). Countries operating coal power plants in average of at least 2,000 FLh are included in the analysis.



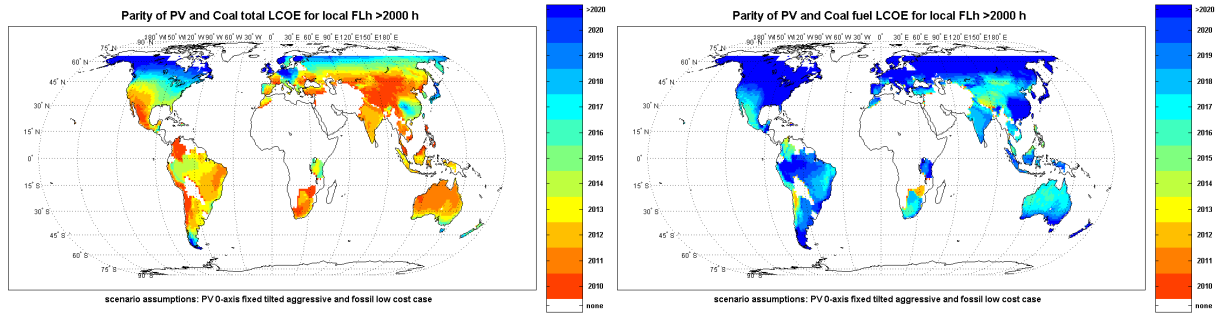


Figure 6.4-18: Parity of fixed optimally tilted PV and coal power plants for total plant LCOE (left) and fuel-only LCOE (right) for PV aggressive and coal base case (top) and low cost (bottom) scenario assumptions. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.4-1 and Figure 6.4-16 (coal). Countries operating coal power plants in average of at least 2,000 FLh are included in the analysis.

Only in very sunny regions in the world, PV power plants are lower in LCOE than coal power plants on total plant basis and for realistic scenario (PV) and base case (coal) conditions in the second half of the 2010s (Fig. 6.4-17). PV LCOE compared to fuel-only LCOE of coal fired power plants begin their breakeven after the year 2020 even in the very sunny regions, however the adequate economic reference is the total plant basis and the fuel-only level is the economically strictest reference. Consequence of lower hard coal prices, i.e. looser price coupling to crude oil, would be a delayed economic breakthrough of hybrid PV-Coal power plants. PV LCOE start to be lower than those of coal power plants on a total plant basis in the very sunny regions in the world in the very end of the 2010s. For the aggressive case nearly all relevant regions in the world show lower PV LCOE than coal LCOE in the first half of the 2010s on total plant basis and even for the fuel-only LCOE restriction in at least sunny regions (Fig. 6.4-18) for the fossil base case conditions. As discussed in sub-chapter 3.2, true PV cost might be between the realistic and aggressive scenario assumptions. Consequently, PV power plants are already competitive to coal power plants in the at least sunny regions in the world at a crude oil price level of 80 USD/barrel.

Financial benefits are depicted in Figure 6.4-19 and 6.4-20 for the most competitive conditions of PV LCOE versus fuel-only coal LCOE.

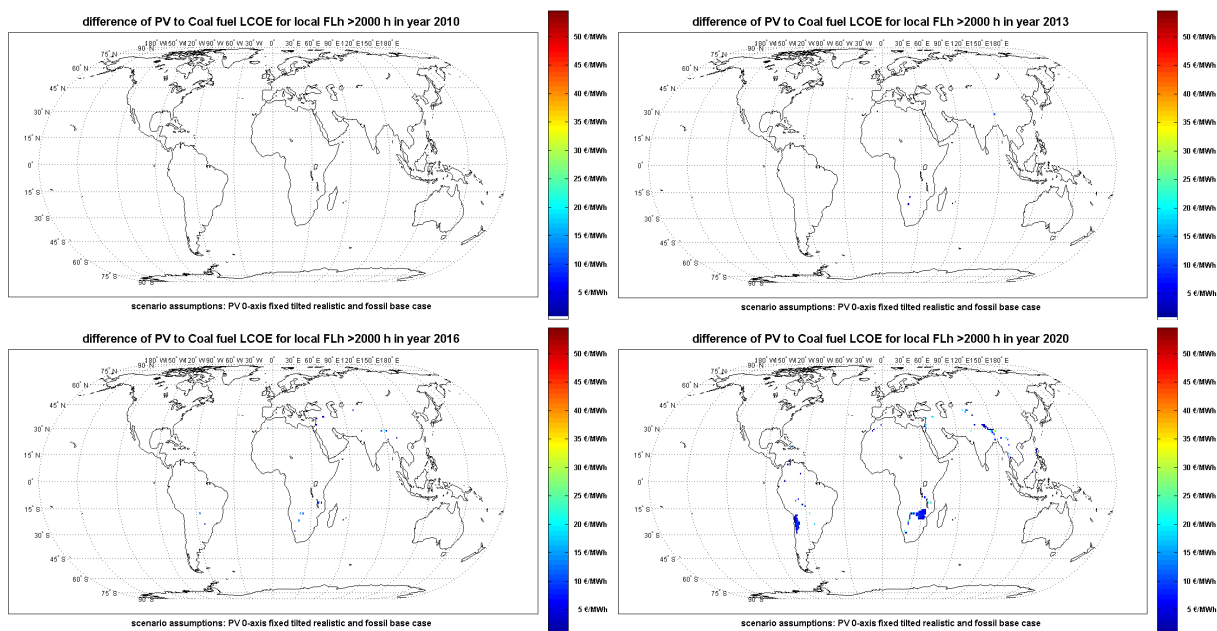


Figure 6.4-19: PV LCOE benefit in comparison to fuel-only coal LCOE for fixed optimally tilted PV realistic and coal base case scenario assumptions in the 2010s. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.4-1 and Figure 6.4-16 (coal). Countries operating coal power plants in average of at least 2,000 FLh are included in the analysis.

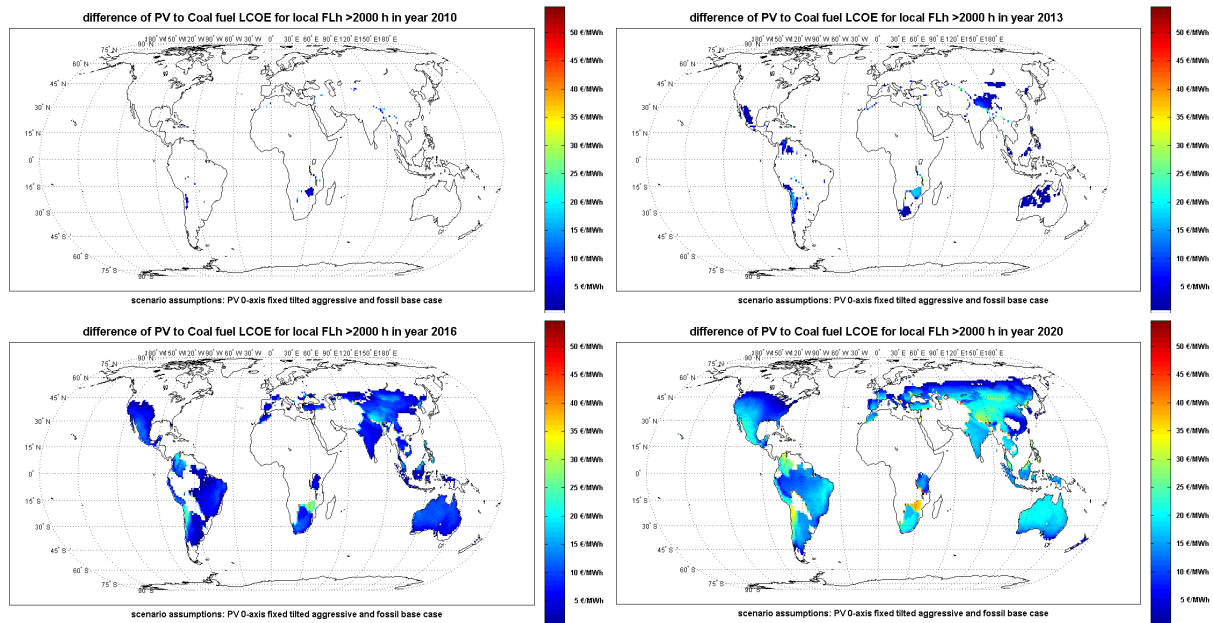


Figure 6.4-20: PV LCOE benefit in comparison to fuel-only coal LCOE for fixed optimally tilted PV aggressive and coal base case scenario assumptions in the 2010s. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.4-1 and Figure 6.4-16 (coal). Countries operating coal power plants in average of at least 2,000 FLh are included in the analysis.

The LCOE advantage of PV power plants in respect to those of coal power plants in the economically strictest case of fuel-only LCOE reveals the fast growing competitiveness of PV versus coal power plants. However, aggressive PV scenario is needed to generate financial benefits on the aforementioned LCOE basis in the second half of the 2010s in at least sunny regions. Nevertheless, in general competitiveness of PV versus coal power plants is evident on basis of total plant LCOE (Fig. 6.4-17 and 6.4-18). For realistic (PV) and base case (coal) scenario assumptions PV LOCE are not lower than fuel-only coal LCOE in the entire decade of the 2010s, although this becomes the case in 2010 for total plant LCOE (Fig. 6.4-19 and 6.4-17). For aggressive (PV) and base case (coal) scenario assumptions PV LOCE are lower than fuel-only coal LCOE by about 0 €/MWh (2010), 5 €/MWh (2013), 10 €/MWh (2016) and 20 €/MWh (2020) in very sunny regions (Fig. 6.4-20). These results are based on a crude oil price of 80 USD/barrel in 2010 and an escalation rate of 3%, i.e. 107 USD/barrel in 2020. In case of faster crude oil escalation the benefits of PV power plants are significantly higher.

Based on fuel-parity analyses of PV versus coal power plants (Fig. 6.4-17 and 6.4-18) a global hybrid PV-Coal power plant demand curve can be derived. Regions of coal power plants operated less than 2,000 FLh are excluded from the analysis, this is the case for only a negligible capacity of about 14 GW of the total of about 1,470 GW coal power capacity (Table 5.1-1). Moreover, coal power plants firing coal of lower quality not internationally tradable have been excluded. Lignite and subbituminous coal are not transported over significant distances due to the low primary energy content of about 16 to 25 MJ/kg being significantly below anthracite coal of about 36 MJ/kg.¹⁸⁹ Core assumption of this analysis is that substituted fossil fuels can be sold on the world market, which is not the case for not

¹⁸⁹ Kohlenwirtschaft, Internationale Klassifikation der Kohle, 2010

tradable low quality coal, hence the respective power plant capacity of about 310 GW has been excluded from the demand curve calculations. All coal power plants in the world are available by their georeferenced coordinates (Fig. 6.4-2) enabling a direct comparison of PV LCOE at the respective site. For each coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude the year of PV LCOE (plus higher coal capital cost due to reduced FLh) lower than total and fuel-only coal LCOE is recorded. All the coordinates are aggregated afterwards to the country of their location. Global hybrid PV-Coal power plant demand curves for PV realistic and aggressive and coal base case scenario assumptions are plotted in Figures 6.4-21 and 6.4-22 and respective coal low cost scenario assumptions are summarized in Figure 6.4-23.

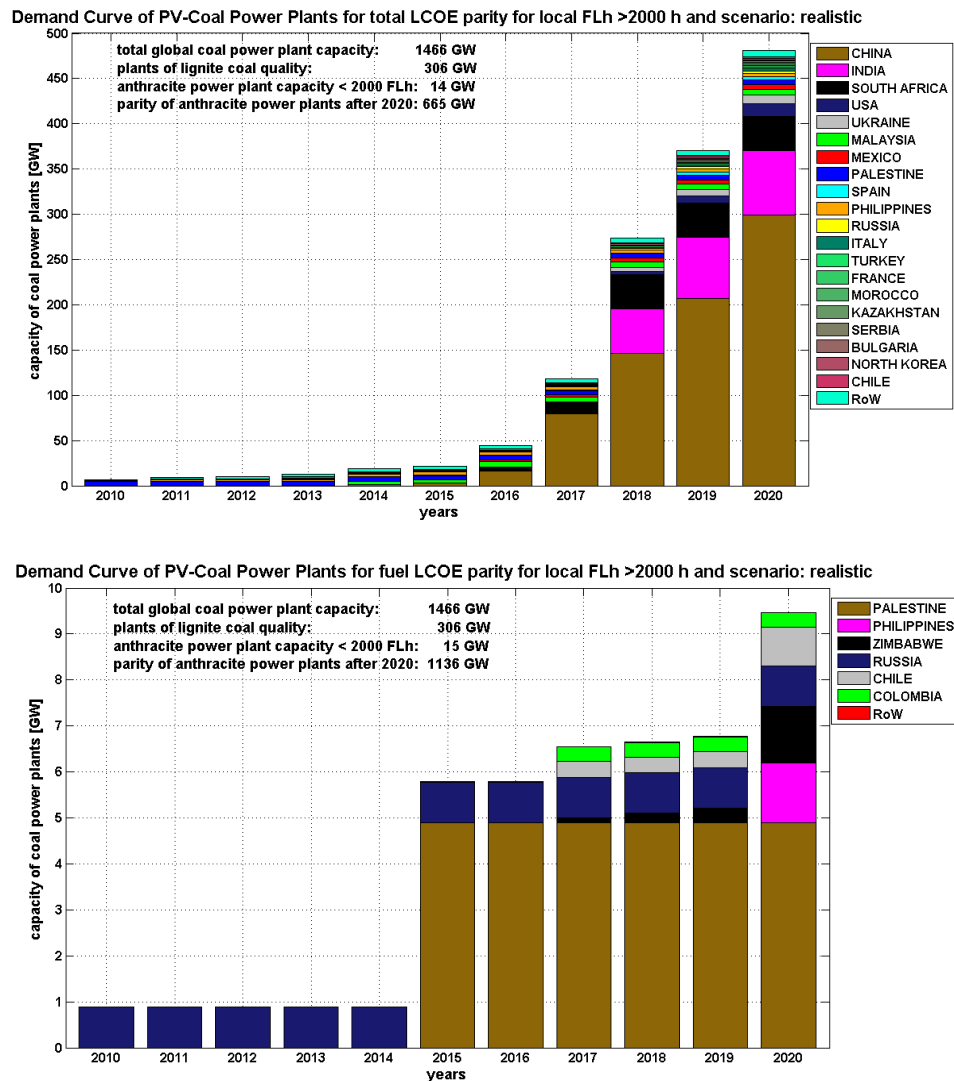


Figure 6.4-21: Global hybrid PV-Coal power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV realistic and coal base case scenario assumptions in the 2010s. Coal power plant capacity is counted only in case of PV LCOE (plus higher coal capital cost due to reduced FLh) lower than total and fuel-only coal LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 and Figure 3.2-16 (PV) and Table 6.4-1 and Figure 6.4-16 (coal). Countries operating coal power plants in average of at least 2,000 FLh and plants firing coal of at least bituminous coal are included in the analysis. Data for coal power plant capacity are taken from UDI World Electric Power Plants database¹⁹⁰.

¹⁹⁰ Platts, UDI World Electric Power Plants data base, 2009

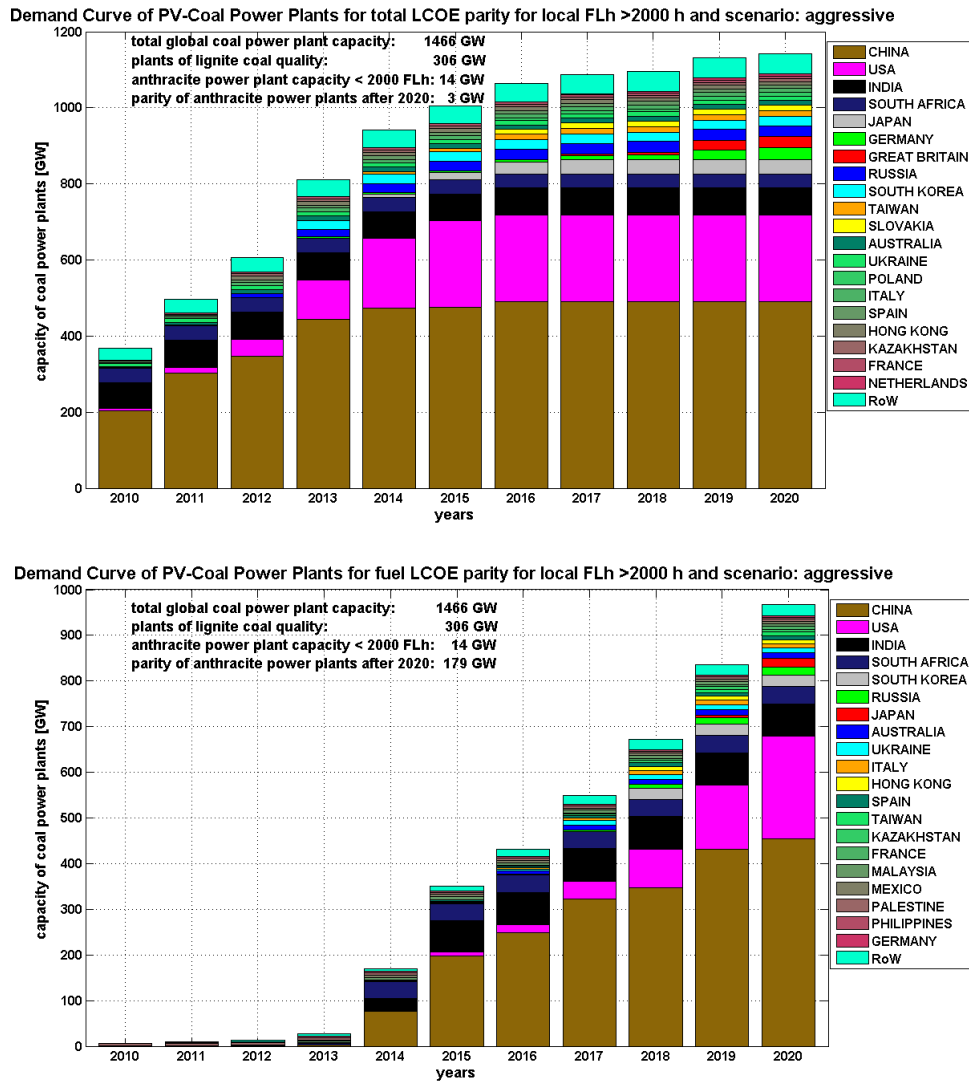
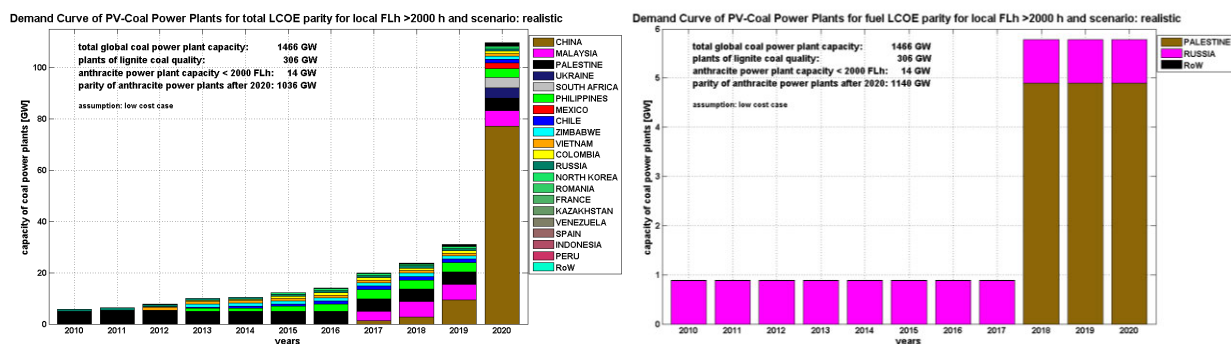


Figure 6.4-22: Global hybrid PV-Coal power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV aggressive and coal base case scenario assumptions in the 2010s. Coal power plant capacity is counted only in case of PV LCOE (plus higher coal capital cost due to reduced FLh) lower than total and fuel-only coal LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.4-1 and Figure 6.4-16 (coal). Countries operating coal power plants in average of at least 2,000 FLh and plants firing coal of at least bituminous coal are included in the analysis. Data for coal power plant capacity are taken from UDI World Electric Power Plants database¹⁹¹.



¹⁹¹ Platts, UDI World Electric Power Plants data base, 2009

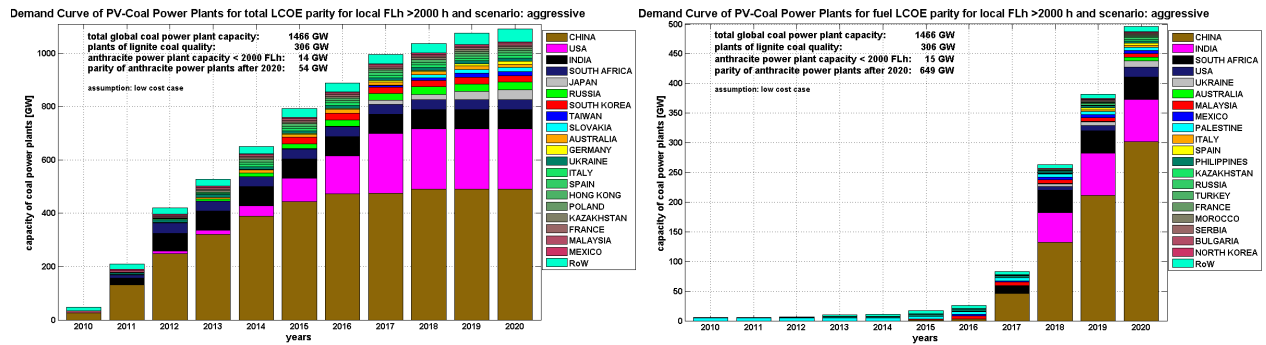


Figure 6.4-23: Global hybrid PV-Coal power plant demand curve in the 2010s on total (left) and fuel-only (right) LCOE parity for fixed optimally tilted PV in the realistic (top) and aggressive (bottom) and coal low cost case scenario assumptions in the 2010s. Coal power plant capacity is counted only in case of PV LCOE (plus higher coal capital cost due to reduced FLh) lower than total and fuel-only coal LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the countries of the world. Power plant scenario assumptions are defined in Table 3.2-1 (PV) and Table 6.4-1 (coal). Countries operating coal power plants in average of at least 2,000 FLh and plants firing coal of at least bituminous coal are included in the analysis. Data for coal power plant capacity are taken from UDI World Electric Power Plants database ¹⁹².

In the mid of the 2010s, first coal power plants of a significant capacity in very sunny regions show higher LCOE than nearby PV power plants on a total power plant LCOE basis even for the realistic scenario assumptions of PV power plants (Fig. 6.4-21). The by far largest market for hybrid PV-Coal power plants becomes China. By the end of the 2010s, the largest markets for hybrid PV-Coal power plants are China, India, South Africa, the US and Ukraine. In the aggressive scenario, i.e. fast PV cost reduction dynamic, five further major markets are beyond economic breakeven: Japan, Germany, UK, Russia and South Korea. Even countries of moderate solar resource conditions show favourable economics by end of the 2010s for hybrid PV-Coal power plants.

Depending on scenario assumptions market potential for hybrid PV-Coal power plants has been more than 20 GW in 2015 and might fast rise to 480 GW by the end of the 2010s. The maximum market potential is about 1,150 GW due to limited coal power plant capacity operated in average for at least 2,000 FLh and firing at least bituminous coal quality.

The results for hybrid PV-Coal power plant economics show several characteristics for a beneficial combination. Already existing coal power plants should be operated for at least 2,000 FLh during daytime and firing at least bituminous coal quality. Fuel represents the highest fraction of power plant LCOE, e.g. about 50% for a crude oil price of 80 USD/barrel, hence coal LCOE are significantly influenced by crude oil price. Capital cost contribute to LCOE by about 40%, therefore lowering FLh causes significantly higher remaining capital cost needed to be covered by respective lower PV LCOE. The solar resource quality at local sites of existing power plants is very important for PV LCOE and thus hybrid PV-Coal power plant economics, but the crude oil price is more decisive. Coal producing countries have the identical coal LCOE due to the respective opportunity cost in case of burning coal priced lower than world market price. However, in case of coal the logistic cost for international coal transport might be in a significant order. Moreover, countries having coal resources of only low quality cannot trade their coal on the world market, this is the case for Brazil, Thailand, Laos, Pakistan, Turkey and Greece. PV power plants might be in competition to wind power plants due to excellent wind power economics (sub-chapters 4.2 and 4.3). In case of

¹⁹² Platts, UDI World Electric Power Plants data base, 2009

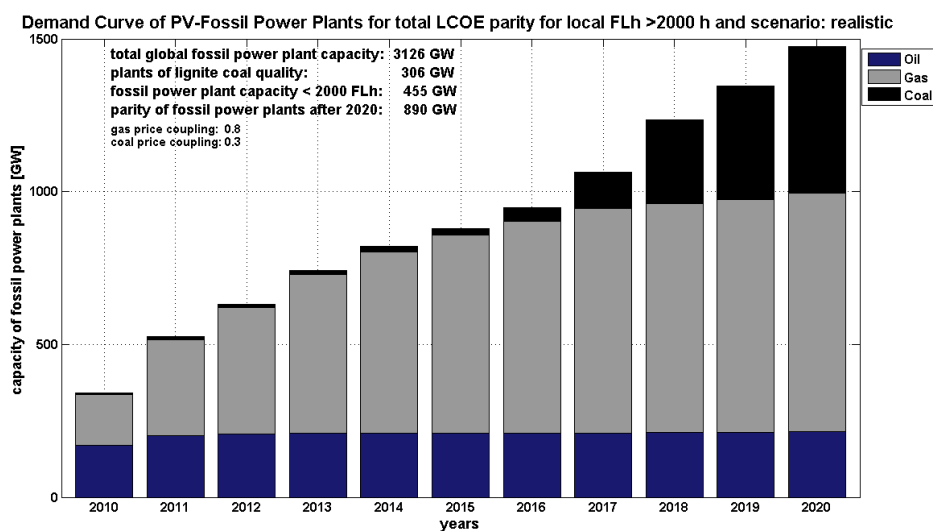
complementary wind and solar resource availability the economics of hybrid PV-Coal power plants might be further improved by integrating wind power and establishing hybrid PV-Wind-Coal power plants. Complementary versus competitive characteristics of solar and wind resources are discussed in sub-chapter 7.3.

Summing up, results for hybrid PV-Coal power plant economics give plenty of insights for fast growing competitiveness of this approach for upgrading existing coal fired power plants. Many regions in the world in which coal power plants are operated on a significant FLh level and of sufficient coal quality have good and excellent solar resources which lead to favourable PV power plant economics. Already in the mid of the 2010s, several coal power plants in the world could lower the LCOE by upgrading with nearby PV power plants. Financial upgrading benefit for resulting hybrid PV-Coal power plants is fast increasing as a consequence of fast PV LCOE reductions and higher than expected crude oil price escalation and collateral coal price adaption.

6.5 Hybrid PV-Fossil Power Plant Demand Curve

The approach of upgrading existing fossil fuel fired power plants by PV power plants is widely discussed in this chapter for the fuels: oil (sub-chapter 6.2), natural gas (sub-chapter 6.3) and coal (sub-chapter 6.4). Major impact on competitiveness of this approach has the PV cost reduction dynamic complemented by fossil fuel price scenario assumptions. Global demand curves are derived, i.e. for hybrid PV-Oil power plants (section 6.2.3), hybrid PV-Gas power plants (section 6.3.3) and hybrid PV-Coal power plants (section 6.4.3). The focus of this sub-chapter is the integrated global demand curve for hybrid PV-Fossil power plants.

Global hybrid PV-Fossil power plant demand curve based on fuel-parity is depicted in Figure 6.5-1 for the case of total plant and fuel-only LCOE parity for the realistic case (PV) and base case (oil, gas and coal) scenario assumptions for fossil power plants operated in countries in average of at least 2,000 FLh and for plants firing coal of at least bituminous coal quality. Outcome for aggressive scenario assumptions for PV power plants is shown in Figure 6.5-2.



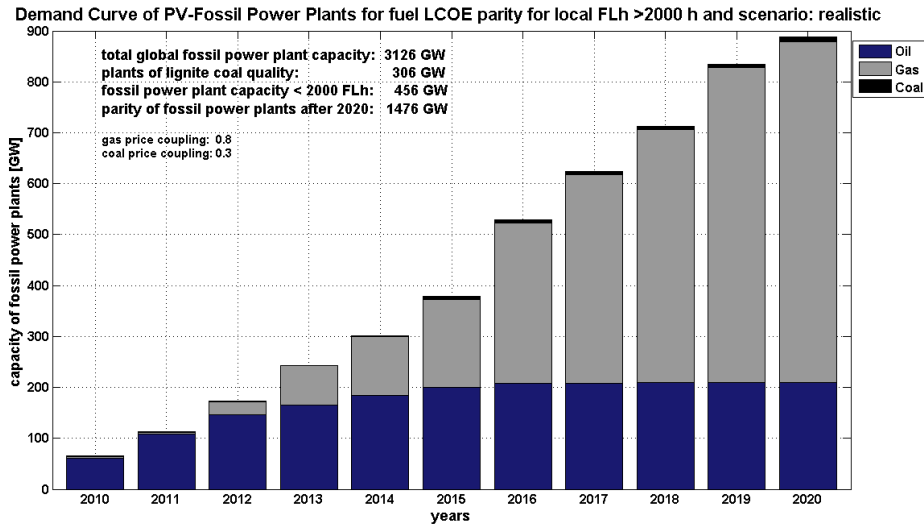
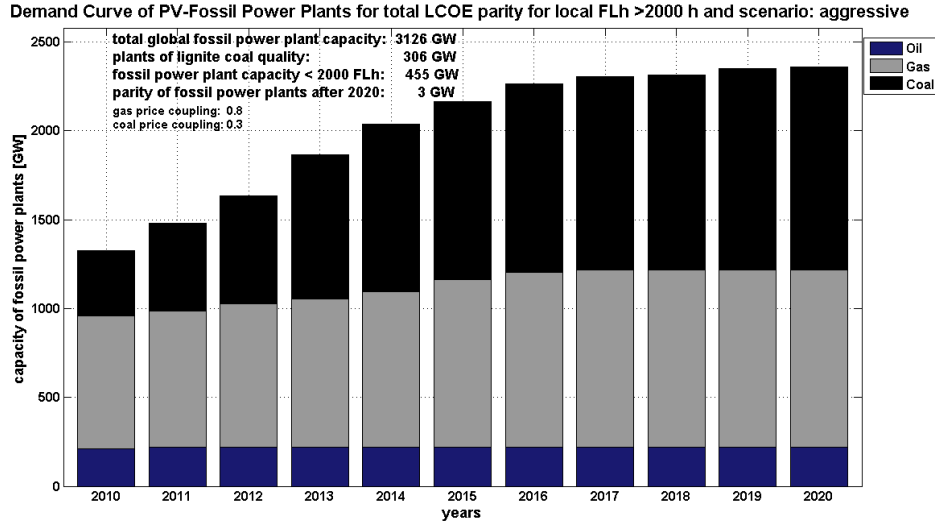


Figure 6.5-1: Global hybrid PV-Fossil power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV in the realistic and fossil base case scenario assumptions in the 2010s. Fossil power plant capacity, i.e. oil, natural gas and bituminous and anthracite coal, is counted only in case of PV LCOE (plus higher fossil capital cost due to reduced FLh) lower than total and fuel-only fossil LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the fuel categories. Power plant scenario assumptions are defined in Table 3.2-1 (PV), Table 6.2-1 (oil), Table 6.3-1 (gas) and Table 6.4-1 (coal). Countries operating respective fossil power plants in average of at least 2,000 FLh and coal plants firing coal of at least bituminous coal are included in the analysis. Data for fossil power plant capacity are taken from UDI World Electric Power Plants database ¹⁹³.



¹⁹³ Platts, UDI World Electric Power Plants data base, 2009

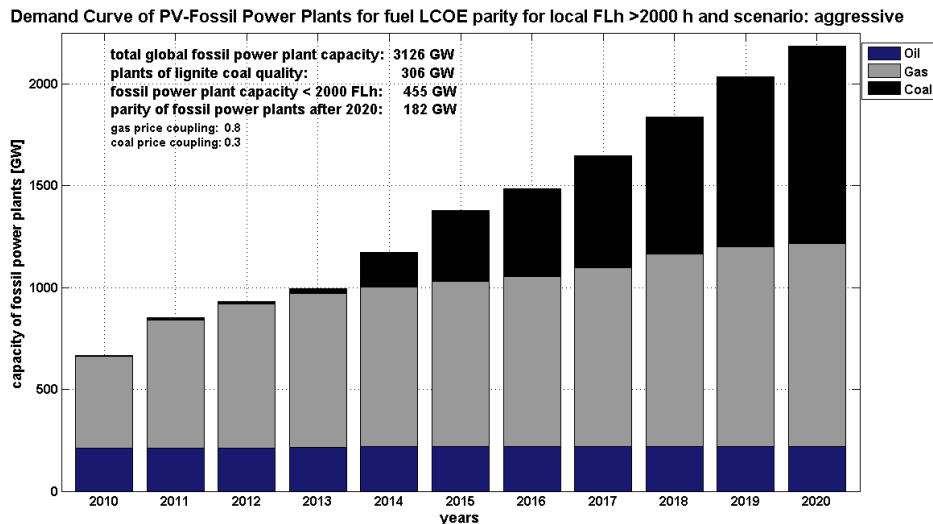


Figure 6.5-2: Global hybrid PV-Fossil power plant demand curve in the 2010s on total (top) and fuel-only (bottom) LCOE parity for fixed optimally tilted PV in the aggressive and fossil base case scenario assumptions in the 2010s. Fossil power plant capacity, i.e. oil, natural gas and bituminous and anthracite coal, is counted only in case of PV LCOE (plus higher fossil capital cost due to reduced FLh) lower than total and fuel-only fossil LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the fuel categories. Power plant scenario assumptions are defined in Table 3.2-1 (PV), Table 6.2-1 (oil), Table 6.3-1 (gas) and Table 6.4-1 (coal). Countries operating respective fossil power plants in average of at least 2,000 FLh and coal plants firing coal of at least bituminous coal are included in the analysis. Data for fossil power plant capacity are taken from UDI World Electric Power Plants database ¹⁹⁴.

Global hybrid PV-Fossil power plant market potential is structured for the combination of realistic (PV) and base case (Fossil) assumptions as following: Total plant LCOE parity is already given for about 350 GW (oil and gas) in 2010, rising to 750 GW (oil, gas and beginning of coal) in the mid of the 2010s and reaching about 1,500 GW (oil, gas and coal) by the end of the 2010s. Fuel-only LCOE parity is already given for about 60 GW (oil) in 2010, rising to about 380 GW (oil, gas and beginning of coal) in the mid of the 2010s and reaching about 900 GW (oil, gas and still very little coal) by the end of the 2010s. Global total fossil power plant capacity is about 3,130 GW by early 2009. About 460 GW of that capacity is identified as being operated less than 2,000 FLh and therefore excluded from the analysis. Further about 310 GW coal power capacity is excluded due to the use of low quality coal not tradable on the world market. The remaining about 2,370 GW fossil fuel power plant capacity can be economically upgraded by PV power plants by 2020 to approximately 63% and 38% for total plant and fuel-only LCOE parity, respectively.

In case of the aggressive scenario (PV) the numbers are for total plant LCOE parity about 1,300 GW (oil, gas and coal) in 2010, rising to about 2,100 GW (oil, gas and coal) in the mid of the 2010s and reaching about 2,350 GW (oil, gas and coal) by the end of the 2010s. Fuel-only LCOE parity is already given for about 700 GW (oil and gas) in 2010, rising to 1,400 GW (oil, gas and coal) in the mid of the 2010s and reaching about 2,200 GW (oil, gas and coal) by the end of the 2010s. Global total fossil power plant capacity is about 3,130 GW by early 2009. The fossil fuel power plant capacity of about 2,370 GW available for upgrading by PV power plants can be economically addressed by 2020 to approximately 99% and 93% for total plant and fuel-only LCOE parity, respectively.

¹⁹⁴ Platts, UDI World Electric Power Plants data base, 2009

The outcome for low cost scenario assumptions is summarized in Figure 6.5-3.

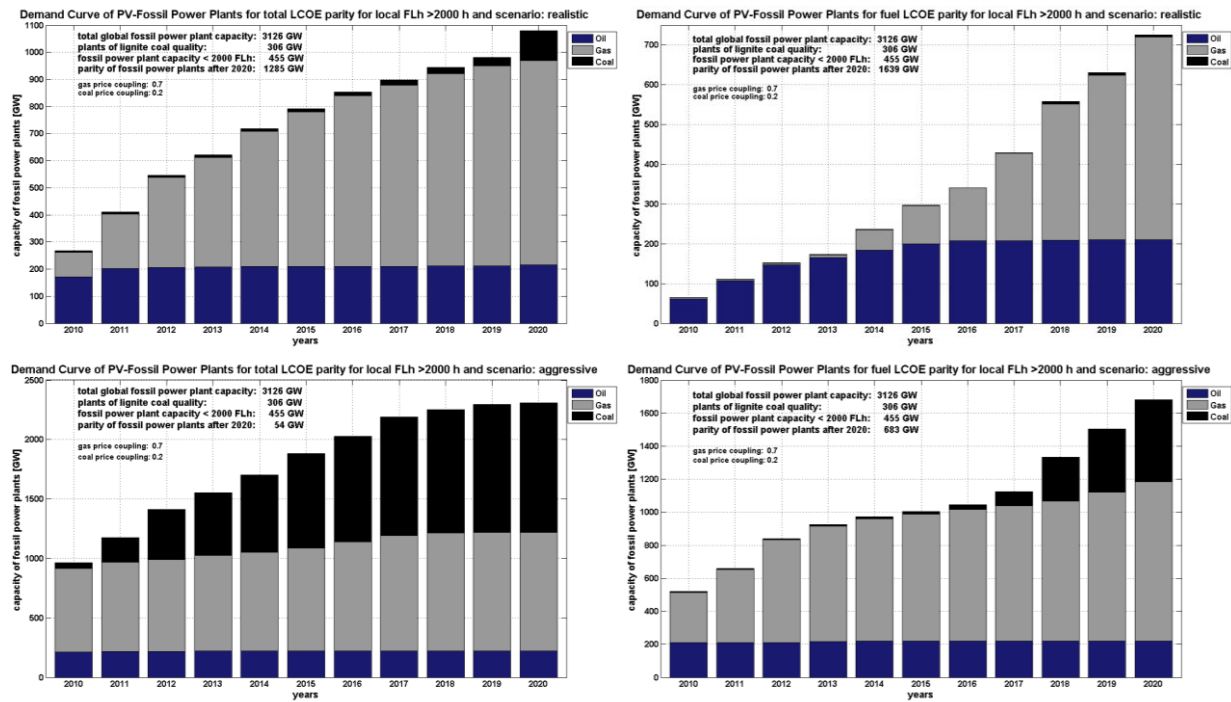


Figure 6.5-3: Global hybrid PV-Fossil power plant demand curve in the 2010s on total (left) and fuel-only (right) LCOE parity for fixed optimally tilted PV in the realistic (top) and aggressive (bottom) and fossil low cost case scenario assumptions in the 2010s. Fossil power plant capacity is counted only in case of PV LCOE (plus higher fossil capital cost due to reduced FLh) lower than total and fuel-only fossil LCOE. Every coordinate of a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N is separately checked for the years 2010 to 2020. Subsequently, all coordinates are aggregated to the fuel categories. Power plant scenario assumptions are defined in Table 3.2-1 (PV), Table 6.2-1 (oil), Table 6.3-1 (gas) and Table 6.4-1 (coal). Countries operating respective fossil power plants in average of at least 2,000 FLh and coal plants firing coal of at least bituminous coal are included in the analysis. Data for fossil power plant capacity are taken from UDI World Electric Power Plants database ¹⁹⁵.

Global hybrid PV-Fossil power plant market potential is structured for the combination of realistic (PV) and low cost case (Fossil) assumptions as following: Total plant LCOE parity is already given for about 280 GW (oil and gas) in 2010, rising to about 800 GW (oil, gas and beginning of coal) in the mid of the 2010s and reaching about 1,100 GW (oil, gas and coal) by the end of the 2010s. Fuel-only LCOE parity is already given for about 60 GW (oil) in 2010, rising to 300 GW (oil and gas) in the mid of the 2010s and reaching about 720 GW (oil and gas) by the end of the 2010s. Global total fossil power plant capacity is about 3,130 GW by early 2009. The fossil fuel power plant capacity of about 2,370 GW available for upgrading by PV power plants can be economically addressed by 2020 to approximately 46% and 30% for total plant and fuel-only LCOE parity, respectively.

In case of the aggressive scenario (PV) the numbers are for total plant LCOE parity about 950 GW (oil, gas and beginning of coal) in 2010, rising to about 1,800 GW (oil, gas and coal) in the mid of the 2010s and reaching about 2,300 GW (oil, gas and coal) by the end of the 2010s. Fuel-only LCOE parity is already given for about 500 GW (oil and gas) in 2010, rising to 1,000 GW (oil, gas and beginning of coal) in the mid of the 2010s and reaching about 1,700 GW (oil, gas and coal) by the end of the 2010s. Global total fossil power plant capacity is about 3,130 GW by early 2009. The fossil fuel power plant capacity of about 2,370 GW

¹⁹⁵ Platts, UDI World Electric Power Plants data base, 2009

available for upgrading by PV power plants can be economically addressed by 2020 to approximately 97% and 72% for total plant and fuel-only LCOE parity, respectively.

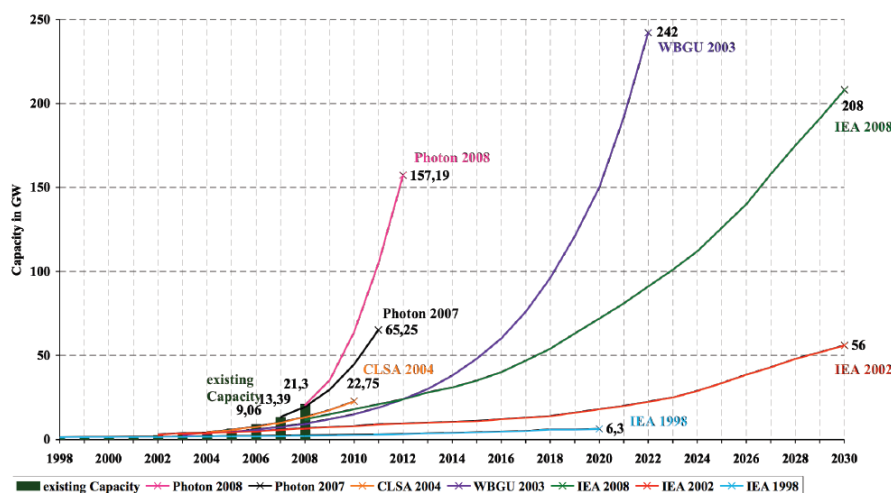
Summing up, total fossil fuel power plant capacity of 3,130 GW by early 2009 is by about 70% (2,170 GW) suitable for upgrading with PV power plants. By 2020, this PV power plant upgrading market potential is at least 30% of the suitable capacity due to very conservative scenario assumptions, i.e. realistic (PV), low cost case (Fossil) and fuel-only LCOE parity. A more realistic, maybe slightly optimistic, consideration is beyond 90% of suitable capacity, i.e. aggressive (PV), base case (Fossil) but still fuel-only LCOE parity. The fuel-parity market potential for hybrid PV-Fossil power plants can be expected to be in the range of at least 700 GW up to even more than 2,100 GW by 2020. These numbers are very likely to grow in parallel to new net installed fossil power plant capacity during the 2010s.

6.6 Total Global PV Market Potential

The previous sub-chapter documents an enormous economic market potential for PV power plants. Similar results are derived for PV grid-parity analyses (sub-chapter 3.3). This sub-chapter gives an overview on PV scenarios published in the last years (section 6.6.1) and compares this to the overall economic PV market potential (section 6.6.2). A brief and indicative stakeholder analysis summarizes likely reaction strategies of the different groups.

6.6.1 Overview on PV Scenarios

Energy scenarios are a very helpful tool for guiding different stakeholder groups what might happen in future in dependence of various policy options. Such scenarios show long-term consequences of potential policy decisions and enable an assessment whether respective developments would be acceptable in reference to relevant constraints, e.g. diminishing fuel resources, greenhouse gas emissions or social cost of energy supply. Gredler compared the recent development of PV production to forecasts of various institutions (Fig. 6.6-1).^{196,197}



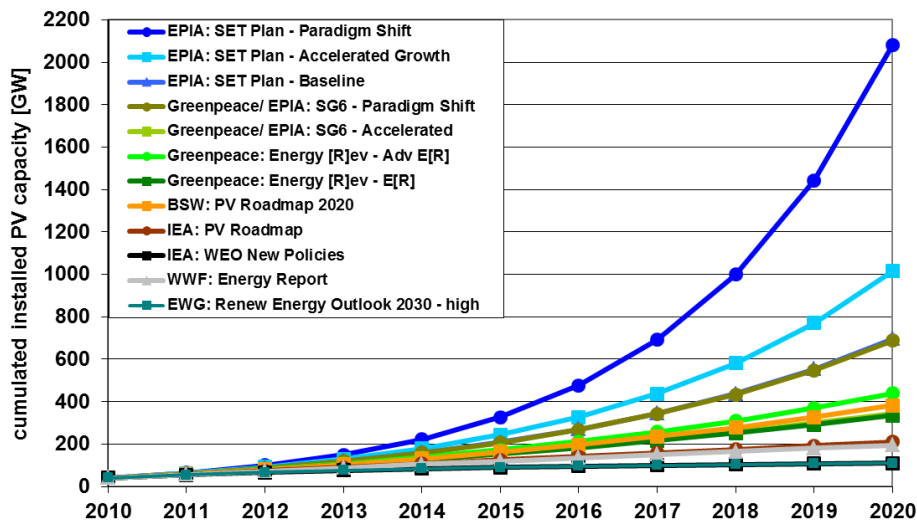
¹⁹⁶ Gredler C., Update of PV and wind power market development compared to forecasts, private communication, 2009

¹⁹⁷ Gredler C., Das Wachstumspotenzial der Photovoltaik und der Windkraft – divergierende Wahrnehmungen zentraler Akteure, 2008

Figure 6.6-1: Forecasts of PV development and real cumulated installed PV capacity for the status of the year 2008. It needs to be mentioned that the production numbers for PV are depicted and the cumulated installed PV capacity as of end of year would be 6.9 GW (2006), 9.4 GW (2007) and 15.7 GW (2008) according to EPIA.¹⁹⁸ The references for mentioned studies are: ‘Photon 2008’¹⁹⁹, ‘Photon 2007’²⁰⁰, ‘CLSA 2004’²⁰¹, ‘WBGU 2003’²⁰² and ‘IEA 2008’²⁰³.

Results indicate, that projections of the International Energy Agency structurally underestimate the growth rate of PV and even the German Advisory Council on Global Change remains significantly below the real development. Market research performed with deep insights and a broad coverage of the PV industry, i.e. studies performed under the lead of Michael Rogol, show the necessity for upwards adaption, as well, but implying substantial higher growth rates.

This thesis is mainly focussed on the progress of PV in the decade of the 2010s, thus PV market projections of various sources are visualised in an integrated view for displaying the substantial variance in market expectation (Fig. 6.6-2). The numbers of the studies are depicted for the cumulated installed PV capacity and the annual installations. For being included in this integrated view, the studies need to cover at least the time span from the year 2010 to 2020, therefore all short-term reports have to be excluded, i.e. PV industry research companies like Photon Consulting, EuPD Research and IHS Research but also the reports of all financial analysts.



¹⁹⁸ EPIA, Global Market Outlook for Photovoltaics until 2014, 2010

¹⁹⁹ Rogol M. et al., Solar Annual 2008: Four Peaks, 2008

²⁰⁰ Rogol M. et al., Solar Annual 2007: Big Things in a Small Package, 2007

²⁰¹ Rogol M. et al., Sun screen: Investment opportunities in solar power, 2004

²⁰² WBGU, World in Transition: Towards Sustainable Energy Systems, 2003

²⁰³ IEA, World Energy Outlook 2008, 2008

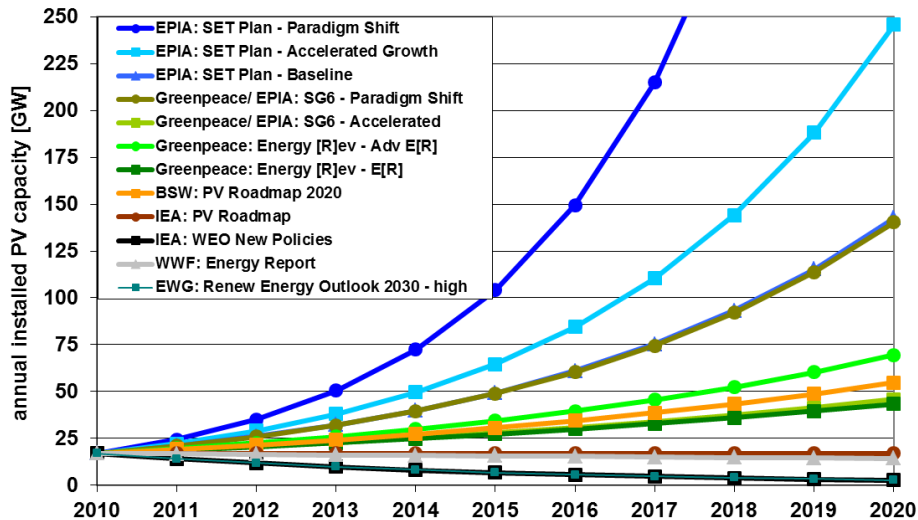


Figure 6.6-2: Projections of cumulated (top) and annual (bottom) installed PV capacity of various institutions. Numbers of EPIA are only provided for Europe and have been extended on a global basis according to total installed power plant capacity²⁰⁴, since this is the only study representing the market potential of PV being in line with the outcome of this thesis. Data are taken from EPIA²⁰⁵, Greenpeace^{206,207}, BSW²⁰⁸, IEA^{209,210}, WWF²¹¹ and EWG²¹².

The most obvious result of the integrated view on the relevant studies covering PV market development in the 2010s is the enormous range of market projections. There are roughly three fundamental different projections: Firstly, PV will become a major source of global energy supply (EPIA and partly Greenpeace). Secondly, PV will grow but growth rate will decline on a fraction of the mean of the past 15 years (BSW and partly Greenpeace). Thirdly, growth rates of annual PV installations will become negative, i.e. decline in further market development is expected (IEA, WWF and EWG). The projected annual PV market growth rates are for these three major groups roughly 25% - 45% (EPIA and partly Greenpeace), 10% - 12% (BSW and partly Greenpeace) and 0% - -17% (IEA, WWF and EWG). The average annual growth rate of PV for all major diffusion phase has been never below 30% and for the last 15 years it was about 45% (Fig. 3.1-1).

The annual installations at the end of the 2010s show again three fundamental different expectations, as the very conservative group projects average installations at the end of the 2010s below the numbers of 2010, the moderate group expects annual installations between 40 GW and 70 GW and the progressive group takes into account that annual installations might be 140 GW and higher. These numbers can be compared to overall power plant installations having been doubled from about 80 GW in the 1990s to about 160 GW in the 2000s (Fig 5.1-9). Moreover, in average all power plants are operated at about 4,300 annual full load hours, whereas PV power plants will range between 1,000 and 2,500 full load hours. Either PV complements the other sources of electricity or PV plus storage solutions fulfil all

²⁰⁴ Platts, UDI World Electric Power Plants data base, 2009

²⁰⁵ EPIA, SET FOR 2020: Solar Photovoltaic Electricity, 2009

²⁰⁶ EPIA and Greenpeace, Solar Generation 6 – Solar Photovoltaic Electricity Empowering the World, 2011

²⁰⁷ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

²⁰⁸ BSW, Wegweiser Solarwirtschaft: PV-Roadmap 2020, 2010

²⁰⁹ IEA, Technology Roadmap: Solar photovoltaic energy, IEA, 2010

²¹⁰ IEA, World Energy Outlook 2010, 2010

²¹¹ WWF, The Energy Report: 100% Renewable Energy by 2050, 2011

²¹² Peter S. and Lehmann H., Renewable Energy Outlook 2030, 2008

requirements for full power supply ²¹³, but in any case new PV installations in the order of new installed conventional power plant capacity are not technically limited at all.

Comparing the market projections to the realised growth in the past, the only reasonable expectation might be progressive assessment by EPIA and some Greenpeace scenarios. It remains unclear why the other institutions assume such a decline in market growth or even a decline in annual installations, i.e. negative growth rates, strongly violating the long-term growth trend of PV. No arguments have been found in the studies explaining such an enormous deviation from the trend being fully intact for more than five decades. This is very surprising, as nearly all of these institutions draw a drastic view on the business-as-usual scenario of conventional power business and some of them claim a reduction in greenhouse gas emissions as soon as possible, e.g. WWF and EWG.

6.6.2 Overall Economic PV Market Potential

The heterogeneous PV installation projections of major institutions in the field of PV presented in the previous section (Fig. 6.6-2) is cross-checked in this section with the economic PV market potential based on PV grid-parity and fuel-parity analyses (sub-chapters 3.3 and 6.5).

Based on the global grid-parity analysis (sub-chapter 3.3), the market potential for on-grid end-user PV electricity is estimated. On the 2010 electricity consumption basis the grid-parity market volume of the entire power market by end of the 2010s is about 13,000 TWh in total composed by about 3,900 TWh (residential), about 3,600 TWh (small medium enterprises) and about 5,500 TWh (industrial).

To translate the aforementioned market volume into a cumulated installed PV capacity potential, the following assumptions are made: a population weighted average annual irradiation on fixed optimally tilted PV systems on a per country level (section 2.3.2), a global performance ratio of 80% (residential) and 82% (industrial), a global maximum PV supply contribution between 10% (without storage) and 80% (including storage) and a global market penetration of this supply contribution of not more than 50%, i.e. maximum PV share is assumed to not exceed 40% of total power supply. The 10% PV supply contribution threshold requires a flexible power plant portfolio but enables the full utilization of the PV capacity even without storage. Based on these assumptions, an upper and a lower limit of the sustainable economic market potential for PV systems is estimated for the year 2020. The upper limit for the grid-parity economic market potential would be the net metering grid-parity, i.e. parity of PV LCOE and the electricity price for the end-users. A more appropriate upper limit would be the cost of PV plus storage solutions compared to the electricity price. First work in progress insights indicate roughly a PV plus storage grid-parity about four years after the net metering grid-parity (Fig. 3.3-11).²¹⁴ The lowest limit for the economic grid-parity market potential assumes the case of no storage availability, thus an effective 10% energy contribution based on the maximal fully utilizable PV power in the grid.

In result, these assumptions lead to a total fully economically sustainable installed end-user PV capacity potential of about 980 GW without any storage solutions (lower limit) and up to 3,930 GW (upper limit) including storage in case of the financial net metering approach.

²¹³ Werner C., Grid-Parity für Photovoltaik mit Energiespeicher, 2011

²¹⁴ Werner C., Grid-Parity für Photovoltaik mit Energiespeicher, 2011

However, the appropriate economic PV plus storage grid-parity comprises the storage cost resulting in 2,070 GW (upper limit) full economic market potential by 2020, if advanced economic storage systems for PV electricity are available.

The key question is who will own and operate the economically feasible PV systems of the residential and industrial end-users. In some markets the majority of the PV systems could be owned by the individual electricity end-users, but in other markets the most PV systems might be owned by utilities partly in decentralised applications and partly in centralised PV power plants.

In the year 2020, fuel-parity of PV power plants and conventional fossil fuel fired power plants might be in the order of 1,500 GW for realistic scenario assumptions, whereas a capacity of approximately 900 GW fulfils the most aggressive criteria of PV LCOE parity to fuel-only LCOE of fossil power plants (Fig. 6.5-1). In case of applying an aggressive scenario, the fuel-parity analysis results in an economic PV market potential of up to 2,300 GW (Fig. 6.5-2). Significant amounts of conventional power plant capacity which can be economically upgraded by PV power plants (sub-chapter 6.5) might also be used for installations of hybrid Wind-Fossil power plants, but insights of respective research activities (sub-chapter 7.3) indicate a critical overlap range of full load hours of PV and wind power plants of about 1% - 8% and an average value for most sites in the world of about $2\% \pm 1\%$. Hence, PV and wind power can be considered as nearly fully complementary.

Based on the grid-parity and fuel-parity concept, an upper and a lower limit of the sustainable economic market potential for PV systems can be estimated. The upper limit for the grid-parity would be the net metering grid-parity, i.e. parity of PV LCOE and the electricity price for the end-users. The lower and more appropriate limit would be the cost of PV plus storage solutions compared to the electricity price. The upper limit for the fuel-parity would be the comparison to the total plant LCOE of fossil fuel fired power plants reduced by increasing capital cost due to lower full load hours as a consequence of hybridization with PV systems. The lower limit for the fuel-parity refers to the marginal cost of fossil fuel fired power plants, i.e. the fuel-only LCOE. For avoiding double counting of capacities the overlap of grid-parity and fuel-parity has to be quantified. Therefore, in case of reaching grid-parity and fuel-parity the smaller accessible market potential for PV systems has been counted as overlap and excluded from the integrated total parity capacity. This consideration has been applied on an annual and per country basis and aggregated afterwards on a worldwide scale. This implies not whether it is more favourable to install the PV systems in a more decentralised end-user structure or a more centralised utility-scale manner. The global economic market potential for PV systems analysed is based on a global grid-parity analysis for more than 99% of global electricity consumption (sub-chapter 3.3) and a comparable global fuel-parity analysis for all fossil fuel fired power plants in the world on a per power plant basis (sub-chapters 6.2 to 6.5). The outcome is depicted in Figure 6.6-3 for the first integrated sustainable economic market potential estimate for PV systems on basis of a learning rate of 20% for modules and inverter and 15% for the other balance of system (BOS) components. The total economic market potential can be estimated to about 2,700 GW to 4,200 GW for the year 2020.

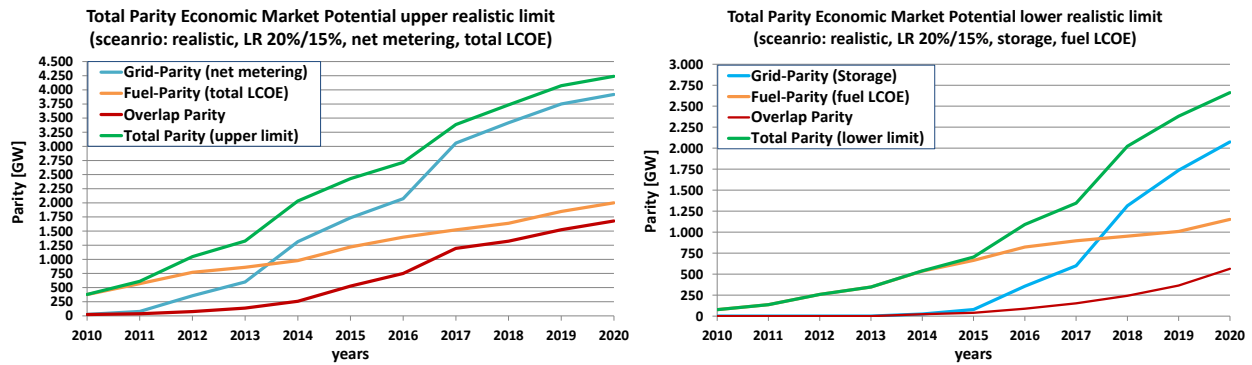


Figure 6.6-3: Total economic on-grid market potential for PV systems in the 2010s in the upper (left) and lower limit (right). The key assumptions are: grid-parity and fuel-parity approach, learning rate of 20% for modules and inverter and 15% for other BOS components, growth rate of 30% in 2010s, substitution of 80% of the single end-users power demand and 50% maximal addressable market potential in case of grid-parity and hybrid PV-Fossil power plants without any storage capacities in case of fuel-parity. Results are based on grid-parity (sub-chapter 3.3) and fuel-parity analyses (sub-chapters 6.2 to 6.5).

The economic market potential for PV systems is comparably low in the very early 2010s but growing fast during the entire decade particularly for the lower limit of PV plus storage grid-parity and marginal cost fuel-parity. In the beginning, the majority of the global economic market potential is driven by fuel-parity (typically PV power plants) and later by grid-parity (typically decentralized roof-top applications). A lower learning rate reduces the market growth but would be no show stopper at all. Significantly lower learning rates of 10% for modules and inverters and 5% for the additional BOS components would reduce this potential accessible in the 2010s, but PV market diffusion would be delayed only by a few years, typically below four years.

Off-grid PV applications in rural areas are highly profitable for years (sub-chapter 3.4). 1.4 billion people have no access to electricity, but for the poorest of them solar home systems (SHS) and pico systems are an excellent solution due to financial amortization periods of 12 to 36 months for SHS and 6 to 18 months for pico systems. For emerging countries requiring larger amounts of electricity per capita local mini-grids are an energy option realisable in a fast way, especially compared to costly expansions of national grids. Market potential for off-grid PV systems in rural regions is in the order of about 70 GW and dominated by mini-grids in the amount of capacity, but dominated by SHS in the amount by people using a PV off-grid solution. This is caused by diverse energy consumption patterns.

In result, the economic market potential for total installed on-grid PV capacity in year 2020 can be estimated to about 2,700 GW to 4,200 GW based on grid-parity and fuel-parity analyses. The additional market potential for rural off-grid PV applications, however, is by at least one order of magnitude smaller and estimated to be about 70 GW. Nevertheless, this capacity would be equivalent to a quantum jump for the 1.4 billion people currently without access to electricity. The total overall economic PV market potential can be, thus estimated to roughly 2,800 GW to 4,300 GW based on grid-parity, fuel-parity and off-grid amortization analyses. However, only a fraction of this economic market potential will be realised in time, i.e. 20% (pessimistic), 35% (realistic) and 50% (optimistic) might be assumed. Applying these scenario assumptions the author of this thesis expects a cumulated installed PV capacity in the year 2020 for a pessimistic case of about 560 – 860 GW, for a realistic case about 980 – 1,510 GW and for an optimistic case about 1,400 – 2,150 GW. To be more on the save side the final expectation is about 600 GW (pessimistic), 1,000 GW (realistic) and about 1,600 GW (optimistic). These three cases are roughly equivalent to average annual growth rates of

new installations of 20%, 30% and 40%, i.e. fully in line to the long-term growth of global PV installations. Technological restrictions for these installation numbers need not to be feared, since the fuel-parity approach requires only grid access of PV power plants nearby to existing power plants and many grid-parity market segments become profitable even including local storage options.

These PV market expectations are in drastic contrast to market projections of major institutions in the field of PV scenarios, since only the progressive group (section 6.6.1) fulfils the pessimistic case derived in this section, i.e. only EPIA and partly Greenpeace can really imagine that PV can show such a fast progress towards the long-term target of becoming a major source of energy supply. The ‘SET FOR 2020’ study from EPIA ²¹⁵ is the only publication expecting a cumulated installed PV capacity in the order of the realistic case derived in this section.

As a consequence of PV economics, there will be at least two driving forces for the economic pressure of on-grid PV systems on conventional fossil fuel fired power plants. Firstly, grid-parity economics for end-users will generate highly attractive returns for PV investments for partly substituting high priced end-user electricity cost mainly dominated by conventional fossil fuel fired power plants. Secondly, in the beginning of the 2010s, the PV LCOE are expected to be below those of respective nearby conventional fossil fuel fired power plants at an increasing number of sites in the world, starting with oil, than natural gas and in the end also coal fired power plants. The question for all players active in the business of conventional fossil fuel fired power plants is how to manage this economic trend of fast decreasing PV LCOE being in contradiction to the trend for fossil fuel which dominates the cost structure of fossil power plants.

For **utilities** the answer seems to be not too difficult, i.e. either investing in PV systems (decentralised and/ or centralised) or trying to hinder the market diffusion of PV systems. The last option might generate higher profits in the first years but lead to disruptive economic stress mid- to long-term. The option of investing in PV systems might be significantly more sustainable and in the end a process easier to control.

For **power plant technology providers** the answer seems to be rather obvious. Overall investments in renewable power plants will be much higher than for conventional power plants, simply as an effect of capitalization of the fuel expenditures in the capex and for the case of PV due to lower full load hours, which need to be managed by hybridization and in the mid- to long-term by storage solutions. Consequently, the market for renewable and PV power plants will grow much faster than for conventional power plants. For maximizing the individual benefit, the best strategy for power plant technology providers is to invest in the renewable power plant value chain.

For **policy makers** the answer seems to be not too difficult, as well. PV LCOE trend generates benefits for end-users, but also for operators of conventional fossil fuel fired power plants, at least those being interested in least total LCOE of their power plant portfolio. Furthermore, social cost of PV are very low unlike fossil and nuclear power plants. Policy makers interested in public welfare will tend to PV systems for sure, but lobbying pressure might create other decisions in the short- and mid-term, but the enormous economic benefit of PV systems will convince dependent policy makers in the long-term, either by own insights or by indirect economic forces.

²¹⁵ EPIA, SET FOR 2020: Solar Photovoltaic Electricity, 2009

The stakeholder analysis for **fossil fuel producing and mining companies** is more differentiated. The large national fossil fuel companies could enlarge and maximize public welfare by investing in renewable and PV systems. In particular this is the current reality for those companies near to their production maximum which is often coupled to a fast growing domestic fossil energy demand, but also existing long-term export supply contracts. They could reduce their stress by focussing on a domestic renewable and PV power strategy to free capacities to fulfil their export contracts. The financial perspective is quite different for public listed and privately held fossil fuel companies. Their profits will grow fast for the case of strong global demand growth and lower growth or stagnation of fossil fuel production. It is nearly impossible for this group to earn comparable margins by investments in the renewable and PV industry, hence their best strategy is to hinder the growth of renewable and PV industry.

For **electricity end-users** the answer is not too difficult. Mid- to long-term they benefit from massive global renewable and PV investments, due to the cost stabilizing effect indicated for the case of PV by grid-parity and fuel-parity analyses.

In summary, a stakeholder analysis gives some indication that positive effects of strong PV economics are attractive for power plant technology providers, electricity end-users and utilities. Attractiveness remains somewhat unclear for some policy makers and some fossil fuel producing and mining companies, whereas attractiveness seems to be negative for most public listed and privately held fossil fuel companies and policy makers in close relation to these companies. The impact of PV on the fossil fuel power plant business will be very beneficial for those being aware of the enormous dynamic of PV economics, as most of the players can increase their profits or lower their cost, but there will be also players that are not capable of generating benefits for their own businesses and interests.

Chapter 7

Hybrid Photovoltaic Renewable Power Plants

Hybrid PV-Fossil power plants can be only the first step towards a 100% sustainable power supply. PV power plants can be also operated as one sub-plant among other renewable (RES) sub-plants of a hybrid PV-RES power plant. For the case of full dispatchability of the RES sub-plant the hybrid PV-RES power plant is also fully dispatchable. Two such combinations are briefly discussed: the **hybrid PV-Hydro power plant** (sub-chapter 7.1) and the **hybrid PV-STEG power plant** (sub-chapter 7.2). The two major power sources in this century might be PV and wind power, hence a **hybrid PV-Wind power plant** (sub-chapter 7.3) is of utmost relevance. But both PV and wind power show a fluctuating power availability, thus flexible balancing capacities are needed. For balancing the hybrid PV-Wind sub-plant power to the load, some additional storage sub-plant components could guarantee a stable power supply over the entire year including even seasonal storage. Such an option could be the **hybrid PV-Wind-Renewable Power Methane-Combined Cycle Gas Turbine power plant** (sub-chapter 7.4). The latter hybrid power plant is also analysed in its global energy supply potential.

In the years to come, an intensified research, development and demonstration for all fields of PV grid-integration is essential. Systematic research and development is needed on symbiotic relations among renewable energy sources and respective technologies. Key objective should be to achieve the ability to dispatch decentralised PV installations and utility-scale PV power plants on demand, which could include all types of renewable power methane powered combined cycle power plants, peaking geothermal power plants, pumped hydro storage or other kinds of storage technologies, in particular with regard to arising electric vehicles.

7.1 Hybrid PV-Hydro Power Plant

In this sub-chapter possible hybrid PV-Hydro power plants are briefly discussed. An overview on the already installed global hydro power capacity (section 7.1.1) sets the basis for some first considerations on hybrid PV-Hydro power plants (section 7.1.2).

7.1.1 Global Overview on Hydro Power Capacity

Hydro power was already used in preindustrial times for driving mills, sawmills and hammer works. Both the kinetic energy and the potential energy from flowing water can be converted into mechanical rotational power by a turbine wheel, which in turn can drive machines or generators. Today, hydro power is used almost exclusively for generating electricity.¹

There are large hydro power storage dams and river run-off plants ranging from large schemes with several 100 MW and even several GW capacity to micro hydro power systems with less than 1 kW capacity. Hydro power from dams can be delivered on demand, but it is usually subject to seasonal fluctuations. If used in times when PV power and wind power are low, it acts like a natural complement and as a storage system for those resources.

¹ Wengenmayr R., Wasserkraftwerke: Fließende Energie, 2007

Global potential of hydro power is shown in Figure 7.1-1. Most of the potential is used in developed countries, whereas new hydro power stations are expected in developing countries. There is still large potential in Africa, South America and Asia. Total technical hydro power potential is estimated to about 15,000 TWh per year.²

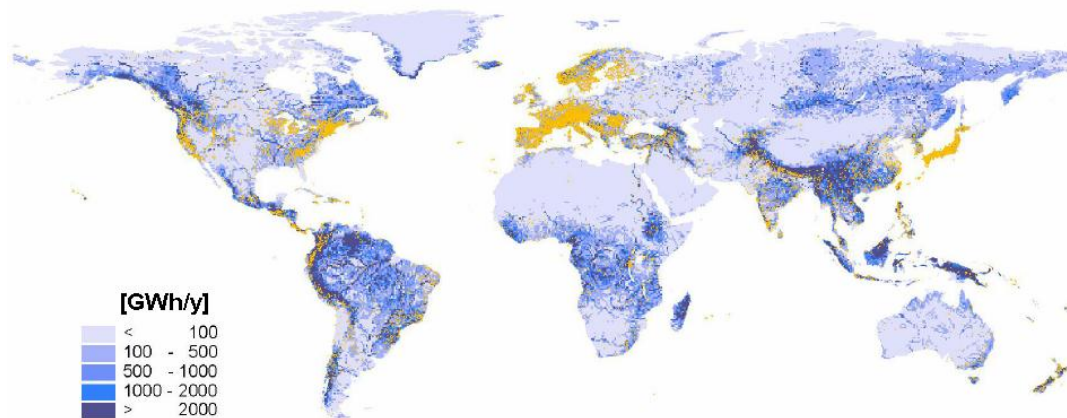


Figure 7.1-1: Global potential of hydro power and locations of hydro power plants (yellow).^{3,4} Gross physical hydro power potential is illustrated in GWh/y for unit elements of 30 km x 50 km size.

Total global installed hydro power capacity was 945 GW by end of 2008 and generated electricity was 3,208 TWh in the year 2008, translating to 3,390 full load hours.⁵ About 114 GW (12%) of the aforementioned hydro power capacity is used for pumped hydro storage, thereof in Europe (40 GW), North America (19 GW), Asia (50 GW) and other regions (5 GW). Full load hours excluding pumped hydro storage would be about 3,860.

It is necessary to know the coordinates of the hydro power plants for further analysis. Due to that the UDI World Electric Power Plants database⁶ has been enhanced by coordinates of all 145,000 power plants in the world.⁷ The database comprises a power plant capacity of 4,570 GW being in operation by early 2009. However, a cross-check reveals a missing capacity of about 55 GW of hydro power plants (890 GW in the database versus 945 GW real capacity). The reason for such a significant deviation remains unclear.

In several regions in the world it has been quite challenging to get the exact coordinates, however the coordinates of the capital of the respective local administration has been taken in these cases. The result of the georeferenced global power plant capacity being in operation is depicted in Figure 7.1-2.

² Bartle A., Hydropower potential and development activities, 2002

³ Czisch G., Szenarien zur zukünftigen Stromversorgung - Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien, 2005, p. 94

⁴ Alcamo J. et al., The Global Integrated Water Model WaterGAP 2.1, 2001

⁵ IEA, World Energy Outlook 2010, 2010

⁶ Platts, UDI World Electric Power Plants data base, 2009

⁷ Görig M., Elektrische Kraftwerke – weltweite Verteilung, Verknüpfung mit geografischen Koordinaten, 2010

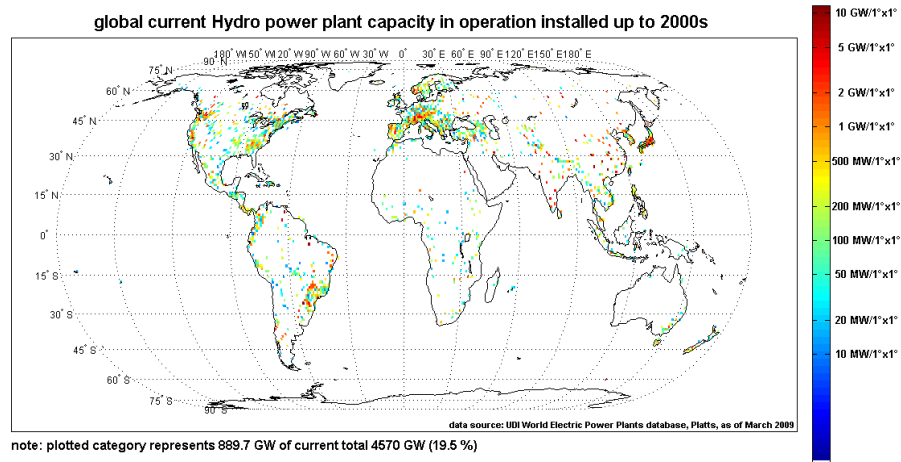


Figure 7.1-2: Global hydro power plant capacity in georeferenced coordinates by early 2009. Only power plants in operation are regarded. However, there are recorded 890 GW of total installed 945 GW in the database leaving capacity of 55 GW dislocated. Data are plotted in a $1^\circ \times 1^\circ$ mesh of latitude and longitude. Data are taken from UDI World Electric Power Plants database⁸ and enhanced by exact coordinates of all power plants.

Coupling of georeferenced hydro power plant data (Fig. 7.1-2) to solar resource data, e.g. irradiation on fixed optimally tilted module surfaces (Fig. 2.2-3), generates new insights on solar resource quality at sites of current hydro power plant capacity (Fig. 7.1-3). About 340 GW out of 890 GW included in the database are located in areas of more than 1,800 kWh/m²/y irradiation on fixed optimally tilted module surfaces, i.e. 38% of global hydro power installed base is already installed in regions of very good solar resource quality. It is not possible to distinguish hydro power storage dams and river run-off plants. The former would be a perfect balancing plant for PV (section 7.1.2), but also the latter might roughly match to PV due to seasonal effects.

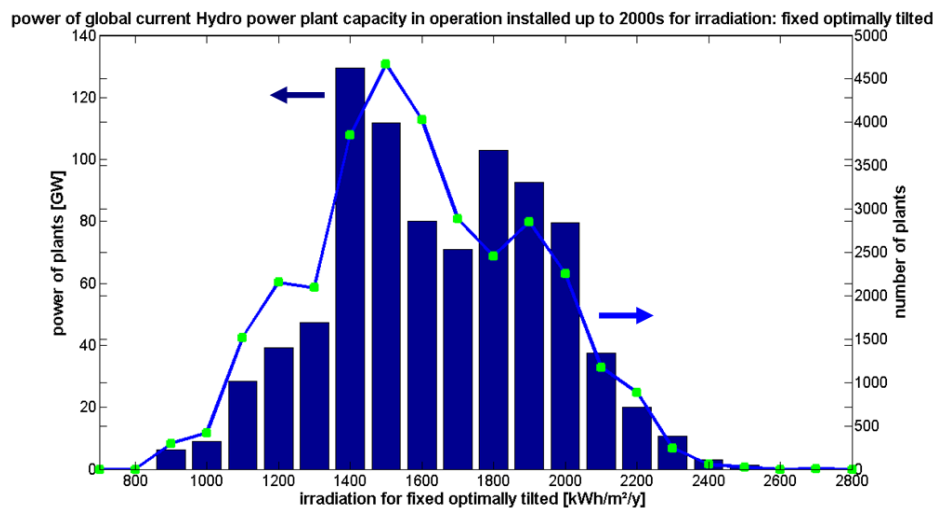


Figure 7.1-3: Global hydro power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems. The line is referred to the right axis and represents the number of power plants for the respective irradiation interval. The bars are referred to the left axis and represent electricity generation. Data are derived from results for georeferenced power plants (Fig. 7.1-2) and solar resource for fixed optimally tilted modules (Fig. 2.2-3).

⁸ Platts, UDI World Electric Power Plants data base, 2009

It might be of relevance to understand the number and power capacity of power plants per power size class. This is illustrated in Figure 7.1-4 and shows that most power plants are in the power class of 1 - 10 MW or even smaller in size. However, their contribution to global power capacity is nearly negligible. Almost 38% of global power plant capacity consists of power plants of 10 - 100 MW in size and 56% in the power class of 100 - 1000 MW.

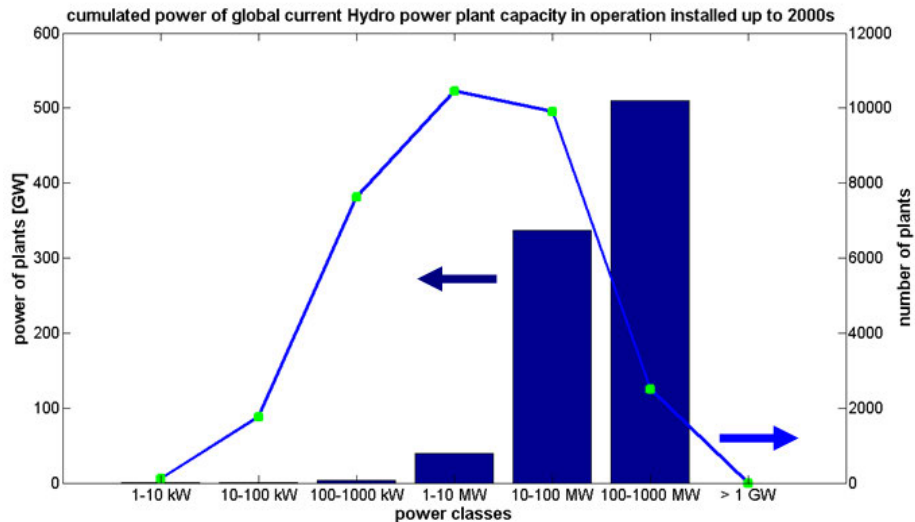
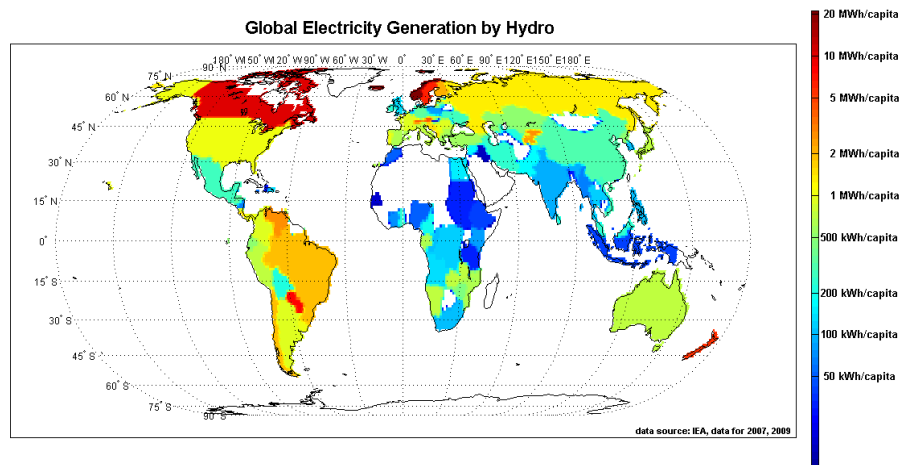


Figure 7.1-4: Global hydro power plant capacity in dependence on respective power plant size. The line is referred to the right axis and represents the number of power plants for the respective plant size. The bars are referred to the left axis and represent power plant capacity. Data are taken from UDI World Electric Power Plants database⁹.

Contribution of hydro power to global electricity supply is very significant and accounts for about 20%. Global average total electricity generation per capita is about 3.0 MWh_{el} but 5 – 10 MWh_{el} in industrialised countries (sub-chapter 5.1). Leading hydro electricity per capita countries in the world are Norway and Iceland achieving 25 and 22 MWh_{el} per capita, respectively (Fig. 7.1-5). Several other countries reach high hydro power supply per capita, as well. Comparison of global hydro power generation (Fig. 7.1-5) to global hydro power resource (Fig. 7.1-1) reveals further significant potential in Africa, South America and Asia. But hydro power plants are always an enormous intervention to the local ecosystems and need to be evaluated in respect to sustainability criteria.



⁹ Platts, UDI World Electric Power Plants data base, 2009

Figure 7.1-5: Global electricity generation by hydro per capita for the year 2007. No data or values below 10 kWh/capita have been available for white coloured countries. Data are provided by International Energy Agency¹⁰ and United Nations¹¹.

Global installed hydro power plant capacity per country is illustrated in Figure 7.1-6. Leading countries by cumulated hydro power capacity are China, the US, Brazil and Canada by end of 2008. However, hydro power resource (Fig. 7.1-1) is also excellent in Africa, South America and South Asia, hence significant further hydro power installations in these regions can be expected in future.

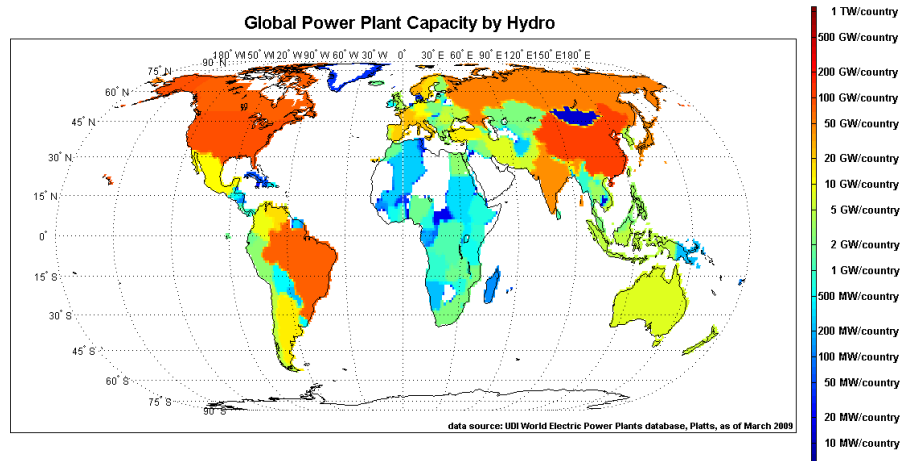


Figure 7.1-6: Global hydro power plant capacity per country by early 2009. Only power plants in operation are regarded. However, about 890 GW of total installed 945 GW are recorded in the database leaving capacity of 55 GW dislocated. Data are taken from UDI World Electric Power Plants database¹².

The structure of power plant capacity can be illustrated on a per country basis for average annual full load hours (Fig. 7.1-7) and relevance of respective domestic overall electricity generation (Fig. 7.1-8). Hydro power can be used in different operation modes, i.e. either base load but also for full power supply. There are several countries in the world achieving a hydro power supply contribution of nearly 100%, e.g. Norway, Tajikistan, Mozambique, Zambia, Albania, DR Congo, Ethiopia, Nepal and Paraguay. Full load hours of hydro power plants are dependent on the operation mode and seasonal hydro power resource availability. Combination of PV and hydro power could be a real option and is discussed in the next section.

¹⁰ IEA, Key World Energy Statistics 2009, 2009

¹¹ UN, World Population Prospects: The 2008 Revision Highlights, 2009

¹² Platts, UDI World Electric Power Plants data base, 2009

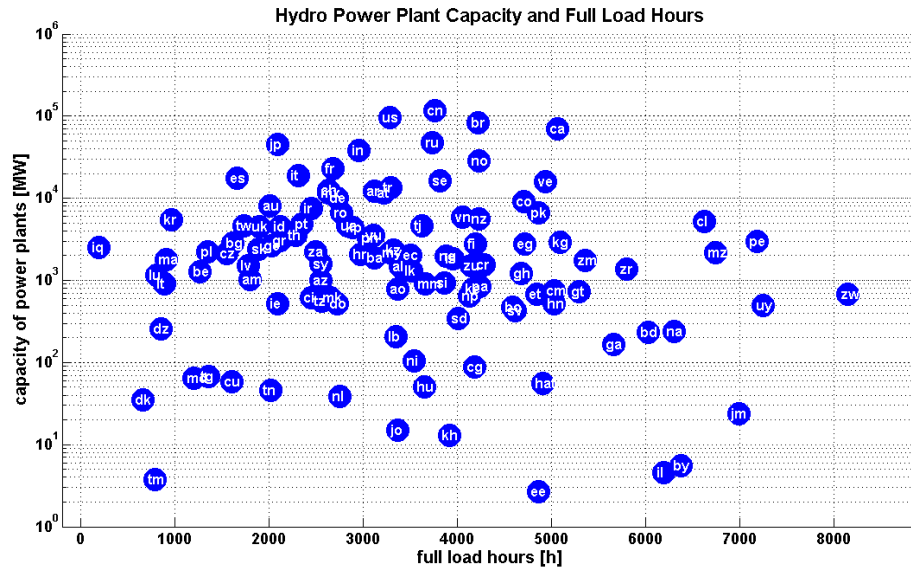


Figure 7.1-7: Hydro power plant capacity in dependence on full load hours per country. Each dot represents the absolute hydro power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ¹³ and International Energy Agency ¹⁴.

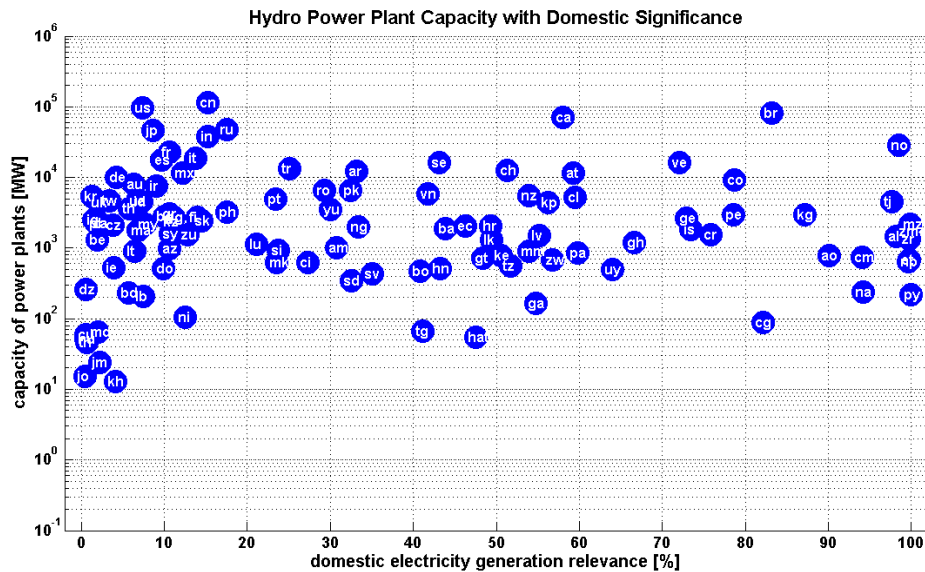


Figure 7.1-8: Hydro power plant capacity in dependence on domestic electricity generation relevance per country. Each dot represents the absolute and relative hydro power structure of one country in the world. Countries are named by their country code of top level web domain (Appendix Table 4). Data are taken from UDI World Electric Power Plants database ¹⁵ and International Energy Agency ¹⁶.

Global distribution of full load hours and ratio to total domestic electricity generation is depicted in Figure 7.1-9 for visualising purposes. Identical information is given in Figures 7.1-7 and 7.1-8, but for subjective perception and for an analysis coordinate wise this kind of illustration is very helpful.

¹³ Platts, UDI World Electric Power Plants data base, 2009

¹⁴ IEA, Key World Energy Statistics 2009, 2009

¹⁵ Platts, UDI World Electric Power Plants data base, 2009

¹⁶ IEA, Key World Energy Statistics 2009, 2009

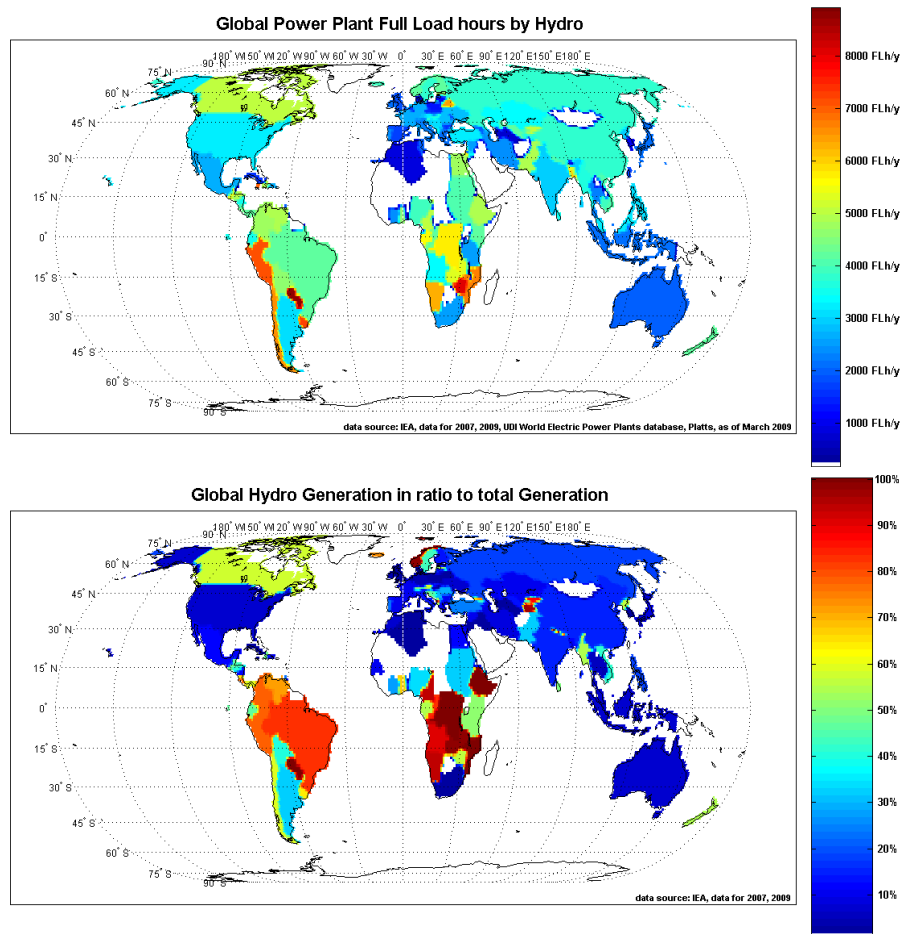


Figure 7.1-9: Global distribution of hydro power plant full load hours (top) and the ratio to total domestic electricity generation (bottom). Data are taken from UDI World Electric Power Plants database ¹⁷ and International Energy Agency ¹⁸.

Summing up, global hydro power plant capacity of 945 GW is in average 3,390 full load hours in operation and generate annually about 3,210 TWh of electricity, representing 20% of total global installed power capacity and 16% of global generated electricity. In industrialised countries hydro power potential is largely utilised, e.g. in Europe, Japan and the US. However, in some regions in the world, further significant installations can be expected in future, e.g. in Africa, South America and South Asia. Combination of fluctuating PV and wind power to hydro power is an excellent match in case of hydro power storage dams and might be a viable option for river run-off plants. In the following section, hybrid PV-Hydro power plants are discussed in more detail.

7.1.2 Considerations on Hybrid PV-Hydro Power Plants

In the last section an enormous market potential for hybrid PV-Hydro power plants is identified, since about 340 GW of hydro power capacities are located in regions of more than 1,800 kWh/m²/y irradiation on fixed optimally tilted module surfaces, which corresponds to about 38% of global hydro power capacity (Fig 7.1-3).

¹⁷ Platts, UDI World Electric Power Plants data base, 2009

¹⁸ IEA, Key World Energy Statistics 2009, 2009

Despite of this enormous market potential for hybrid PV-Hydro power plants only very few realised projects are known. The existing hybrid PV-Hydro systems are smaller micro-grid or mini-grid applications (section 3.4.2), for instance a 14 kWp PV system in the natural park of O’Invernadeiro in Galicia which is coupled to a 2.5 kW hydro turbine^{19,20} or a 10 kWp PV system as sub-systems of a hybrid PV-Wind-Hydro-Diesel system on the Isle of Eigg in Scotland²¹. Recently, plans have been proposed for integrated hybrid PV-Hydro power plants in European countries, e.g. Croatia, Switzerland and Spain.^{22,23,24} Outside Europe similar considerations have been published for hybrid PV-Hydro power plants in Brazil and India.^{25,26}

However, in the case of Croatia a hybrid PV-Hydro storage solution including a 41 MWp PV sub-plant and a pumped hydro storage of 20 mio m³ and 235 m height difference is suggested for supplying the Island of Vis.²⁷ Nordmann et al. suggest a PV upgrade of hydro power storage lakes.²⁸ PV systems would be installed on floating structures on the water surface. The local power infrastructure can be used for both PV and hydro power and as a consequence the area already covered by the hydro power storage lake could be further energetically used by PV systems. The generated energy of the 440 MWp PV system would be two times higher than that of the 158 MW hydro power system despite of only covering 25% of the lake’s surface for the case study of Silsee. The hybrid PV-Hydro power plant uses the hydro power storage lake as a virtual storage battery, since the power generation of the hydro power sub-plant can be reduced during daytime, thus using the valuable stored energy only in those periods when solar electricity is not available. The energy density of the PV electricity is remarkably high in comparison to the already existing hydro power plant. In Switzerland about 17 m² per capita are used for hydro power generation reaching about 50% of total Swiss electricity supply, whereas only 6.3 m² per capita would be necessary for a 10% PV electricity share. This example for the case of Switzerland shows the relatively high energy density of PV systems. As similar analysis for the case of Spain confirms the high energy density of PV systems compared to hydro power storage lakes.²⁹ In Spain the surface of all hydro power storage lakes is about 980 km², which could be upgraded by about 30 GW of PV systems if only 25% of the already covered surface of the lakes would be used for additional PV power generation being equivalent to about 39 TWh per year representing 14% of annual Spanish electricity demand.

In 2001 a comprehensive ‘PV-Hydro Initiative’ study on hybrid PV-Hydro plants was published by Lahmeyer International and Solar-Institut Jülich on behalf of Kreditanstalt für Wiederaufbau, UNEP and GEF.³⁰ The objective of the study was to identify power systems in developing countries that are suitable for the installation of MW-scale PV generation capacity

¹⁹ Vallvé X. et al., First Experiences from the Electrification of Rural Villages in Spain with Multi-user Solar Hybrid Grids (MSG), 2001

²⁰ Vázquez M. et al., A 14 kWp Stand-alone Photovoltaic Plant in the Natural Park of O’Invernadeiro in Galicia, Spain, 2004

²¹ Thim F. et al., Conception and Operation of a Unique Large-scale PV Hybrid System on a Hebridean Island, 2010

²² Glasnovic Z. and Margeta J., Optimal Sizing of Photovoltaic-hydro Power Plant, 2009

²³ Nordmann T. et al., Large Scale Hybrid PV Hydro Electricity Production in Floating Devices on Water, 2009

²⁴ Nordmann T. et al., Large Scale PV Implementation and Grid Integration with Hybrid PV Hydro Power Plants Using Floating PV Devices Potential Study and Future Markets, 2010

²⁵ Beluco A. et al., Hybrid Plants Based on Complementary Hydro and Photovoltaic Energy Resources, 2001

²⁶ CEA, Integration of Solar Systems with Thermal/ Hydro Power Stations, 2010

²⁷ Glasnovic Z. and Margeta J., Optimal Sizing of Photovoltaic-hydro Power Plant, 2009

²⁸ Nordmann T. et al., Large Scale Hybrid PV Hydro Electricity Production in Floating Devices on Water, 2009

²⁹ Nordmann T. et al., Large Scale PV Implementation and Grid Integration with Hybrid PV Hydro Power Plants Using Floating PV Devices Potential Study and Future Markets, 2010

³⁰ KfW, PV-Hydro Initiative, 2001

connected to the grid and operated in conjunction with existing hydro plants which are energy, i.e. water, constrained. These hydro power plants possess spare storage capacity which could be used to a higher extent the installed generation capacity. The intermittent and non-dispatchable PV power plants could be converted in higher value plants through peak-shaving and in particular re-scheduling of the hydro power sub-plants using the unused storage capacities as a virtual battery. The hybrid PV-Hydro power plant would thereby increase the amount of firm energy available to supply the system during times of peak demand and displace an equivalent amount of fossil fired power generation and thus avoid greenhouse gas emissions.

In the 'PV-Hydro Initiative' study the total market potential for hybrid PV-Hydro power plants was assessed nearly identical to the outcome in Figure 7.1.3, since 315 GW hydro power capacity already installed or under construction in the year 2001 were identified for regions of at least 1,700 kWh/m²/y global horizontal irradiation.³¹ About 40% of the identified capacity was considered to be suitable for a hybrid PV-Hydro power plant operation. Case studies had been performed for six exemplarily countries, which could receive World Bank funding for respective investments. These countries are Namibia, Sri Lanka, Ethiopia, Peru, Mexico and Venezuela. The breakeven price for the PV sub-plant for the oil importing countries, i.e. Namibia, Sri Lanka, Ethiopia and Peru, is estimated to be around 3,000 – 4,300 €/kWp for a crude oil price of 70 USD/barrel (Table 7.1-1). The breakeven PV costs depend on some interdependent factors which cannot be isolated from each other. The most important ones have been found to be the shape of the seasonal load duration curves, shape of the daily load curves, type of hydro dispatch, coincidence of daily peak and PV power supply and type of energy replaced by PV power.³²

oil price [USD/bl]	discount rate [%]	carbon credits [USD/tCO ₂]	breakeven for PV sub-plant of hybrid PV-Hydro power plant					
			Sri					
			Namibia	Lanka	Ethiopia	Venezuela	Mexico	Peru
			€/kWp	€/kWp	€/kWp	€/kWp	€/kWp	€/kWp
30	10%	0	1,200	1,180	1,160	880	800	1,390
30	10%	10	1,300	1,310	1,220	970	920	1,500
30	5%	0	1,920	1,770	1,720	1,280	1,130	2,110
30	5%	10	2,090	1,970	1,820	1,420	1,300	2,300
70	5%	10	4,250	4,300	3,000			3,850

Table 7.1-1: Breakeven cost for PV sub-plant of hybrid PV-Hydro power plant in dependence of oil price, discount rate and carbon credits for several developing countries.³³ The breakeven prices for the crude oil price of 70 USD/barrel are calculated on basis of the identical conditions assumed in the study but performed in the year 2009.³⁴

The realistic scenario for PV power plant Capex in the year 2010 ranges between 1,800 – 2,050 €/kWp and the PV industry cost curve for the year 2010 revealed PV power plant Capex of 1,900 – 2,100 €/Wp in the two most competitive markets in the world (section 3.2.2). As a consequence at least in the four oil importing countries of the 'PV-Hydro Initiative' it would be very beneficial to upgrade existing hydro power plants by PV power

³¹ KfW, PV-Hydro Initiative, 2001

³² KfW, PV-Hydro Initiative, 2001

³³ KfW, PV-Hydro Initiative, 2001

³⁴ Klaus W., private communication, 2009

plants to hybrid PV-Hydro power plants. It is very likely, that considerable capacities of the 40% suitable hydro power plants of the 315 GW derived capacity in sunny regions have already reached profitability, i.e. about 125 GW.

In a comprehensive analysis of hybrid PV-Hydro power plants it would be very fruitful to evaluate the results found for hybrid Wind-Hydro power plants^{35,36,37} and how to transfer this outcome to hybrid PV-Hydro power plants. The results for hybrid PV-Wind power plants (sub-chapter 7.3) are of utmost relevance, since in many cases hybrid PV-Wind-Hydro power plants might be the most beneficial solution, at all.

Summing up, not only fossil fuel fired power plants can be used for upgrading with PV power plants to hybrid PV-Fossil power plants, but also hydro power plants are well suited for upgrading to hybrid PV-Hydro power plants. About 340 GW existing hydro power plant capacities are installed in regions of very good solar resource conditions and about 40% of these capacities might be appropriate as hydro power sub-plant of potential hybrid PV-Hydro power plants. At a crude oil price of at least 70 USD/barrel most of these capacities are expected to generate additional financial benefits if upgraded by PV power plants.

7.2 Hybrid PV-STEG Power Plant

Resource assessment for concentrating and non-concentrating PV shows excellent resource availability for both technological approaches (section 2.2.9). This can be fully transferred to the comparison of non-concentrating solar PV and solar thermal electricity generation (STEG). However, the analysis of STEG economics (sub-chapter 4.1) and the integrated assessment of STEG, PV and wind power economics (sub-chapter 4.3) clearly outlines the low competitiveness of STEG versus PV and wind power in terms of levelized cost of electricity (LCOE). Nevertheless, STEGs can provide fully dispatchable power supply due to favourable thermal energy storage, whereas limitations in seasonal storage might be still a challenge to overcome, dependent on local seasonal solar resource variations and load patterns.

Key advantage of STEG is the thermal energy storage which enables a flexible and dispatchable power plant configuration being easily adaptable to existing power grids and power plant portfolios. A major advantage of PV power plants is the very fast cost degression as a consequence of high learning and growth rates (sections 3.1.1 and 3.1.2). The cost advantage of PV seems to be very stable in time due to significantly higher learning and growth rates than STEG. Combining both major solar electricity technologies creates a hybrid PV-STEG power plant. The PV sub-plant provides power to the grid whenever the sun is shining. The STEG sub-plant is used only in case of power demand and no available power by the PV sub-plant, in particular in the evenings or at night. The principle structure of the hybrid PV-STEG power plant is depicted in Figure 7.2-1.

³⁵ Denault M. et al., Complementarity of hydro and wind power: Improving the risk profile of energy inflows, 2009

³⁶ Bélanger C. and Gagnon L., Adding wind energy to hydropower, 2002

³⁷ Førsund F.R. et al., Phasing in wind-power in Norway: Network congestion and crowding-out of hydropower, 2008

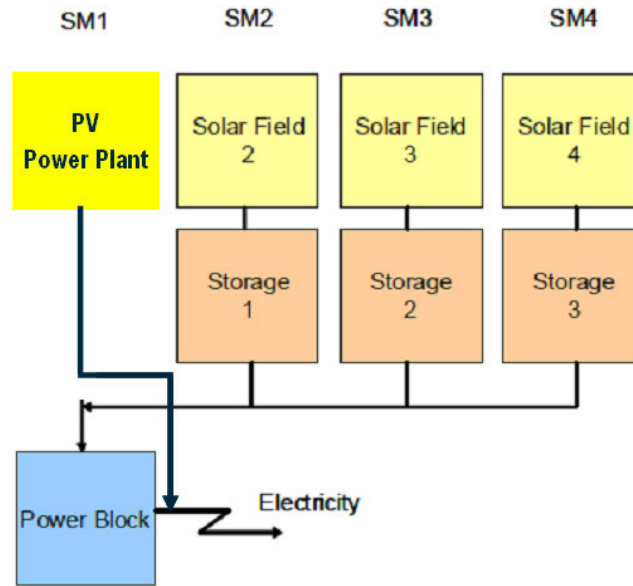


Figure 7.2-1: Principle structure of a hybrid PV-STEG power plant configuration with different solar multiples (SM). The structure is in analogy to a STEG plant (Fig. 4.1-2).³⁸

Major technical preconditions are the integrated control and interdependent adjustment of both sub-plants, as it needs to be the case for all hybrid power plants (section 6.1.1), and a nearby power feed-in, in particular not too far away from each other. The latter is very relevant for stable grids, however the two sub-plants might be located within a radius of about 100 km and connected to the same power grid infrastructure.³⁹ Furthermore, the combination of PV and STEG power plants need to be financially beneficial, otherwise the increase in complexity would make no sense compared to the single components.

In the following the economics of hybrid PV-STEG plants are analysed for answering the principle question whether there could be a financial room for such a power plant configuration. The LCOE analysis in this sub-chapter is fully based on the respective scenarios applied for PV (Table 3.2-1) and STEG (Table 4.1-1). The inclusion of a PV sub-plant would reduce the full load hours (FLh) of the power block of the STEG plant, hence these scaling disadvantage need to be covered by the PV sub-plant. This LCOE disadvantage is illustrated in Figure 7.2-2 and is based on the respective LCOE analyses of single STEG plants (Fig. 4.1-12).

³⁸ Trieb F. et al., Global Potential of Concentrating Solar Power, 2009

³⁹ Breyer Ch. et al., Kraftwerk, German Patent and Trademark Office, 2010f

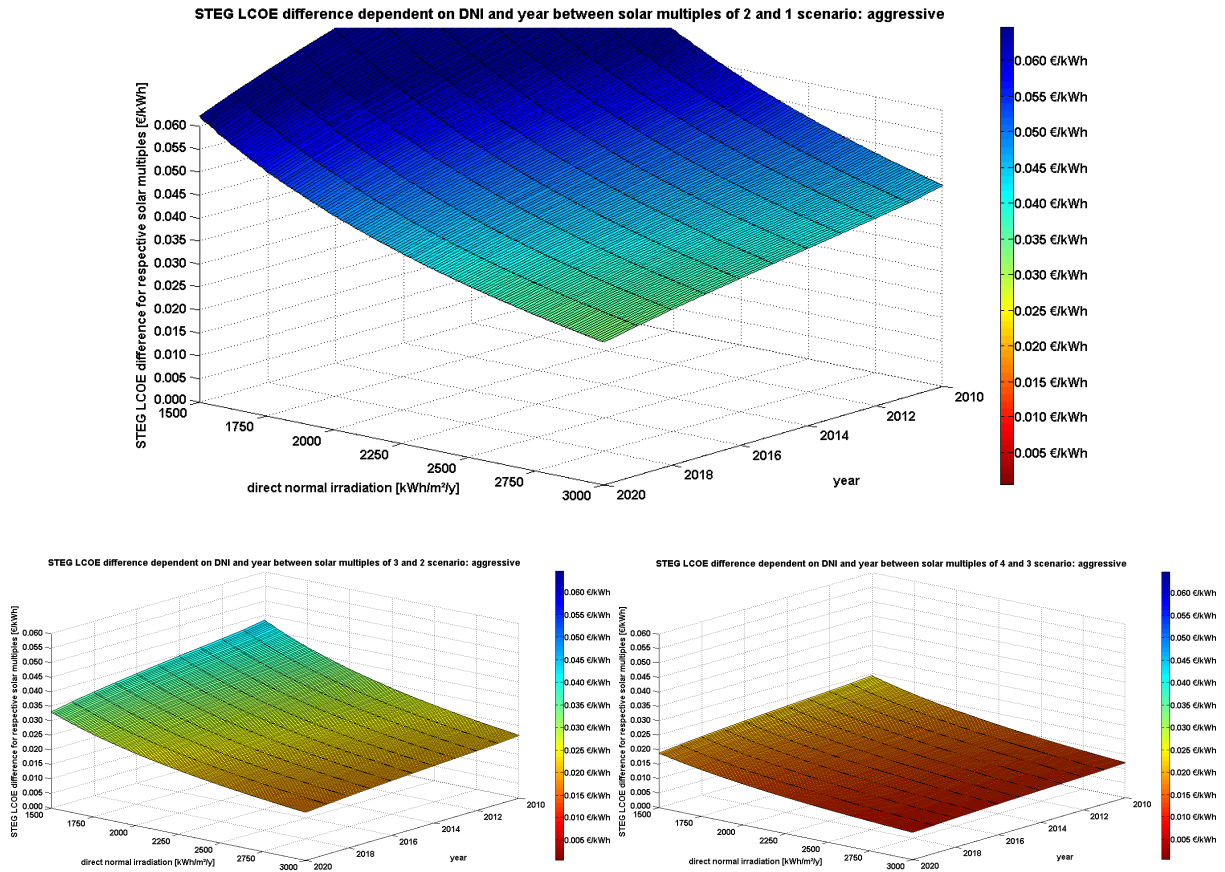


Figure 7.2-2: STEG LCOE differences in dependence on DNI resource and the year in the 2010s for the solar multiple reduction two to one (top), three to two (bottom, left) and four to three (bottom, right) in the aggressive scenario. The aggressive scenario is defined in Table 4.1-1.

Depending on direct normal irradiation (DNI), solar multiple (SM) and year in the 2010s the increase in STEG LCOE due to a reduction in FLh is in the range of 1 – 6 €/kWh. These numbers show a fundamental trade-off, since the highest additional cost are induced for the reduction of STEG SM2 to SM1, but STEG LCOE of SM2 are also higher than those of higher SM. This effect need to be better understood, hence the PV LCOE potential is derived and plotted in Figure 7.2-3. The PV LCOE potential is defined by STEG LCOE of SMn minus STEG LCOE differences for SMn and SMn-1. This adjustment is in analogy to the necessary compensation of reduced FLh of the fossil fuel fired sub-plant by the PV sub-plant of a hybrid PV-Fossil power plant in sub-chapters 6.2 to 6.4. This estimate is a rough approximation, but PV FLh and STEG SM1 FLh are more or less in the same order. PV LCOE identical to PV LCOE potential would generate no financial benefit, hence PV LCOE need to be significantly below that limit.

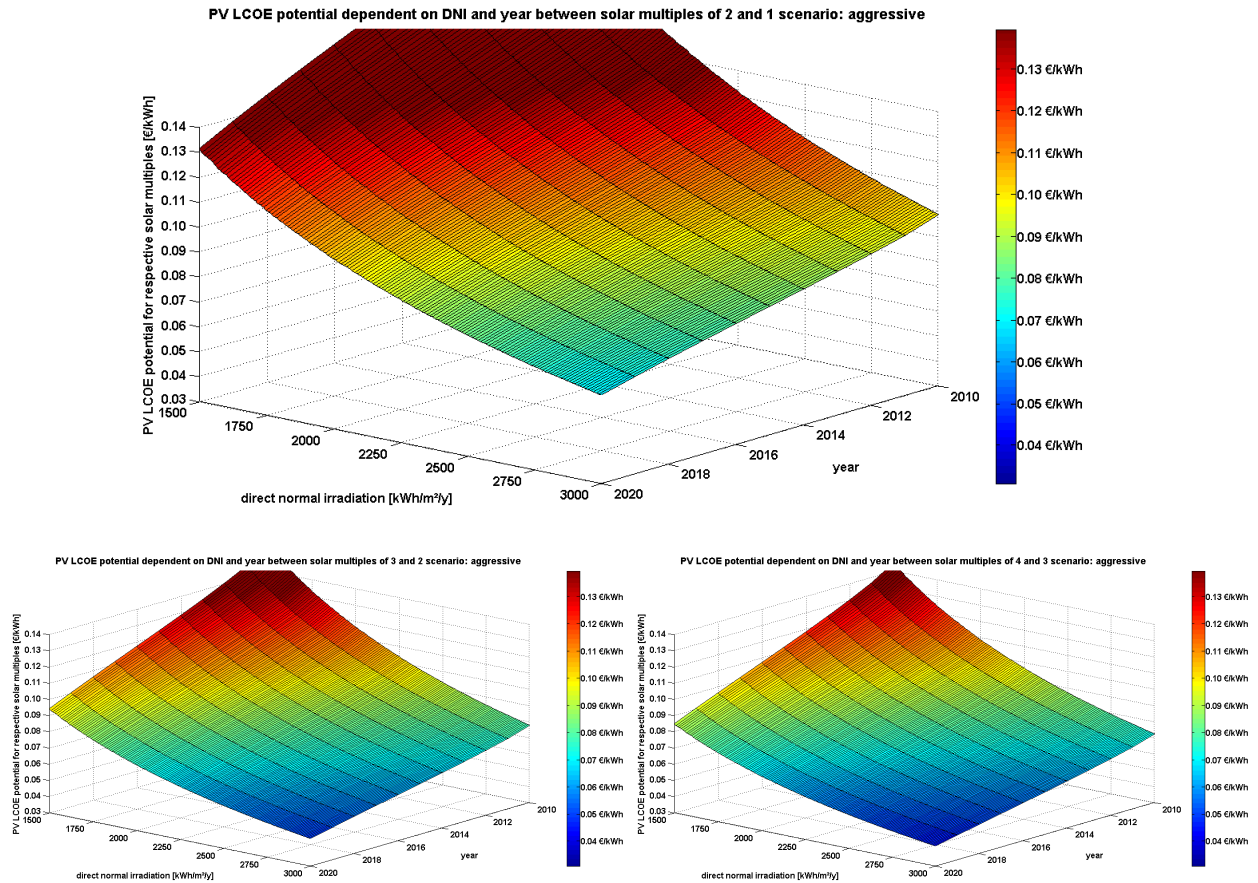


Figure 7.2-3: PV LCOE potential for the PV sub-plant of hybrid PV-STEG plants in dependence on DNI resource and the year in the 2010s for the solar multiple reduction two to one (top), three to two (bottom, left) and four to three (bottom, right) in the aggressive scenario. The PV LCOE potential is defined by STEG LCOE of SM_n minus STEG LCOE differences for SM_n and SM_n-1 . The aggressive scenario for STEGs is defined in Table 4.1-1.

Hybrid PV-STEG power plants for STEGs of an original SM_2 creates the highest PV LCOE potential, i.e. in the range of 7 – 13 €/kWh for good to excellent solar resource conditions during the 2010s. The PV LCOE potential is lower for a higher solar multiple, i.e. 5 – 10 €/kWh and 4 – 9 €/kWh for an original STEG SM_3 and SM_4 , respectively. These LCOE trajectories are right in the range of the realistic and aggressive PV scenario (Fig. 3.2-17 and 3.2-18).

Attractiveness of hybrid PV-STEG power plants for PV sub-plants is dependent on the absolute and relative PV LCOE in relation to the PV LCOE potential (Fig. 7.2-3). The attractiveness is a function of the scenario assumptions and the solar multiple of the original STEG sub-plant. The attractiveness is derived and illustrated for the case of aggressive scenario assumptions and original SM_2 (Fig. 7.2-4) and SM_3 (Fig. 7.2-5).

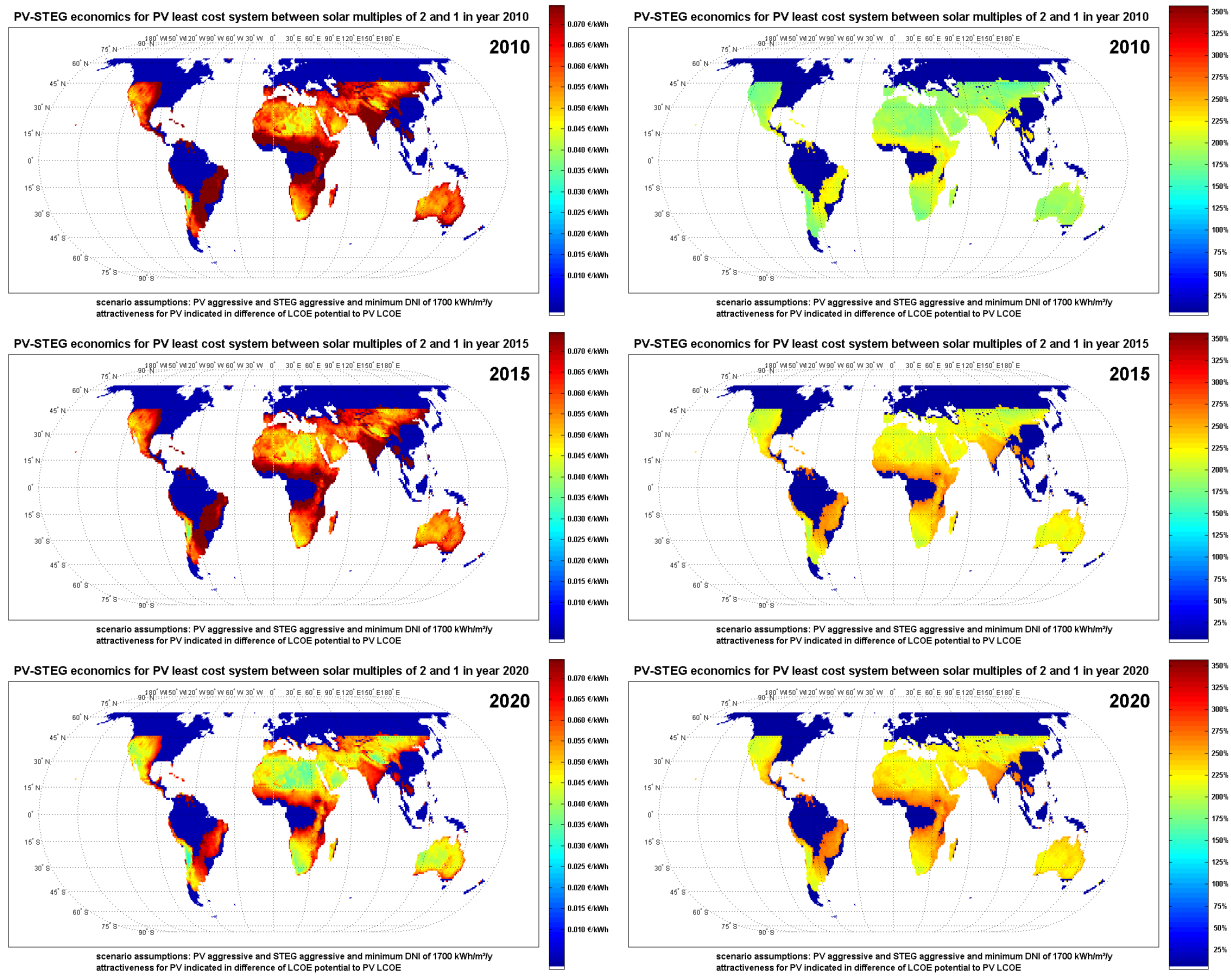
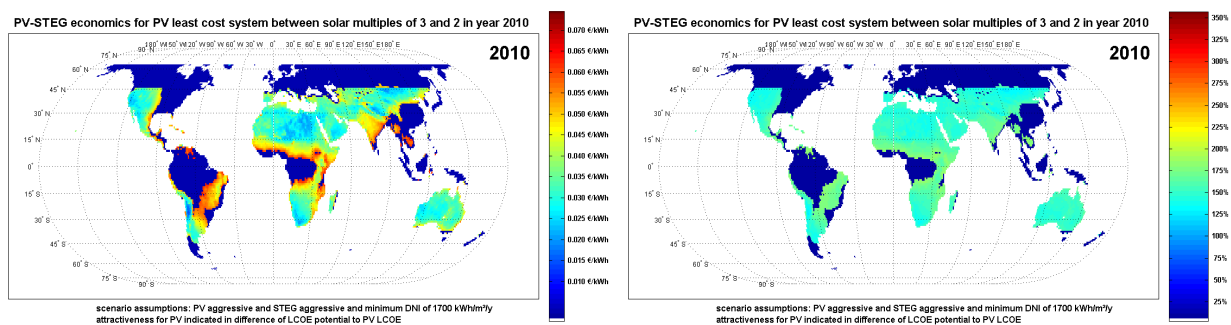


Figure 7.2-4: Attractiveness for a PV sub-plant within a hybrid PV-STEg plant indicated by PV LCOE benefit in absolute (left) and relative (right) numbers for an original STEg SM2 sub-plant for aggressive scenario assumptions of PV and STEg sub-plants and for the years 2010 (top), 2015 (centre) and 2020 (bottom). The absolute (left) PV LCOE benefit is defined by PV LCOE potential minus PV LCOE of least cost system. The relative attractiveness (right) is defined by the ratio of PV LCOE potential to PV LCOE of least cost system. Results are plotted for a DNI of at least 1,700 kWh/m²/y due to minimum economics. The aggressive scenario is defined and illustrated for PV in Table 3.2-1 and Figure 3.2-14 and for STEg in Table 4.1-1 and Figure 4.1-6.



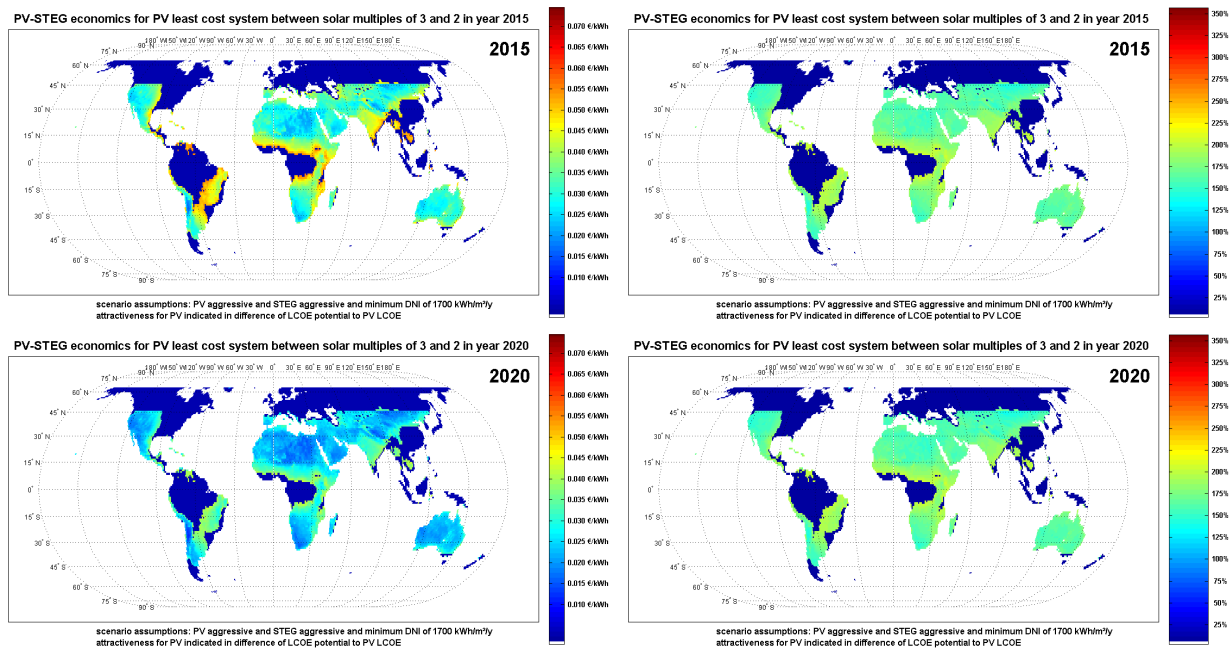


Figure 7.2-5: Attractiveness for a PV sub-plant within a hybrid PV-STEG plant indicated by PV LCOE benefit in absolute (left) and relative (right) numbers for an original STEG SM3 sub-plant for aggressive scenario assumptions of PV and STEG sub-plants and for the years 2010 (top), 2015 (centre) and 2020 (bottom). The absolute (left) PV LCOE benefit is defined by PV LCOE potential minus PV LCOE of least cost system. The relative attractiveness (right) is defined by the ratio of PV LCOE potential to PV LCOE of least cost system. Results are plotted for a DNI of at least 1,700 kWh/m²/y due to minimum economics. The aggressive scenario is defined and illustrated for PV in Table 3.2-1 and Figure 3.2-18 and for STEG in Table 4.1-1 and Figure 4.1-7.

In case of an original STEG SM2 the PV LCOE benefit (Fig. 7.2-4), i.e. PV LCOE potential minus PV LCOE of least cost system, is in the range of 4 – 6 €/kWh for the 2010s corresponding to a ratio of PV LCOE potential to PV LCOE of least cost system of about 190% to 230%, i.e. the PV LCOE might be only about 50% of the PV LCOE potential. As a consequence the economics of a hybrid PV-STEG power plant of an original STEG SM2 are excellent, since the total LCOE of the hybrid PV-STEG power plant are lower than the single STEG SM2 plant. These economic benefits might be partially earned by the PV sub-plant developer, the hybrid PV-STEG power plant operator or by the customers of the plant operator via lower electricity prices.

The results for original STEG SM3 plants are less favourable (Fig. 7.2-5) than for SM2 plants, i.e. PV LCOE benefit of about 1.5 – 4.0 €/kWh and PV LCOE being 20% to 40% lower than the maximum PV LCOE potential. This outcome indicate a sufficient high attractiveness for combining PV and STEG SM3 plants, but it is significantly lower than for the SM2 case.

In general, a faster than assumed PV cost reduction would improve respective attractiveness and a slower than assumed STEG cost reduction would also increase the economics of hybrid PV-STEG power power plants, and vice versa. STEG SM2 plants are better suited for hybridization than SM3 plants. In early 2010s, most STEG plants in the planning phase or under construction are of the SM2 or even SM1 type, hence in case of SM2 excellent conditions are given for upgrading them into hybrid PV-STEG power plants. Hybrid PV-STEG power plants would be a new market segment for PV power plants and might further increase the growth rate of PV systems. Hybrid PV-STEG power plants combine the key advantage of each single solar power technology for overcoming the respective key disadvantage, i.e. PV is lower in LCOE than STEG but fluctuates whereas STEG is fully

dispatchable but higher in LCOE than PV. By combining complementary strengths of the two major solar power technologies, both PV and STEG might increase the technological diffusion of each other – an obvious win-win situation for both technologies.

7.3 Hybrid PV-Wind Power Plant

The global energy supply potential of PV and wind power exceeds by far the energy demand of human mankind. Total primary energy demand has been about 151,200 TWh_{th} (12,270 Mtoe) in the year 2008, i.e. about 17 TW of continuous energy flow.⁴⁰ However, substantial amount of this primary energy demand is wasted in inefficient energy use based on burning fuels, i.e. direct use of valuable electricity would reduce the aforementioned energy flow to about 11.5 TW provided for instance by solar PV or wind power.⁴¹ The technical energy potential of solar PV and wind is assessed differently by various authors but always by factors or orders higher than total global energy demand. In 1978 Weingart estimated the solar PV potential energy flow usable for mankind being higher than 100 TW.⁴² In 2003, the German Advisory Council on Global Change derived a harvestable energy flow potential for wind power of about 90 TW and a practically unlimited potential for PV.⁴³ However, these numbers have been adjusted in 2011 to a technical potential of about 54 TW for wind power and about 8,900 TW for solar energy hence also for PV.⁴⁴ In the 2008 ‘energy [r]evolution’ study of Greenpeace the utilizable energy flow has been estimated to about 35 TW for wind power and 150 TW for PV.⁴⁵ Also in 2008, Sawin and Moomaw estimated the energy flow potential to about 145 TW for PV and about 55 TW for wind power.⁴⁶ In 2009, Lu et al. estimated the energy flow for wind power to about 80 – 150 TW.⁴⁷ Jacobson and Delucchi derived an energy flow of 40 – 85 TW for wind and 580 TW for PV.⁴⁸ In 2011 the IPCC derived a theoretically utilizable energy flow of about 190 TW for wind power and about 120,000 TW for PV.⁴⁹ The estimates for the technical potential of PV and wind power is summarized in Table 7.3-1. Other authors clearly pointed out that wind and solar energy will become the backbone of the global energy supply and that this could happen already before 2030.⁵⁰ The awareness of the necessity to establish a solar powered society dates back many decades and was emphasized for instance by Hubbert already in 1949.⁵¹

technical potential		referenced	PV	Wind
			[TW]	[TW]
Weingart	1978	⁵²	> 100	-
WBGU	2003	⁵³	infinite	90
Greenpeace	2008	⁵⁴	150	35

⁴⁰ IEA, World Energy Outlook 2010, 2010

⁴¹ Jacobson M.Z. and Delucchi M.A., A Path to Sustainable Energy by 2030, 2009

⁴² Weingart J.M., The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, 1978

⁴³ WBGU, World in Transition: Towards Sustainable Energy Systems, 2003

⁴⁴ WBGU, Welt im Wandel: Gesellschaftsvertrag für eine Große Transformation, 2011

⁴⁵ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2008

⁴⁶ Sawin J.L. and Moomaw W.R., An enduring energy future, 2008

⁴⁷ Lu X. et al., Global potential for wind-generated electricity, 2009

⁴⁸ Jacobson M.Z. and Delucchi M.A., A Path to Sustainable Energy by 2030, 2009

⁴⁹ IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), 2011

⁵⁰ Kohn W., A world powered predominantly by solar and wind energy, 2010

⁵¹ Hubbert M.K., Energy from Fossil Fuels, 1949

⁵² Weingart J.M., The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, 1978

⁵³ WBGU, World in Transition: Towards Sustainable Energy Systems, 2003

Sawin and Moomaw	2008	⁵⁵	145	55
Lu et al.	2009	⁵⁶	-	80 – 150
Jacobson and Delucchi	2009	⁵⁷	580	40 – 85
WBGU	2011	⁵⁸	8900	54
IPCC SRREN	2011	⁵⁹	120000	190
current global energy demand				
including waste of heat	[TW]		17.0	
direct energy demand	[TW]		11.5	

Table 7.3-1: Technical potential of PV and wind power versus the current global energy demand.

In addition, several analyses in this thesis clearly indicate an excellent power supply potential of PV and wind power, mainly concerning resource availability (chapter 2 and section 4.2.1) and cost projections (sub-chapter 3.2 and section 4.2.3). An integrated economic assessment of PV and wind power clearly results in equalling LCOE levels of both major new renewable power technologies in the range of about 4 - 7 €/kWh projected for the end of the 2010s at sites of at least good resource availability (Fig. 4.3-2 to 4.3-5). Several regions in the world have good or even better resource and thus LCOE availability for both technologies, e.g. the US, southern South America, North Africa, China or Australia.

The competitive edge of PV systems is found to be excellent in rural off-grid markets (sub-chapter 3.4), on-grid smaller to medium scale residential and commercial end-user markets (sub-chapter 3.3) and utility scale power plant markets (chapter 6). Wind power is not well applicable for the small off-grid markets in the power range below a kilowatt, in contradiction to pico PV systems and solar home systems (section 3.4.1), and for most grid-connected end-user markets, in which PV roof-top systems with and without storage solutions are leading (sub-chapter 3.3). However, the utility scale power plant market is the major market for wind power and becomes a very fast growing major market also for PV systems (section 3.1.1 and chapter 6). The demand curve for hybrid PV-Fossil power plants indicates an enormous economically feasible market potential for PV power plants (sub-chapter 6.5). However, in case of at least good wind resource availability a very tough competition between wind power and PV power plants has to be expected, since both technologies might compete for the balancing power of remaining fossil fuel fired power plants and power line capacities. This might be true in case of excellent wind and solar resource availability at the same time. But for largely disjunct resource availability in time, the result would be vice versa, i.e. PV and wind power would be not competitive but complementary. As a consequence the PV and wind power industry should cooperate for a fast diffusion of both technologies and for offering sophisticated renewable power solutions being desperately needed (chapter 1). In the following results on a global scale are presented for this essential scientific question. The need for finding answers has been derived in this thesis, but most of the work has been performed by Ann-Katrin Gerlach in her diploma thesis ⁶⁰ as an integral part of the research presented in this thesis.

⁵⁴ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2008

⁵⁵ Sawin J.L. and Moomaw W.R., An enduring energy future, 2008

⁵⁶ Lu X. et al., Global potential for wind-generated electricity, 2009

⁵⁷ Jacobson M.Z. and Delucchi M.A., A Path to Sustainable Energy by 2030, 2009

⁵⁸ WBGU, Welt im Wandel: Gesellschaftsvertrag für eine Große Transformation, 2011

⁵⁹ IPCC, Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), 2011

⁶⁰ Gerlach A.-K., Interaction of Solar and Wind Resources for Photovoltaic and Wind Power Plants, 2011

Various authors have published results on hybrid PV-Wind systems but almost all are focussed on relatively small systems of the sub-MW scale.^{61,62,63,64,65} Most interesting, some evaluated hybrid PV-(Battery, Diesel), hybrid Wind-(Battery, Diesel) and hybrid PV-Wind-(Battery, Diesel) systems and typically found least LCOE for the hybrid PV-Wind system option.^{66,67,68,69,70} This characteristic is analysed in more detail in sub-chapter 7.4. Only one publication has been found describing utility scale hybrid solar-wind power plants.⁷¹ The Greater Chinese researchers consider all solar electric technologies, i.e. solar PV and STEG, but demonstrate their real case study for a hybrid 564 MW STEG and 500 MW wind power plant in mainland China. However the solar electric sub-system could be also based on solar PV. Literature being available for hybrid PV-Wind systems clearly indicate only less research on utility scale systems and no publication has been found addressing the complementarity question on a global scale, except Hoffmann et al. analysing the power supply potential of hybrid PV-Wind-storage systems for at least Europe⁷².

The data for analysing the competitive versus complementary characteristic of PV and wind power on a global scale has been provided by the German Aerospace Center (DLR).^{73,74} Time resolved global geospatial data covering a period of 22 years (1984 through 2005) are provided by NASA (GHI: Surface Meteorology and Solar Energy SSE Release 6.0 – underlying data obtained from the Surface Radiation Budget 3.0 portion of NASA’s Global Energy and Water Cycle Experiment (GEWEX); Wind speed: Modern Era Retrospective-analysis for Research and Applications (MERRA)). These data have been prepared for energy related analyses by the DLR. Hourly time steps for GHI are obtained using a clear sky index approach, taking into account hourly clear sky irradiance data provided by DLR. Long-term annual averages can be derived to indicate the resources availability on a global scale. An exemplarily hour of this dataset is visualised in Figure 7.3-1.

⁶¹ Zhou W. et al., Battery behaviour prediction and battery working states analysis of a hybrid solar-wind power generation system, 2008

⁶² Wang L. and Singh C., PSO-based Hybrid Generating System Design Incorporating Reliability Evaluation and Generation/Load Forecasting, 2007

⁶³ Zhang B. et al., Dynamic Control of Wind/Photovoltaic Hybrid Power Systems Based on an Advanced Particle Swarm Optimization, 2008

⁶⁴ Senjyu T. et al., Optimal configuration of power generating systems in isolated island with renewable energy, 2007

⁶⁵ McGowan J.G. and Manwell J.F., Hybrid Wind/PV/Diesel System Experiences, 1999

⁶⁶ Fiedler F. et al., PV-Wind hybrid Systems for Swedish Locations, 2008

⁶⁷ Nandi S.K. and Ghosh H.R., A wind-PV-battery hybrid power system at Sitakunda in Bangladesh, 2009

⁶⁸ ARE, Hybrid Mini-Grids for Rural Electrification: Lessons Learned, 2010

⁶⁹ Koutroulis E. et al., Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms, 2006

⁷⁰ Diaf S. et al., A methodology for optimal sizing of autonomous hybrid PV/wind system, 2007

⁷¹ Chen H.H. et al., Strategic selection of suitable projects for hybrid solar-wind power generation systems, 2010

⁷² Hoffmann C. et al., Design of transport and storage capacities for a future European power supply system with a high share of renewable energies, 2008

⁷³ Scholz Y. et al., High Resolution Inventory of Renewable Electricity Generation Potentials in Europe, 2009

⁷⁴ Gerlach A.-K. et al., PV and Wind Power – Complementary Technologies, 2011

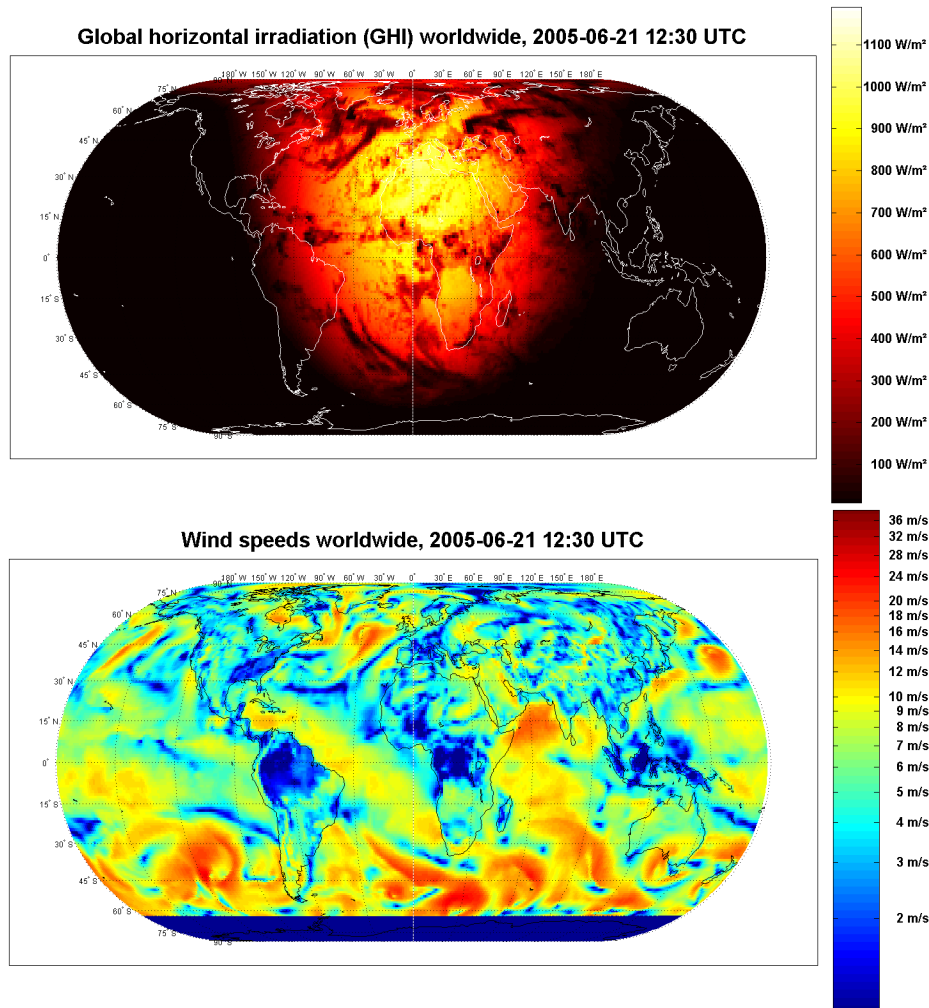


Figure 7.3-1: Hourly solar (top) and wind (bottom) resource data for June 21st 2005 at 12:30 UTC time. The exemplarily data represent one single hour of the available dataset from January 1st 1984 to December 31st 2005. The depicted wind speeds are at 50 m above ground.

Based on the pre-processed resource data (Fig. 7.3-1) it is worked out how much power PV and wind power plants would generate in each hour of the data series at every coordinate in the world averaged for a $1^\circ \times 1^\circ$ mesh of latitude and longitude within 65°S and 65°N . For transforming the solar and wind resource data into power generation data, dynamic power plants are modelled for wind power based on procedures in section 4.2.2.2 but for the E-126 wind turbine from Enercon⁷⁵ and for PV on basis of Huld et al.⁷⁶ and results in chapter 2.⁷⁷

For analysing purposes the rated power capacity of PV and wind power plants is equally set to 1 GW per $1^\circ \times 1^\circ$ mesh of latitude and longitude. Power generation of PV and wind power plants is normalized to hourly full load hours (FLh) and aggregated for periods of months and years (Fig. 7.3-2 and 7.3-3). Such data enable the extraction of overlap FLh of PV and wind power plants in order to eventually derive the critical extent of these overlap FLh. Overlap FLh are defined as the FLh of the minor contributor of the normalized PV and wind power plants on an hourly data basis. Problematic FLh are identified for the amount of feed-in power exceeding the rated power of either PV or wind power plants installed within a region of

⁷⁵ Enercon, Wind Turbines – Product Overview, 2010

⁷⁶ Huld T. et al., Geographical Variation of the Conversion Efficiency of Crystalline Silicon Photovoltaic Modules in Europe, 2008

⁷⁷ Gerlach A.-K., Interaction of Solar and Wind Resources for Photovoltaic and Wind Power Plants, 2011

1°x1° of latitude and longitude on basis of an equally installed rated power capacity. The overlap and critical overlap FLh are defined formally in Equations 7.3-1.

$$FLh_{OL} = \left(\sum_{i=1}^{8760} \min(P_{PV,i}, P_{Wind,i}) \right) \cdot 1GW^{-1} \quad (\text{Eq. 7.3-1a})$$

$$FLh_{COL} = \left(\sum_{\forall i \in \{(P_{PV,i} + P_{Wind,i}) > 1GW\}} P_{PV,i} + P_{Wind,i} - 1GW \right) \cdot 1GW^{-1} \quad (\text{Eq. 7.3-1b})$$

Equation 7.3-1: Definition of overlap and critical overlap full load hours. Abbreviations stand for: full load hours (*FLh*), overlap (*OL*), critical overlap (*COL*), hours of the year (*i*), power (*P*), photovoltaic (*PV*) and wind power (*wind*).

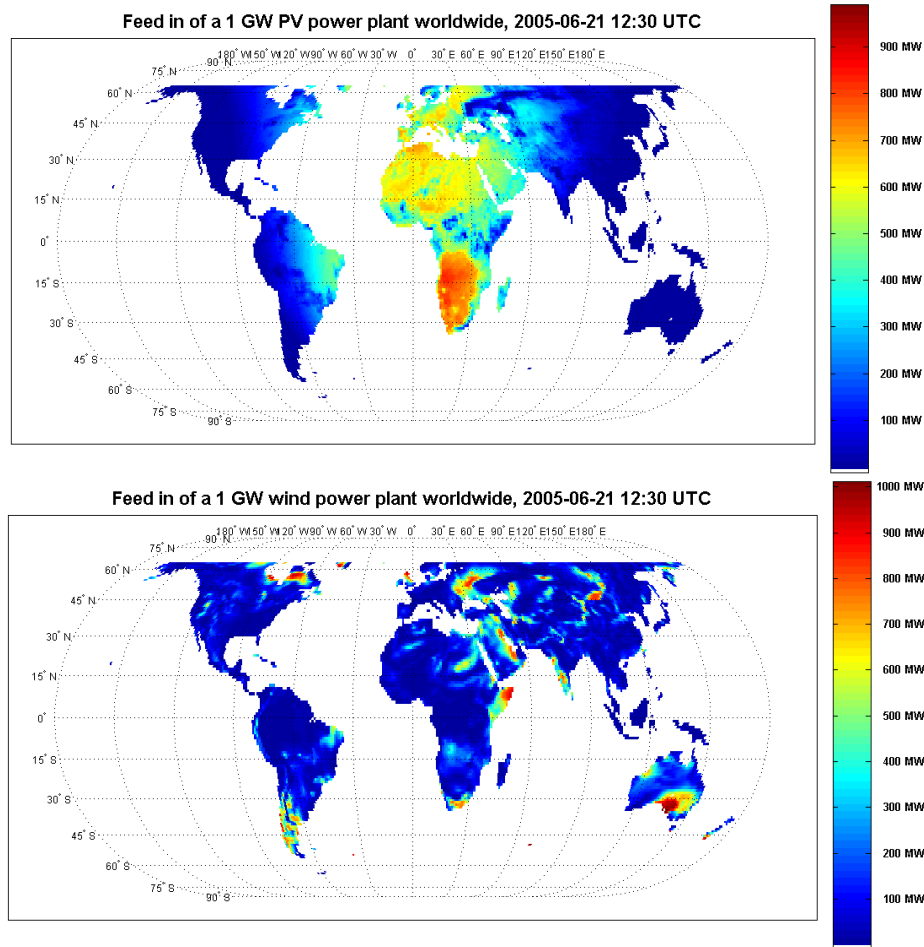


Figure 7.3-2: Feed-in power potential of 1 GW installed PV (top) and wind power (bottom) capacity according to historic data. This illustration shows feed-in of a certain hour which is between 12 and 13 UTC, June 21st 2005. At this time the sun passes the Greenwich meridian and the other hemisphere of the earth is dark reflected by no feed-in of PV power, which is of course no limit for wind power.

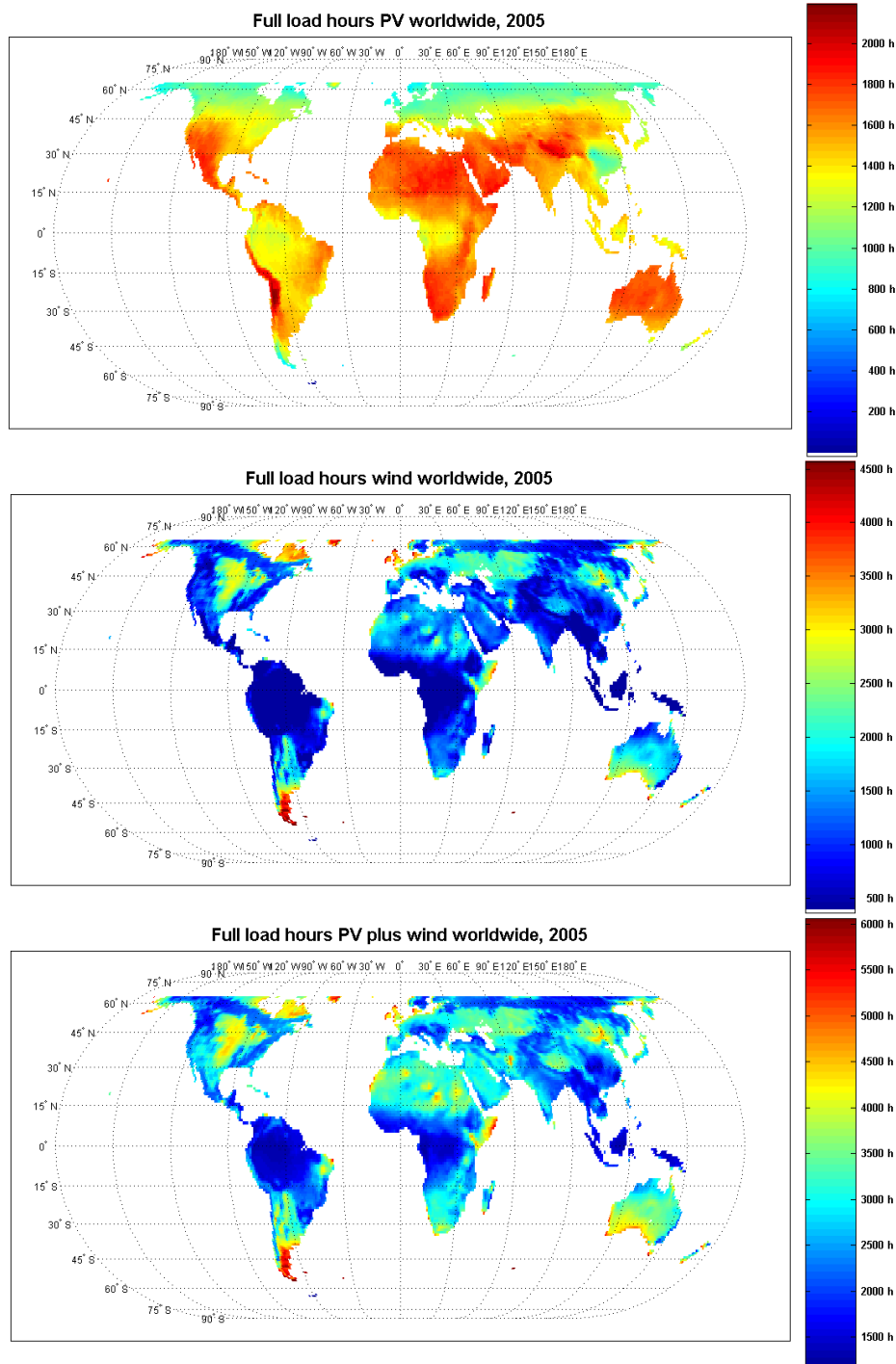


Figure 7.3-3: Global full load hours of fixed optimally tilted PV power plants (top), wind power plants at 150 m hub height (center) and combined PV plus wind power plants (bottom) for the year 2005. The annual values represent the sum of the hourly full load hours highlighted as power values in Figure 7.3-2 and based on resource data exemplarily shown in Figure 7.3-1. Data source for FLh in this sub-chapter is different to all other chapters in this thesis, hence deviations are possible and can be found for wind power FLh within a 10% - 20% range (Fig. 7.3-3 and 7.4-6) but not for PV FLh (Fig. 7.3-3 and 7.4-4).

The overlap FLh (Fig. 7.3-4) and critical overlap FLh (Fig 7.3-5) are key indicators for analysing the competitive or complementary characteristic of PV and wind power. Low overlap FLh and in particular low critical overlap FLh would significantly reduce cost in the entire power system. Since grid capacities could be better used, more overall PV and wind power capacities could be installed and less balancing power plants might be needed. Thus a

higher amount of conventional energy fuels could be substituted by PV and wind power plants. A long-term consequence would be significantly less capital expenditures for storage capacities needed for full substitution of remaining fossil fuel fired balancing power plants.

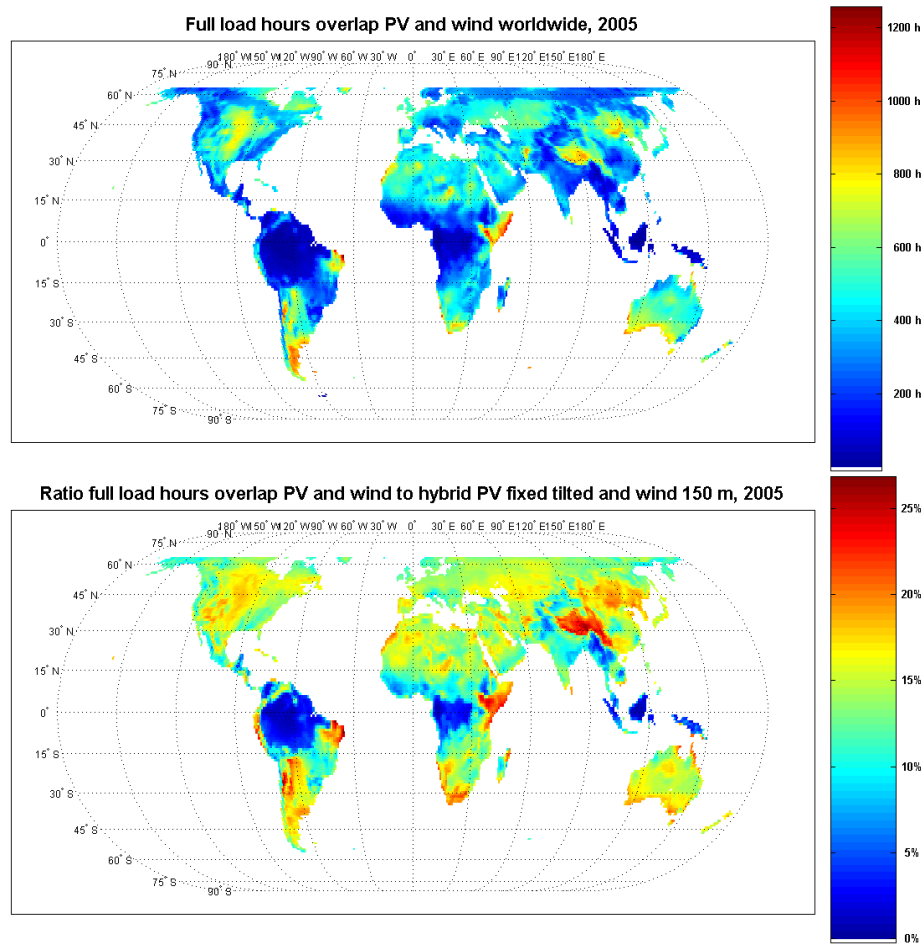
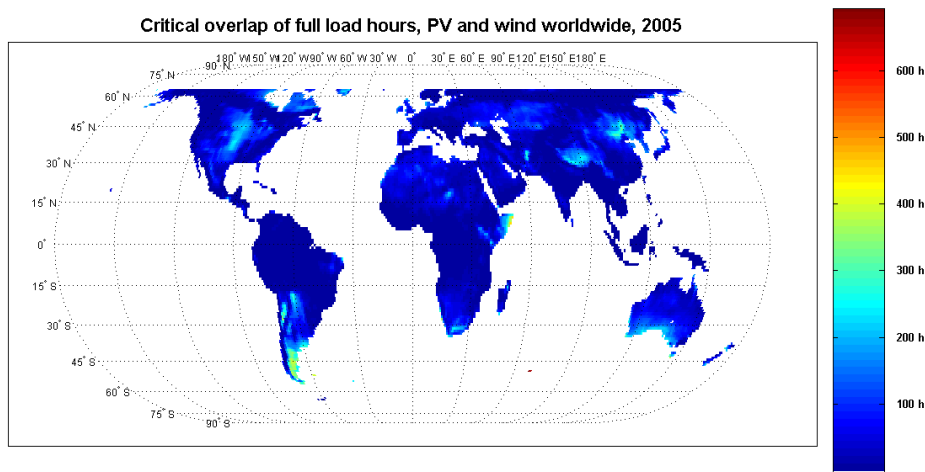


Figure 7.3-4: Global overlap full load hours of PV and wind power plants (top) and the respective ratio to total FLh of hybrid PV-Wind power plants (bottom) for the year 2005. Overlap FLh are defined as the FLh of the minor contributor of the normalized PV and wind power plants on an hourly data basis. The overlap FLh calculation is based on the hourly resolved power feed-in of PV and wind power plants of aggregated FLh displayed in Figure 7.3-3.



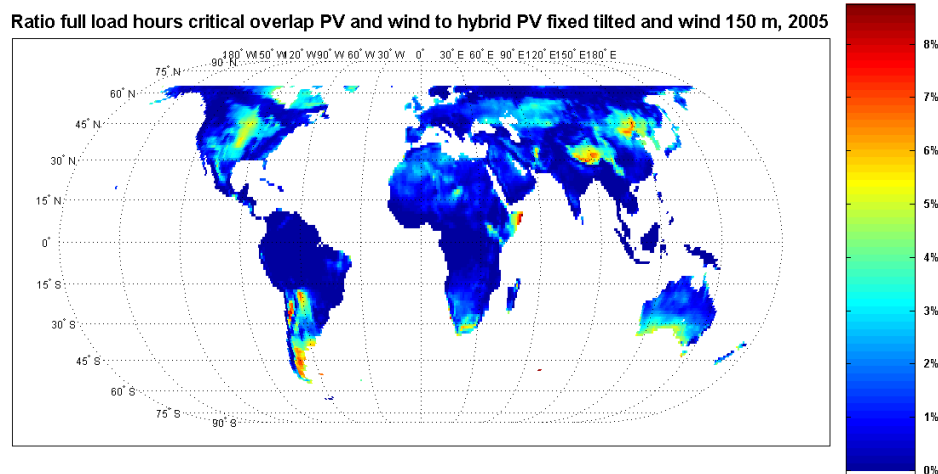


Figure 7.3-5: Global critical overlap full load hours of PV and wind power plants (top) and the respective ratio to total FLh of hybrid PV-Wind power plants (bottom) for the year 2005. Critical FLh are identified for the amount of feed-in power exceeding the rated power of either PV or wind power plants installed within a region of $1^\circ \times 1^\circ$ of latitude and longitude on basis of an equally installed rated power capacity and calculated for the hourly data basis. The overlap FLh calculation is based on the hourly resolved power feed-in of PV and wind power plants of aggregated FLh displayed in Figure 7.3-3.

The overlap FLh (Fig. 7.3-4) range between 5% - 25% of total FLh of PV plus wind power plants. The overlap FLh are about $15\% \pm 3\%$ for most regions in the world. This result is already very promising, since such low overlap FLh indicate almost disjunct solar and wind resource availability, i.e. excellent wind but weak solar resource availability and vice versa and moderate conditions for both resources for most hours of a certain period of time. The highest relative overlap FLh can be typically found near to mountain regions like the Andes, East Africa and the Himalayas.

The critical overlap FLh (Fig. 7.3-5) range between 1% - 8% of total FLh of PV plus wind power plants. The critical overlap FLh are about $2\% \pm 1\%$ for most regions in the world. The highest relative critical overlap FLh is found in regions near the Andes like Bolivia, Chile and Argentina, in some areas of the US Midwest, the Horn of Africa, the Himalayas and areas near Inner Mongolia. All the other regions in the world show very low critical overlap FLh. This result for the critical overlap FLh is of utmost relevance for the power supply in the world in the 21st century. The two major renewable power sources show no competitive but complementary characteristic to a very high extend.

The fluctuation of the hybrid PV-Wind power plant is expected to be lower due to the complementary resource availability. However, the hybrid PV-Wind power plant is still not dispatchable but at least predictable due to the energy meteorology tools (section 6.1.3) and need further balancing power plants or power storage facilities. Nevertheless, the fuel requirements for the balancing power plants and storage capacities are significantly lowered due to the complementary characteristic of PV and wind power plants.

A consequence of the results in this sub-chapter is the confirmation of derived available market potential for hybrid PV-Fossil power plants (sub-chapter 6.5). The next scientific question is the global demand curve of hybrid Wind-Fossil power plants and in particular hybrid PV-Wind-Fossil power plants. However, for an in depth analysis the load curves of the local regions are needed for finding best locally adapted ratios of installed PV to wind power capacity and the remaining FLh requirements of fossil fuel fired power plants. A first step towards such analyses is taken in the diploma thesis of Ann-Katrin Gerlach, as part of this

thesis, due to a much broader view of solar and wind resource availability and respective PV and wind power feed-in for some specific sites in the world.⁷⁸

Summing up, solar and wind resources are by far much higher than the need of mankind. PV and wind power are energy technologies which complement one another exceedingly. Due to no energy resource competition, a perfect basis is given for a comprehensive cooperation of PV and wind power industry. This fundamental characteristic of hybrid PV-Wind power plants is of utmost relevance for the further evolution of the global power system, since PV and wind power capacities can be built in parallel and in cooperation as capital expenditures for further system components are decreased due to better respective utilization.

7.4 Hybrid PV-Wind-Renewable Power Methane-CCGT Power Plants

Photovoltaic is the fastest growing electricity generation technology in the world. Second fastest growing electricity option is wind power. Global solar and wind resource assessment clearly documents sustainable and the by far highest resource potentials for PV and wind of all power technologies available to the market (sub-chapter 7.3). PV and wind power plants are on an excellent cost trend and are expected to achieve LCOE of about 40 – 60 €/MWh in regions of very good resource quality in the year 2020 (section 3.2.3 and 4.2.3). Both technologies are complementary and not competitive confirmed by overlap full load hour (FLh) studies (sub-chapter 7.3). Hence they are predominated for low cost power supply. However, for achieving power supply security balancing power plants are still needed. Natural gas (NG) power plant capacity of more than 1,100 GW is installed worldwide and is perfectly suited for power balancing purposes (sections 6.1.2 and 6.3.1). Hybrid PV-Wind-NG power plants are an excellent power plant option in the years to come, but this technological approach still depends on fossil fuels. Greenhouse gas emissions of NG fired combined cycle gas turbines (CCGT) are in the range of 400 - 500 gCO₂/kWh considering the full life cycle (Table 3.1-7), being too much in a climate change constraint world. Moreover, peak in conventional oil production is a matter of fact and it is only a question of time when peak in NG production will occur (section 1.3.2). Nevertheless, global installed NG infrastructure might be of utmost relevance for fighting climate change and diminishing fossil fuel resources. The purpose of this sub-chapter is a first analysis of the economic impact potential of renewable power methane storage (section 7.4.1 and 7.4.2) which would enable hybrid PV-Wind-Renewable Power Methane power plants (section 7.4.3) establishing a fully dispatchable power supply based on fluctuating wind and solar resources.

In principle, renewable power methane would not be needed since renewable power hydrogen production and reconversion into power is possible in a higher overall efficiency. However, transport and storage of hydrogen would be significantly lower in efficiency than methane and even worse there is no hydrogen infrastructure available in the energy sector in the world at all. This might be the fundamental reasons why a “Hydrogen Economy”⁷⁹ might not happen in contradiction to a “Renewable Power Methane enhanced Electron Economy”. On basis of fundamental physics, i.e. efficiencies of converting chemical energy into electric energy and vice versa, an economic sustainable power supply need to be largely based on direct renewable power enhanced by chemical stored renewable power for guaranteeing a fully stable power grid.⁸⁰ Renewable power methane versus hydrogen shows significant advantages, in particular for a fast transition from non sustainable fossil to sustainable

⁷⁸ Gerlach A.-K., Interaction of Solar and Wind Resources for Photovoltaic and Wind Power Plants, 2011

⁷⁹ Rifkin J., The Hydrogen Economy, 2002

⁸⁰ Bossel U., On the Way to a Sustainable Energy Future, 2005

renewable power supply.

Hybrid PV-Wind-Renewable Power Methane power plants might become the centrepiece of a sustainable and affordable power supply (section 7.4.4) desperately needed for the survival of our technological driven global society (chapter 1).

7.4.1 Renewable Power Methane Storage

The risk mix of climate change impact, diminishing fossil fuels and nuclear hazards induces enormous pressure for restructuring the global energy supply, which is to about 87%⁸¹ dependent on the risk creating sources. The only sustainable energy pathway is based on the various renewable energies (Table. 5.0-1). A stable power supply needs to be based on full daily and especially seasonal adaption of renewable power supply to the load demand in the grids. The balance of seasonal renewable power supply and load demand is challenging, since both hydro storage dams and biomass power supply are very limited due to geographic and resource competition constraints. Additionally, the major renewable power supply options are represented by solar PV and wind power, which are both fluctuating. Hence flexible power generation units are needed for balancing resource availability and load demand for a stable electricity supply. This would be the case for oil, natural gas and coal fired power plants. However, the respective greenhouse gas emissions and diminishing fossil fuel resources allow these conventional power technologies only a very limited function in the transition phase towards a fully renewable power supply. Nevertheless, fossil natural gas fired power plants, technically better called methane power plants, can be also fired by renewable power methane. Renewable power methane can be produced by renewable power, air and water as input sources. The required seasonal storage of methane is already applied today. As a consequence, the power grid and natural gas grid become connected and energy flow is made possible in both directions (Fig. 7.4-1). In the following the renewable power methane (RPM) concept and its structural advantages are discussed in more detail.

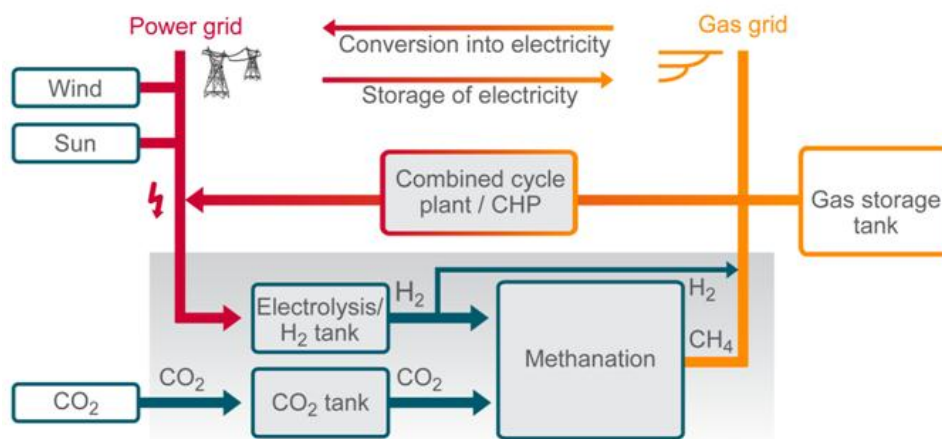


Figure 7.4-1: Hybrid PV-Wind-RPM power plant embedded in the power grid and the natural gas grid.⁸² Energy flows are possible in both directions, i.e. storage of electricity in the natural gas infrastructure and conversion of renewable power methane into electricity. CO₂ can be used from several sources, like extraction from air, by-product of biogas plants, fossil fuel power plants or industrial processes.

⁸¹ IEA, World Energy Outlook 2010, 2010, p. 618

⁸² Breyer Ch. et al., Hybrid PV-Wind-Renewable Power Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 2011a

Three elementary core processes are needed for renewable power methane: electrolysis (conversion of electricity and water into hydrogen and oxygen), CO₂ supply (e.g. extraction from ambient air via dialysis process, by-product of biogas plants, fossil fuel power plants or industrial processes) and methanation (conversion of hydrogen, carbon dioxide and electricity into methane and water).⁸³ Good overview on the renewable power methane concept, the relevant components and energy system integration is given by Sterner⁸⁴, Specht et al.^{85,86,87} and Sterner et al.⁸⁸.

The first core process is the electrolysis converting renewable electricity and water into hydrogen and oxygen. Several electrolysis technologies are available enabling energy conversion efficiencies of up to 80%. The technology is used since decades and can be operated at various pressures, temperatures and is scalable for industrial applications in the range of some kW to MW.⁸⁹

The hydrogen is used in the methanation (Sabatier process), the second core process, to convert hydrogen and carbon dioxide to methane and water. Methanation is used in coal gasification and for biomass gasification, whereas the output product is called substitute natural gas (SNG). The energy conversion can reach efficiencies up to 85% in a catalytic exothermal process on a temperature level of 180 – 350 °C and a pressure of 1 – 100 bars.⁹⁰

Several CO₂ sourcing routes are available, e.g. by-product of biogas plants, fossil fuel power plants or industrial processes, however the most elegant way is the extraction of CO₂ from ambient air. Several processes are known for extracting CO₂ from ambient air⁹¹, whereas in the following it is focussed the energy efficient ZSW process based on absorption and electrodialysis.⁹² A Na₂CO₃ carbonate solution is formed after CO₂ absorption of a caustic NaOH scrubbing solution. CO₂ is extracted from the carbonate by acidifying the solution with sulphuric acid. Both the NaOH solution and the sulphuric acid are used in a cyclical process in an electrodialytical unit of bipolar membranes. In total 8.2 GJ/tCO₂ extraction are needed in the entire process, whereas 1.8 GJ/tCO₂ are needed for the absorption process and the remaining 7.0 GJ/tCO₂ for the dialysis process.⁹³

For producing 10 MJ_{th} renewable power methane, it is needed 16 MJ_{el} for the electrolysis process including the methanation process plus further 4.8 MJ_{el} in case of extraction CO₂ from ambient air via the dialysis process developed by the ZSW.⁹⁴ This translates into a renewable electricity to renewable power methane conversion efficiency of about 63% excluding energy for CO₂ sourcing. Specific energy consumption of the dialysis process extracting CO₂ from ambient air represents an energy conversion efficiency of about 77%. Thus renewable power methane using CO₂ extraction from ambient air can be generated on an

⁸³ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

⁸⁴ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

⁸⁵ Specht M. et al., Speicherung von Bioenergie und Erneuerbarem Strom im Erdgasnetz, 2009

⁸⁶ Specht M. et al., Speicherung von Bioenergie und erneuerbarem Strom im Erdgasnetz, 2010

⁸⁷ Specht M. et al., Renewable Power Methane - Stromspeicherung durch Kopplung von Strom- und Gasnetz - Wind/PV-to-SNG, 2009

⁸⁸ Sterner M. et al., Erneuerbares Methan – Eine Lösung zur Integration und Speicherung Erneuerbarer Energien und ein Weg zur regenerativen Vollversorgung, 2010

⁸⁹ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

⁹⁰ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

⁹¹ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

⁹² Bandi A. et al., CO₂ Recycling for Hydrogen Storage and Transportation – Electrochemical CO₂ Removal and Fixation, 1995

⁹³ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

⁹⁴ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

efficiency level of about 49%, whereas high temperature process heat of the exothermic methanation process might be used for other purposes. About 50% of the electric energy can be chemically stored in renewable power methane and afterwards used for all purposes fossil natural gas is used for. In case of burning renewable power methane in modern gas power plants, i.e. in CCGT of about 58% efficiency (Fig. 6.1-3), the full cycle efficiency would be about 37% and 29% for CO₂ being easily available for the methanation process and CO₂ extracted from ambient air, respectively. This full cycle storage efficiency is rather low and induces high specific cost for such stored electricity, however an easy usable seasonal energy storage would be enabled and the entire natural gas infrastructure could be used. It seems to be questionable whether such a low efficiency might be ever profitable for a daily storage cycle, for which electrochemical storage solutions like sodium sulfur batteries might be a much better solution or even hydrogen powered fuel cells which could reach a full cycle efficiency of more than 50% and storing hydrogen for a daily storage cycle would be much more feasible than seasonal hydrogen storage.

There are only a few and very limited seasonal electricity storage options, in particular for large scale energy storage (Fig. 7.4-2).

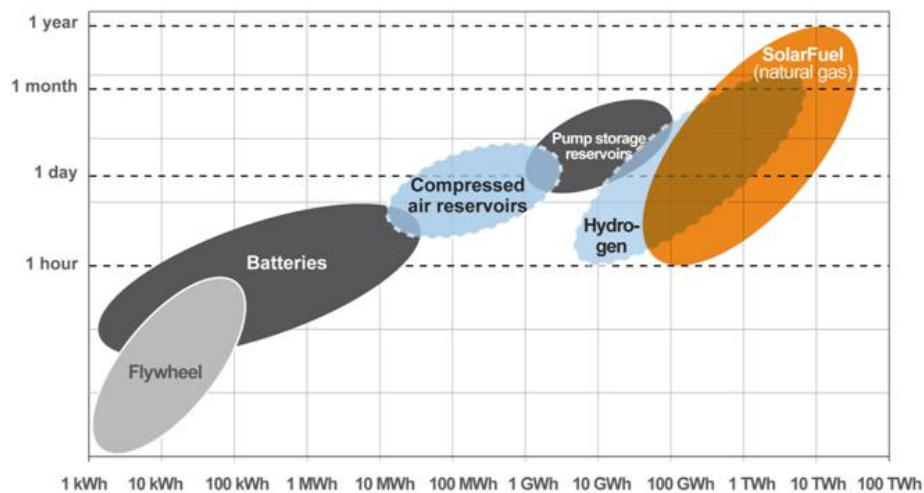


Figure 7.4-2: Overview on major electricity storage technologies in dependence on energetic storage capacity and charge cycling.⁹⁵ Renewable power methane is one of only few seasonal storage options for large scale energy storage. Renewable power methane is equivalent to Solar Fuel.

For very fast storage cycles flywheels, capacitors or supercaps would be an excellent option but only for small amounts of energy. In the time dimension up to some days, the preferred solutions would be batteries, compressed air energy storage and pumped hydro storage. The electricity storage in electrochemical batteries is typically applied for smaller amounts of energy. Compressed air energy storage is currently only used in two facilities in the world but might be more applied in future.^{96,97} Pumped hydro storage is the most preferred energy storage on the power plant and power grid level due to relative low cost, relative high energy storage reservoirs and a high flexibility in switching from charge to discharge operation mode. However, geographic prerequisites of substantial difference in altitude and available topographic sites limit this large scale energy storage. But a seasonal energy storage would

⁹⁵ Breyer Ch. et al., Hybrid PV-Wind-Renewable Power Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 2011a

⁹⁶ Mason J. et al., Coupling PV and CAES Power Plants to Transform Intermittent PV Electricity into a Dispatchable Electricity Source, 2008

⁹⁷ Johnston F. and Sun S., Compressed air energy storage: an expanding opportunity?, 2011

also induce high storage cost due to a respective low cycle frequency. The remaining two seasonal storage solutions are hydrogen and methane. Seasonal storage on renewable power methane basis might be preferred due to higher storage efficiency and already existing transport infrastructure in most regions in the world plus available energy converting units, like power plants, heating for houses, powering the transport sector and using renewable power methane in the chemical industry.

The aforementioned structural advantages of renewable power methane are emphasized by viewing the consequences of integrating it into the existing energy system (Fig. 7.4-3).

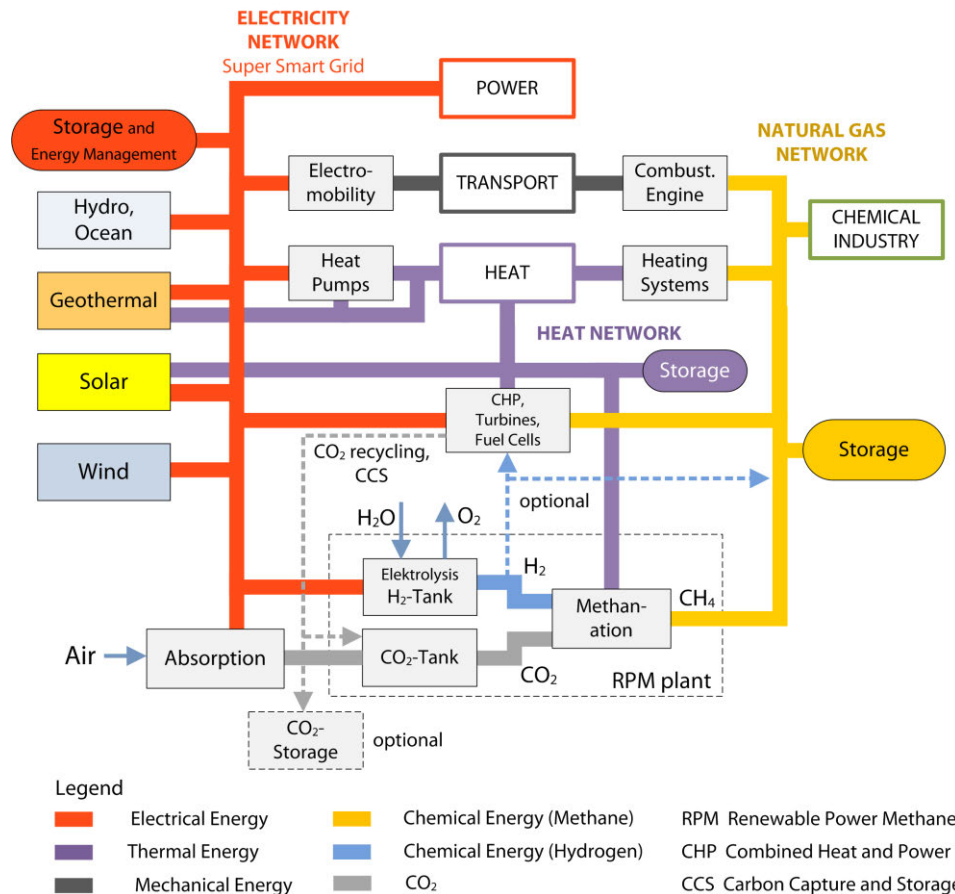


Figure 7.4-3: Hybrid PV-Wind-RPM plant (Fig. 7.4-1) as the integral centrepiece of a future sustainable energy supply system.^{98,99} The four main energy systems are integrated and positively influenced by renewable power methane, i.e. power network, natural gas network, heat network and transportation network.

Several integrated concepts with CO₂ from air, biomass, industrial processes and fossil fuels are designed. In this way, renewable power can be stored in the natural gas network and used temporarily and spatially flexible for balancing power and long-term power storage, for process heat and for (long-distance) transportation with a high-energy density CO₂-neutral energy carrier. The major benefit versus hydrogen is the use of the existing infrastructure. Hydrogen is “stored” in CO₂ and made thus available as natural gas substitute. Renewable power methane can be produced basically anywhere where water, air (CO₂) and renewable power (wind, solar, hydro) are available and thus decrease import dependence on fossil fuels and the need for new transmission lines by using existing gas grids. It can recycle CO₂ in the

⁹⁸ Sterner M., Bioenergy and renewable power methane in integrated 100% renewable energy systems, 2009

⁹⁹ Breyer Ch. et al., Hybrid PV-Wind-Renewable Power Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 2011a

energy system by CO₂ capture from combustion or by the use of the generated O₂ for combustion of renewable power methane in the oxyfuel process in combined cycle plants. This new approach can even act as carbon sink in combination with CO₂ storage and thus create “carbon sink energy systems”.¹⁰⁰

7.4.2 Economics of Relevant System Components

This section is focused on the economics of the core system components of hybrid PV-Wind-RPM-CCGT power plants based on the technological conditions needed for renewable power methane storage. Relevant system components for analyses are fixed optimally tilted PV power plants (PV 0), 1-axis horizontal north-south continuous tracking PV power plants (PV 1N), 150 meter hub height wind power plants (Wind 150m), combined cycle natural gas power plants in the conventional and CCS version (CCGT and CCGT-CCS), hard coal power plants in the conventional and carbon capture and sequestration (CCS) version (coal and coal-CCS) and renewable power methane storage composed by dialysis, electrolysis and methanation units. Most of the components are already discussed in detail in previous chapters, i.e. PV power plants (sub-chapters 2.2 and 3.2), wind power plants (sub-chapter 4.2), conventional gas power plants (sub-chapter 6.3 and section 6.1.2), conventional coal power plants (sub-chapter 6.4 and section 6.1.2) and preconditions for a successful hybridization (sub-chapter 6.1).

A cost model for all components of the hybrid PV-Wind-RPM-CCGT power plant enables the calculation of levelized cost of electricity (LCOE) for all coordinates by applying local full load hours (FLh) for the PV and wind component in combination with FLh assumptions for the entire hybrid power plant. Renewable power methane storage is expected to be available on the large scale by the end of the 2010s, whereas first CCS power plants, as a potential CO₂ source, might be in the demonstration phase at that point in time. Based on the availability of these two major relevant components for a broad hybrid PV-Wind-RPM-CCGT power plant analysis the year 2020 is chosen for scenario evaluation. Besides typical capital expenditures (Capex) and operational expenditures (Opex), major cost positions are expenditures for fuel but not for related carbon emissions due to either CO₂ free power supply or application of CCS techniques. Such derived LCOE make it possible to compare them to LCOE of other renewable and conventional power plant technologies.

Methodology of calculating hybrid PV-Wind-RPM LCOE is similar to that of fossil power plants (Eqs. 6.2-1, 6.3-1 and 6.4-1) and based on that of renewable power plants (Eqs. 3.2-1 and 4.2-4). Adjustments are needed for specific differences of hybrid PV-Wind-RPM power plants, summarized in Equations 7.4-1:

$$LCOE = \sum_i LCOE_i \quad (\text{Eq. 7.4-1a})$$

$$LCOE_i = \frac{Capex_i \cdot crf_i + Opex_{i,fix}}{FLh_{i,el}} + Opex_{i,var} + \frac{fuel_i}{PE_{th,i} \cdot \eta_{i,el}} \quad (\text{Eq. 7.4-1b})$$

$$crf_i = \frac{WACC \cdot (1 + WACC)^{N_i}}{(1 + WACC)^{N_i} - 1} \quad (\text{Eq. 7.4-1c})$$

¹⁰⁰ Breyer Ch. et al., Hybrid PV-Wind-Renewable Power Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 2011a

$$WACC = \frac{E}{E + D} \cdot k_E + \frac{D}{E + D} \cdot k_D \quad (\text{Eq. 7.4-1d})$$

$$FLh_{PV,el} = Y_{ref} \cdot PerfR \quad (\text{Eq. 7.4-1e})$$

$$FLh_{RPM,el} = FLh_{total,el} - (FLh_{PV,el} + FLh_{W,el}) \quad (\text{Eq. 7.4-1f})$$

$$fuel_i = fuel_{crudeoil} \cdot cf_i \quad (\text{Eq. 7.4-1g})$$

Equation 7.4-1: Levelized cost of electricity (LCOE) for hybrid PV-Wind-RPM-CCGT power plants. Abbreviations stand for: capital expenditures (*Capex*), annuity factor (*crf*), annual operation and maintenance expenditures (*Opex*), annual fixed Opex (*Opex_{fix}*), variable Opex (*Opex_{var}*), annual full load hours of component *i* (*FLh_{i,el}*), fuel cost of component *i* (*fuel_i*), thermal energy conversion factor of component *i* (*PE_{th,i}*), primary to electric energy conversion efficiency of component *i* (*η_{i,el}*), weighted average cost of capital (*WACC*), lifetime of component *i* (*N_i*), equity (*E*), debt (*D*), return on equity (*k_E*), cost of debt (*k_D*), reference yield for a specific PV system at a specific site (*Y_{ref}*), PV performance ratio (*PerfR*), renewable power methane components (*RPM*), fuel cost of crude oil (*fuel_{crude oil}*), ratio of fossil fuel *i* to crude oil as coupling factor (*cf_i*) and primary to electric energy conversion efficiency of component *i* (*η_{i,el}*). Components *i* of the hybrid PV-Wind-RPM-CCGT power plant are: PV fixed optimally tilted, PV 1-axis horizontal north-south continuous tracking, Wind 150 meter hub height, renewable power methane storage units (dialysis, electrolysis, methanation), combined cycle gas turbine (CCGT) and carbon capture and sequestration (CCS). These components are compared partly or fully to natural gas (NG) fired CCGT-CCS and coal fired coal-CCS power plants.

The scenario assumptions for calculating LCOE are summarized in Table 7.4-1. Major LCOE component of PV and wind power plants are the capital cost, whereas conventional fossil power plants are more dependent on the fuel cost in contrary to fossil CCS power plants showing a higher dependence on capital cost. Fossil fuel cost are indirectly coupled to the crude oil price due to the specific thermal energy (section 6.1.4) and tend to fluctuations and long-term escalation.

Total FLh of the hybrid PV-Wind-RPM-CCGT power plant are composed by the renewable source, i.e. PV or wind or hybrid PV-Wind, and the balancing combined cycle gas turbine (CCGT) which receives the methane by the renewable power methane component of the hybrid plant. The renewable power methane is generated by not needed excess electricity either by extraction CO₂ from the ambient air (dialysis) or provided by the carbon capture and sequestration (CCS) component of the CCGT plant. The dialysis and electrolysis components show lower FLh due to its adaption to the availability of fluctuating excess electricity. However, the methanation component can be run in baseload operation modus due to internal hydrogen storage. Some minimum FLh are assumed for practical reasons, i.e. minimum 500 FLh of CCGT component, minimum 500 FLh of NG-CCS component, minimum 500 FLh of critical PV and wind overlap being very conservative (sub-chapter 7.3) and minimum total 5,000 FLh of the hybrid PV-Wind-RPM-CCGT power plant. The latter assumption is rather conservative, since the global power plant capacity is operated for about 4,300 FLh in average (sub-chapter 5.1). The hybrid power plant in this configuration can use the renewable power methane as both a daily but also a seasonal storage.

		PV	PV	Wind	CCGT		Coal		Renewable Power		
		fixed	1-axis	150m					Methane		
in year 2020		tilted	horiz.	hub	conv.	CCS	conv.	CCS	Dia-lysis	Electro-lysis	Metha-nation
Capex	[€/kW]	1,000	1,130	800	750	2,100	1,500	2,800	500	300	400
Opex_fix	[€/kW/y]	13	17	15	15	40	20	70	10	6	8
Opex_var	[€/MWh _{el}]	-	-	-	1	2	1	3	1	1	1
plant_lifetime	[y]	30	30	25	30	30	40	40	30	30	30
plant_eff (PerfR)	[%]	80%	80%	95%	58%	48%	44%	34%	78%	78%	82%
price_coupling	[fuel/oil]	-	-	-	80%	80%	30%	30%	-	-	-
in general		remark									
fin_WACC	[%]	6.0%	despite of higher fossil risk identical for comparison reasons								
exchange_rate	[USD/€]	1.40									
FLh_Methanation	[h/y]	8,000	baseload operation								
FLh_min_CCGT	[h/y]	500	min CCGT FLh of hybrid RES-RPM-CCGT plants								
FLh_min_NG-CCS	[h/y]	500	min NG-CCS FLh of hybrid RES-NG-CCS plants								
FLh_min_overlap	[h/y]	500	assumed time resolved FLh overlap of PV and Wind								

Table 7.4-1: Scenario assumptions for hybrid PV-Wind-RPM-CCGT power plant economics in the year 2020. The scenario covers a business-as-usual approach, based on conservative assumptions. PV numbers are comparable to those of the realistic scenario (Table 3.2-1 and Fig. 3.2-5). Wind power numbers are comparable to those of the realistic scenario with tendency to the aggressive one (Table 4.2-1 and Fig. 4.2-15). Natural gas CCGT and coal assumption are nearly identical to the respective base case scenario (Tables 6.3-1 and 6.4-1). Critical overlap of PV and wind FLh is a conservative assumption (sub-chapter 7.3). Numbers mentioned are for power plants of multi-100 MW. General parameters are set identical, in particular for the financial parameters, although fossil WACC should be higher due to a higher price risk profile (section 3.2.1) ¹⁰¹. Abbreviations stand for: capital expenditures (Capex), operational expenditures (Opex), annual fixed Opex (Opex_{fix}) and variable Opex (Opex_{var}), efficiency (eff) performance ratio (PerfR), weighted average cost of capital (WACC), full load hours (FLh), minimum (min), combined cycle gas turbine (CCGT), natural gas (NG), carbon capture and sequestration (CCS), fixed optimally tilted (fixed tilted), 1-axis horizontal north-south continuous tracking (1-axis horiz.N-S), conventional (conv.) and renewable energy sources (RES). Data are taken from various sources like European Climate Foundation ¹⁰², Greenpeace ¹⁰³, IEA ^{104,105}, Solar Fuel ¹⁰⁶, BMU ¹⁰⁷ and IPCC ¹⁰⁸.

PV and wind power core characteristics, i.e. FLh and LCOE, for hybrid PV-Wind-RPM-CCGT power plant analyses are depicted in the following for fixed optimally tilted PV power plants (Fig. 7.4-4), 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5), wind power plants at 150 meter hub height (Fig. 7.4-6), hybrid (fixed tilted) PV-Wind power plant (Fig. 7.4-7) and hybrid (1-axis tracking) PV-Wind power plant (Fig. 7.4-8).

¹⁰¹ Awerbuch S., Portfolio-based electricity generation planning: policy implications for renewables and energy security, 2006

¹⁰² ECF, Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, 2010

¹⁰³ Teske S. (ed.), energy [r]evolution: A Sustainable World Energy Outlook, 2010

¹⁰⁴ IEA, Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, 2008

¹⁰⁵ IEA, Projected Costs of Generating Electricity 2010 Edition, 2010

¹⁰⁶ Breyer Ch. et al., Hybrid PV-Wind-Renewable Power Methane Power Plants, 2011a

¹⁰⁷ BMU, Leitstudie 2010, 2010, p. 74-79

¹⁰⁸ Bolin B. (ed.), Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3), 1996

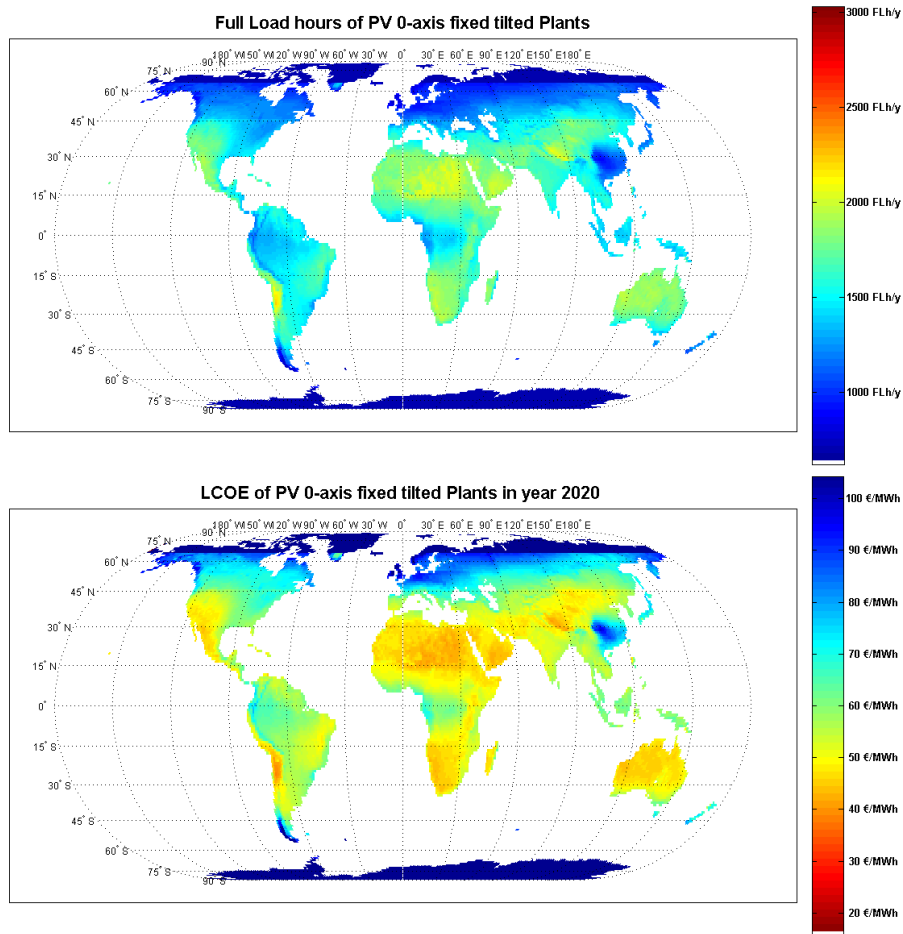
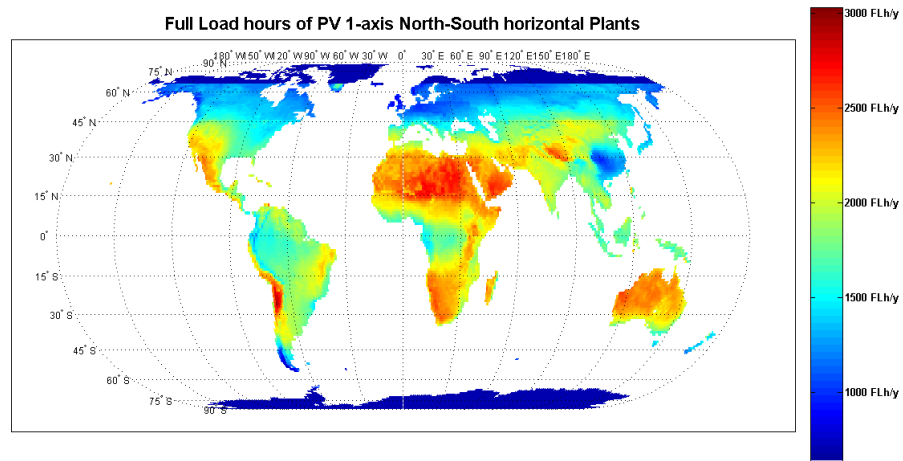


Figure 7.4-4: Fixed optimally tilted PV power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh (top) and LCOE (bottom) expected for the year 2020. PV FLh and LCOE are based on fixed optimally tilted solar resource (Fig. 2.2-3), LCOE and scenario assumptions defined in Table 7.4-1 and Equations 7.4-1 similar to the realistic scenario (Table 3.2-1). Data source for FLh in the sub-chapter 7.3 is different to all other chapters in this thesis, hence deviations are possible and can be found for wind power FLh within a 10% - 20% range (Fig. 7.3-3 and 7.4-6) but not for PV FLh (Fig. 7.3-3 and 7.4-4).



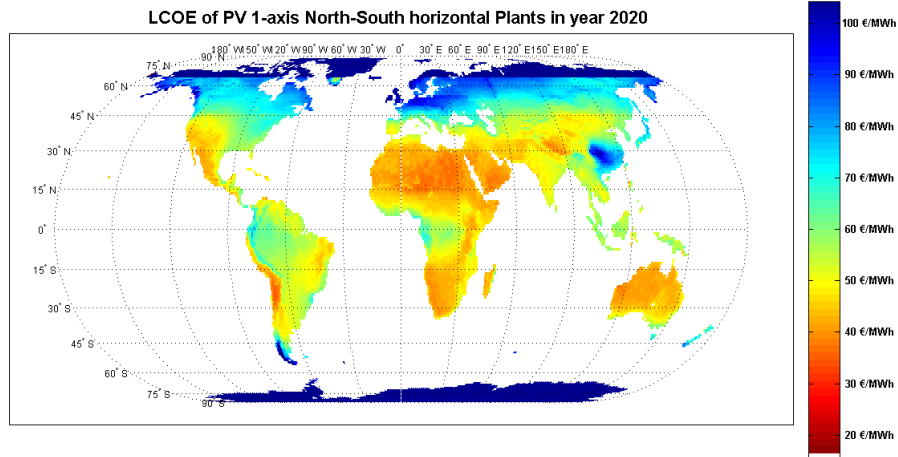


Figure 7.4-5: 1-axis horizontal north-south continuous tracking PV power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh (top) and LCOE (bottom) expected for the year 2020. PV FLh and LCOE are based on 1-axis horizontal north-south continuous tracking solar resource (Fig. 2.2-14), LCOE and scenario assumptions defined in Table 7.4-1 and Equations 7.4-1 similar to the realistic scenario (Table 3.2-1). Data source for FLh in the sub-chapter 7.3 is different to all other chapters in this thesis, hence deviations are possible and can be found for wind power FLh within a 10% - 20% range (Fig. 7.3-3 and 7.4-6) but not for PV FLh (Fig. 7.3-3 and 7.4-4).

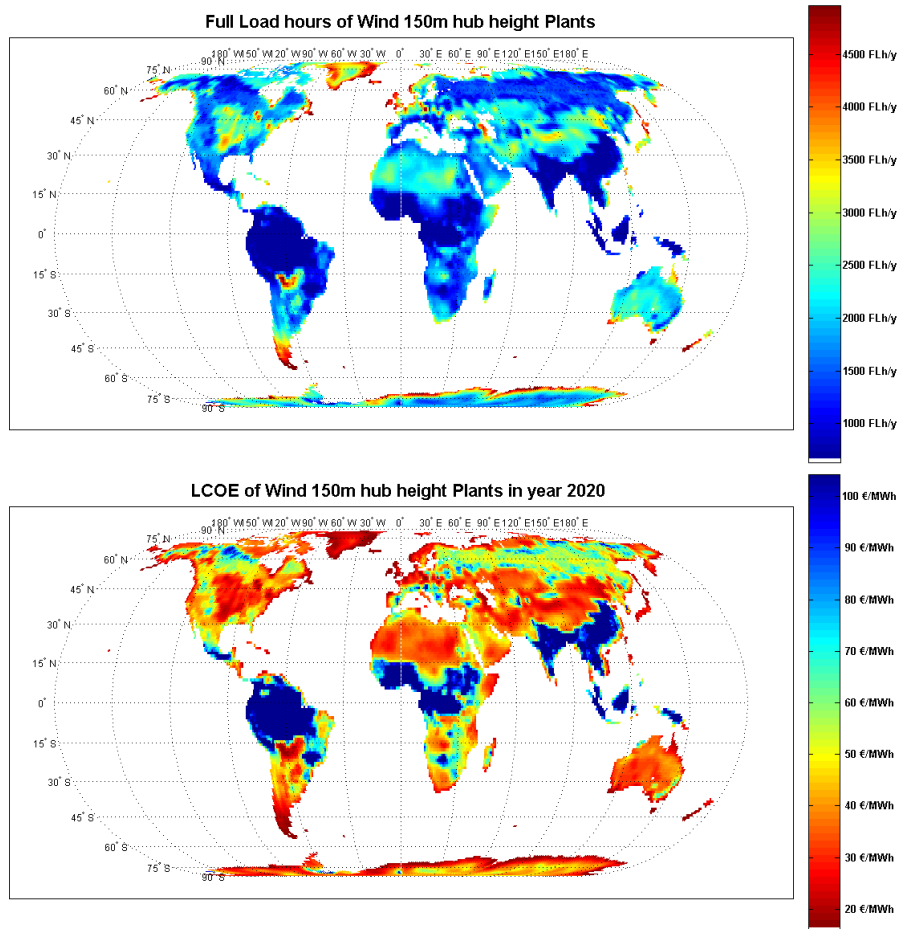


Figure 7.4-6: Wind 150 meter hub height power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh (top) and LCOE (bottom) expected for the year 2020. Wind FLh and LCOE are based on 150 meter hub height wind resource (Fig. 4.2-13), LCOE and scenario assumptions defined in Table 7.4-1 and Equations 7.4-1 similar to the realistic scenario (Table 4.2-1). Data source for FLh in the sub-chapter 7.3 is different to all other chapters in this thesis, hence deviations are possible and can be found for wind power FLh within a 10% - 20% range (Fig. 7.3-3 and 7.4-6) but not for PV FLh (Fig. 7.3-3 and 7.4-4).

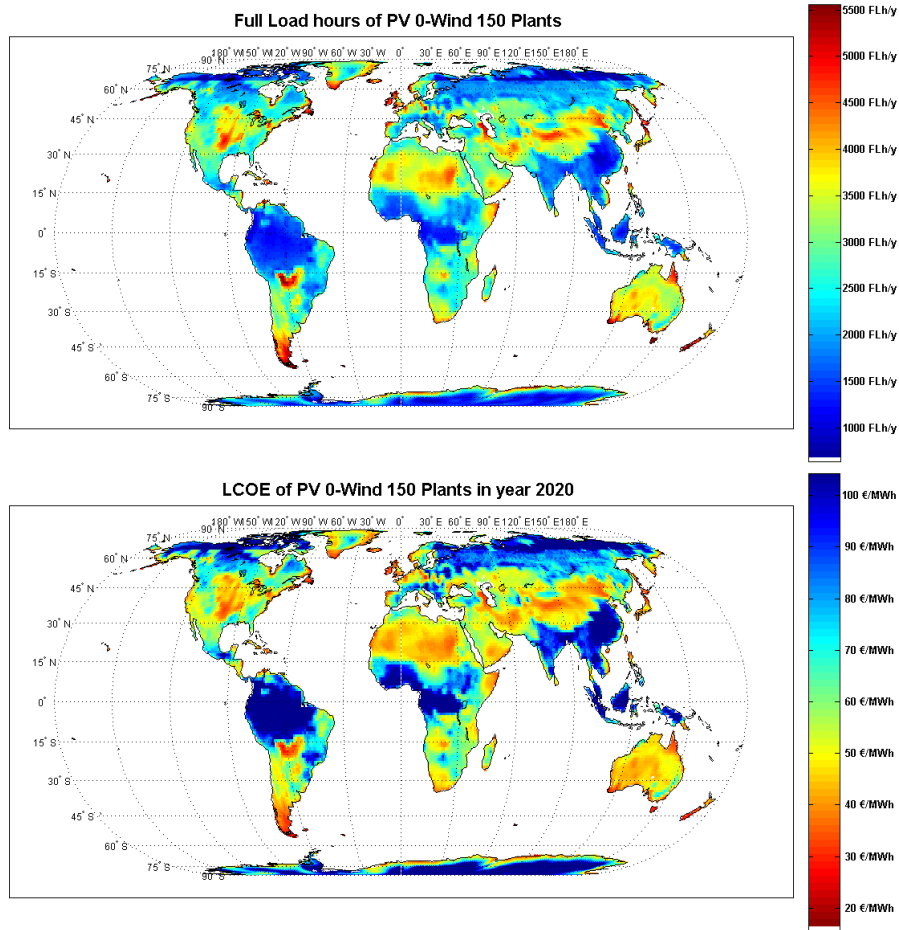
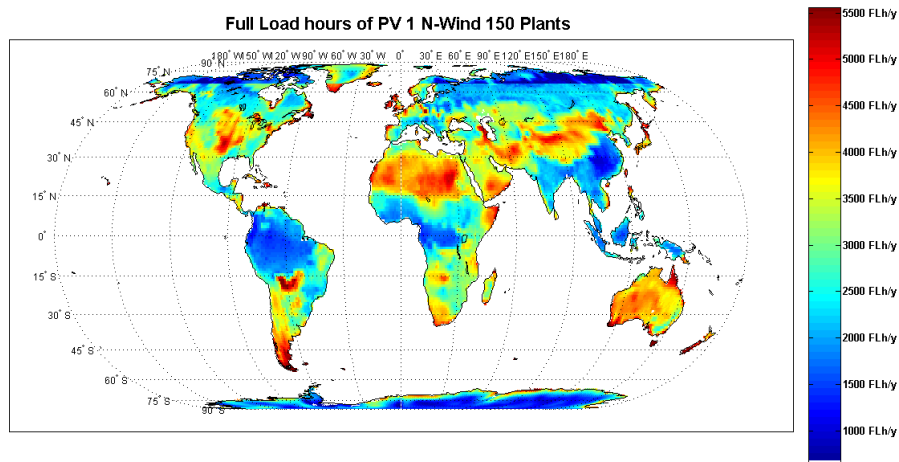


Figure 7.4-7: Hybrid fixed tilted PV Wind 150 meter hub height power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh (top) and LCOE (bottom) expected for the year 2020. FLh and LCOE are based on results for the single renewable power plant components depicted in Figures 7.4-4 and 7.4-6. Data source for FLh in the sub-chapter 7.3 is different to all other chapters in this thesis, hence deviations are possible and can be found for wind power FLh within a 10% - 20% range (Fig. 7.3-3 and 7.4-6) but not for PV FLh (Fig. 7.3-3 and 7.4-4).



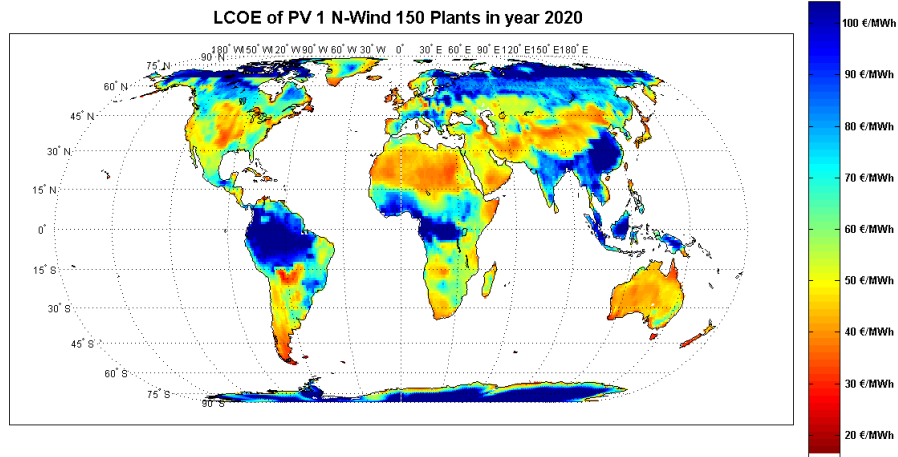


Figure 7.4-8: Hybrid 1-axis PV Wind 150 meter hub height power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh (top) and LCOE (bottom) expected for the year 2020. FLh and LCOE are based on results for the single renewable power plant components depicted in Figures 7.4-5 and 7.4-6. Data source for FLh in the sub-chapter 7.3 is different to all other chapters in this thesis, hence deviations are possible and can be found for wind power FLh within a 10% - 20% range (Fig. 7.3-3 and 7.4-6) but not for PV FLh (Fig. 7.3-3 and 7.4-4).

A comparison of fixed optimally tilted (Fig. 7.4-4) and 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5) clearly indicate the 1-axis tracking variation as the better option due to lower LCOE and higher FLh. In particular the higher FLh are relevant for lowering total LCOE of the hybrid PV-Wind-RPM-CCGT power plant, due to a reduced electrolysis capacity needed for fulfilling total FLh requirements. Similar characteristic can be found for the fixed tilted and 1-axis tracking hybrid PV-Wind power plant options (Fig. 7.4-7 and 7.4-8). Regions of excellent renewable resource availability might reach LCOE levels of about 40 €/MWh (1-axis tracking PV power plants) and 30 €/MWh (wind power plants) and 30 to 40 €/MWh (hybrid PV-Wind). Major advantage of hybrid PV-Wind power plant component is the higher FLh compared to only one renewable power source leading to beneficial total LCOE of the hybrid PV-Wind-RPM-CCGT power plant.

The impact of FLh is very significant on the cost components induced by the electrolysis unit and if needed by the dialysis unit of the renewable power methane production. The methanation component can be decoupled from the electrolysis unit and therefore run under baseload conditions using storage for hydrogen. Cost of renewable power methane production in dependence on input electricity LCOE and FLh of electrolysis and dialysis unit is depicted in Figure 7.4-9. Based on the renewable power methane production cost and 5,000 FLh of the total plant the hybrid PV-Wind-RPM-CCGT LCOE are derived as a function of input electricity LCOE and FLh of electrolysis and dialysis unit (Fig. 7.4-10).

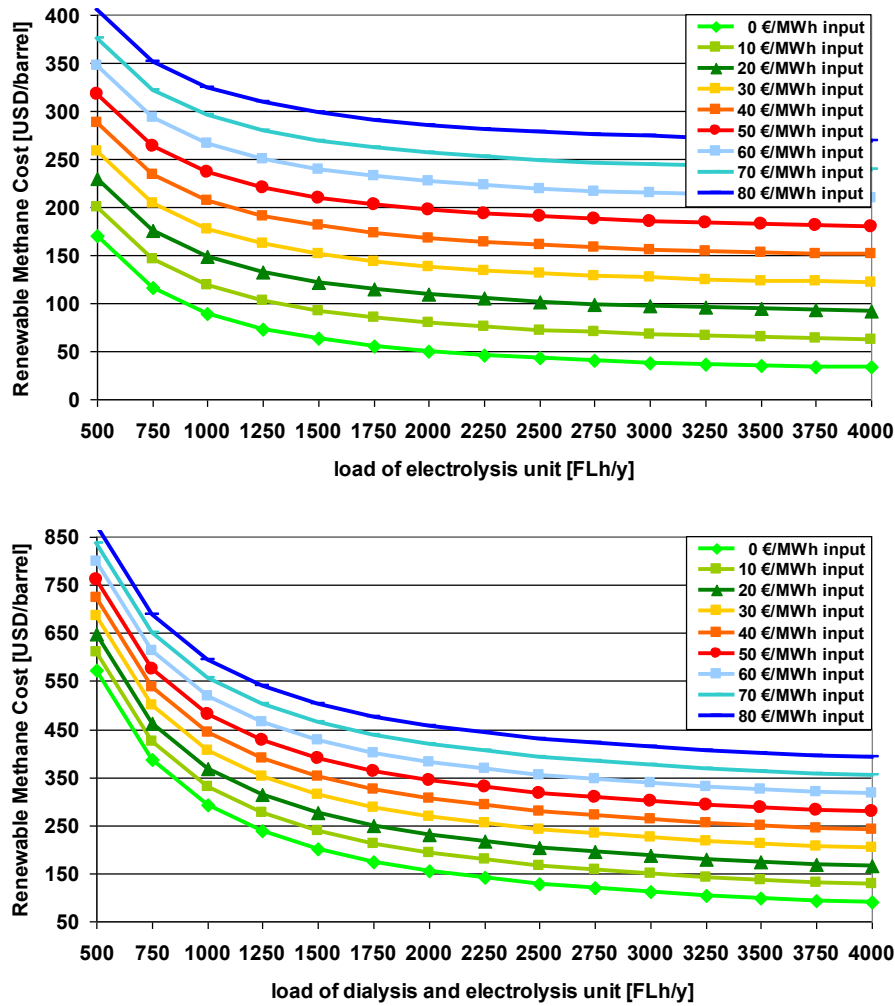
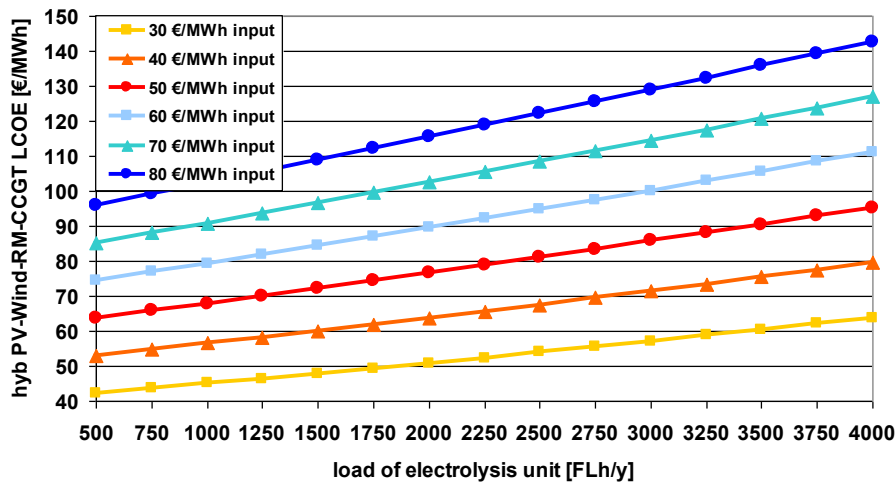


Figure 7.4-9: Renewable power methane production cost in dependence on input electricity LCOE and FLh of electrolysis (top) and dialysis and electrolysis (bottom) unit. Only an electrolysis unit is applicable in case of access to a CO₂ source and dialysis and electrolysis is needed for extracting CO₂ from ambient air. Assumptions for cost calculation are taken from Table 7.4-1.



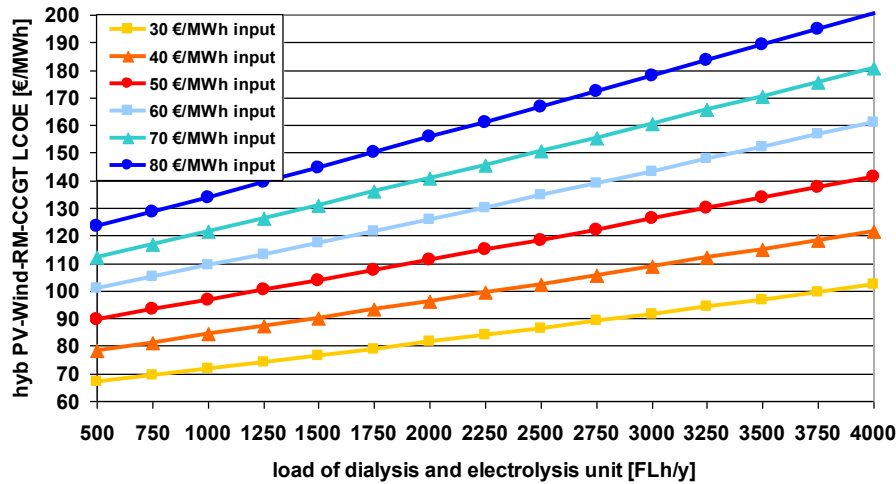


Figure 7.4-10: Hybrid PV-Wind-RPM-CCGT LCOE in dependence on input electricity LCOE and FLh of electrolysis (top) and dialysis and electrolysis (bottom) unit for 5,000 FLh of the hybrid power plant. Only an electrolysis unit is applicable in case of access to a CO₂ source and dialysis and electrolysis is needed for extracting CO₂ from ambient air. Further assumptions for LCOE calculation are taken from Table 7.4-1.

Renewable power methane production is a costly way for storing energy (Fig. 7.4-9), however the energy storage is long-term stable. Nevertheless, in cases of very inexpensive electricity of not more than 30 €/MWh and electrolysis FLh of 1,000 to 2,000 the renewable power methane production cost are not higher than 150 USD/barrel assuming access to a CO₂ source (Fig. 7.4-9). If the CO₂ has to be taken from the ambient air, the renewable power methane production cost are significantly higher, but still for very competitive input electricity cost of 30 – 50 €/MWh and dialysis and electrolysis FLh of about 2,000 the renewable power methane production cost are between 250 and 350 USD/barrel. Typical diesel price in industrialised countries is about 1.2 – 1.3 €/l (Fig. 3.4-5), which is equivalent to a renewable power methane cost of 270 – 290 USD/barrel, excluding effects by taxation or subsidies. For methane supply the technological approach might be too costly based on the scenario assumptions defined in Table 7.4-1, however further technological progress resulting in lower Capex, higher energy conversion efficiency and higher FLh could be a breakthrough for very large scale renewable power methane production.

Nevertheless, renewable power methane production might become a central cornerstone in electricity systems based on hybrid PV-Wind-RPM-CCGT power plants. Total LCOE of hybrid PV-Wind-RPM-CCGT power plants are very competitive for a broad parameter range (Fig. 7.4-10), i.e. assuming access to a CO₂ source and electrolysis FLh of 1,750 in maximum the total LCOE stay below 100 €/MWh for input LCOE of not more than 70 €/MWh and total plant FLh of 5,000. The aforementioned parameter range is very likely to be accessible in many regions in the world by 2020 (Fig. 7.4-8). Including dialysis results in 50 €/MWh input LCOE for a maximum of 100 €/MWh in total LCOE of the hybrid power plant for the example discussed before. Again, many regions might fulfil these requirements in the year 2020 (Fig. 7.4-8). Moreover, the hybrid PV-Wind-RPM-CCGT power plant approach might be very interesting for island supply. Typical power generation cost on islands are about 150 €/MWh or more due to costly diesel gensets and oil power plants. The hybrid power plant can be designed as decentralised plant where only the renewable power methane unit and the CCGT unit need to be centralised, hence applicability on islands should be possible. Assuming maximum total LCOE of 150 €/MWh and electrolysis or dialysis and electrolysis FLh of in maximum 2,000, the allowed input LCOE need to be about 75 €/MWh for the dialysis and electrolysis option of extraction CO₂ from the ambient air for total plant FLh of

5,000 (Fig. 7.4-10). Many islands in the world will fulfil this requirement (Fig. 7.4-8), therefore the hybrid PV-Wind-RPM-CCGT power plant approach might be an excellent technological option for power supply on many islands in the world.

Production cost of renewable power methane by PV and wind power supply is visualized in Figure 7.4-11 for extracting CO₂ from ambient air and in Figure 7.4-12 for CO₂ accessible by CCS. Calculations are based on scenario assumptions defined in Table 7.4-1 and visualized for 1-axis tracking PV power plants in Figure 7.4-5, for wind power plants on 150 m hub height in Figure 7.4-6 and for respective hybrid PV-Wind plants in Figure 7.4-8.

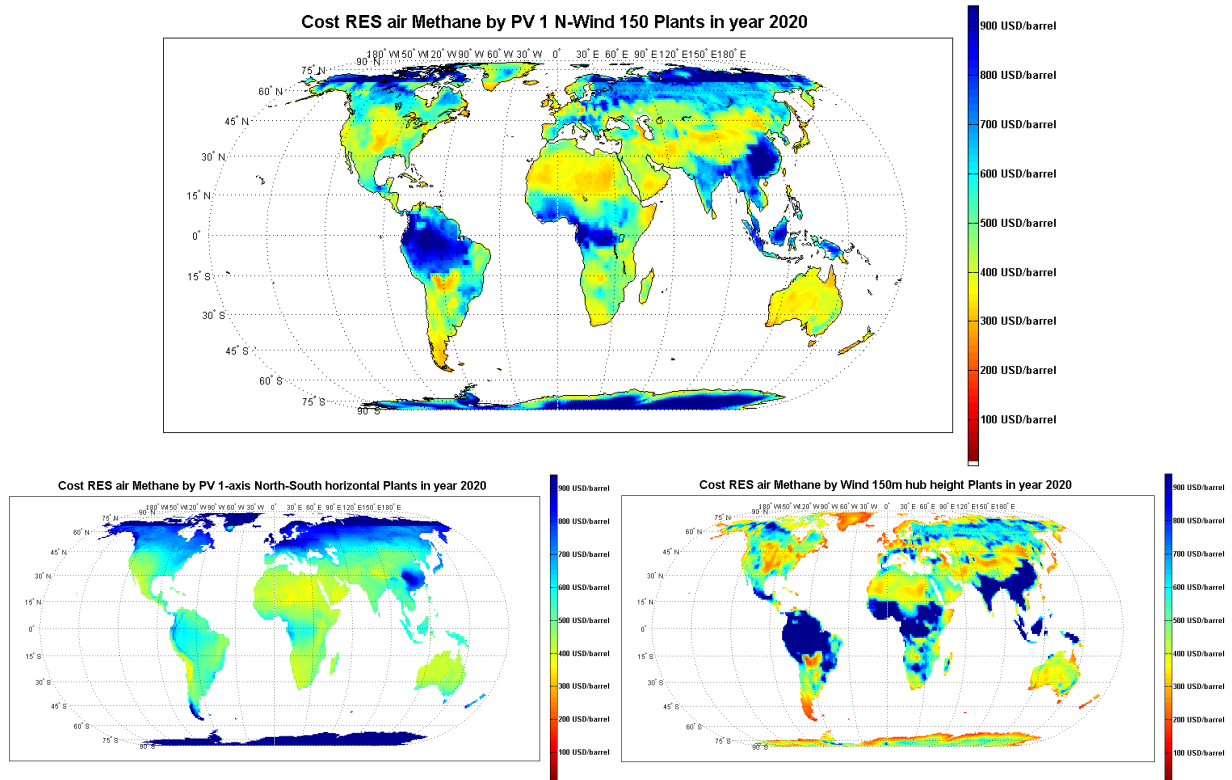
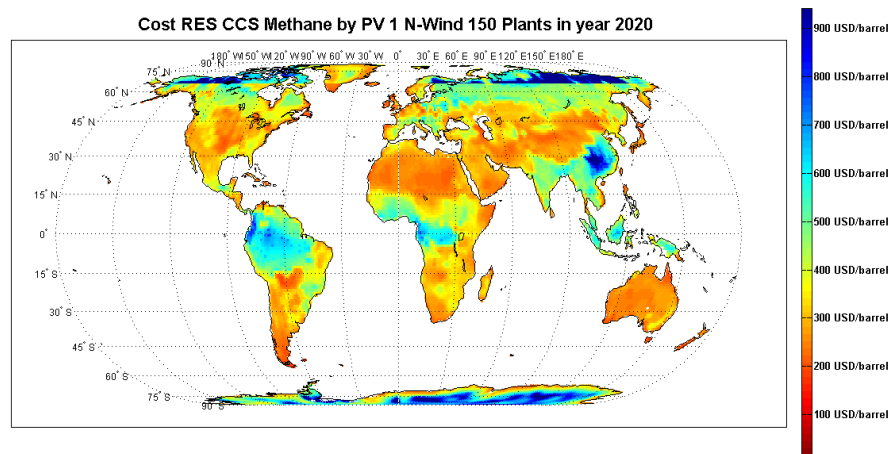


Figure 7.4-11: Renewable power methane production cost in dependence on input hybrid PV-Wind (top), PV (bottom, left) and Wind (bottom, right) LCOE and CO₂ extracted from ambient air in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). Hybrid PV-Wind component is composed by the two aforementioned PV and wind components and illustrated in Figure 7.4-8. A renewable power methane cost of 300 USD/barrel would be equivalent to a diesel price of 1.35 €/l, excluding taxation and subsidies. Further assumptions for cost calculation are taken from Table 7.4-1.



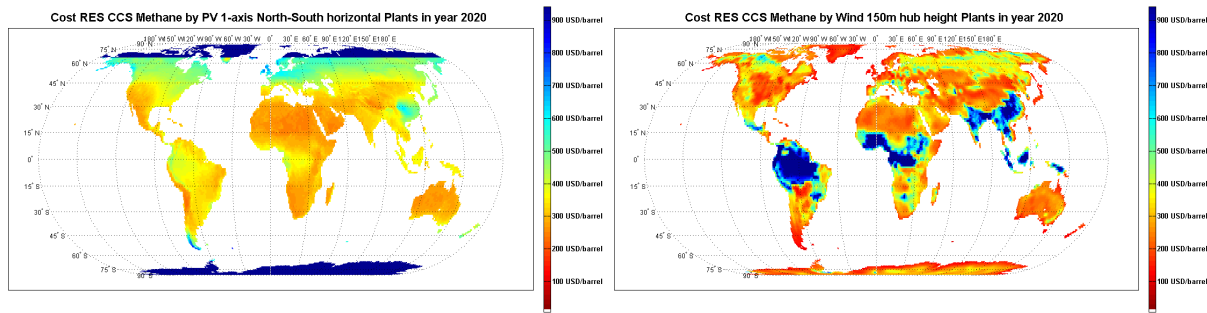


Figure 7.4-12: Renewable power methane production cost in dependence on input hybrid PV-Wind (top), PV (bottom, left) and Wind (bottom, right) LCOE and CO₂ accessible by CCS in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). Hybrid PV-Wind component is composed by the two aforementioned PV and wind components and illustrated in Figure 7.4-8. A renewable power methane cost of 300 USD/barrel would be equivalent to a diesel price of 1.35 €/l, excluding taxation and subsidies. Further assumptions for cost calculation are taken from Table 7.4-1.

Results for renewable power methane production cost based on PV and wind FLh and LCOE show challenging cost levels even in regions of excellent resource availability. In case of extracting CO₂ from ambient air, a cost level of about 300 – 400 USD/barrel can be reached (Fig. 7.4-11). For CO₂ being available due to CCS the cost level is equivalent to about 200 – 300 USD/barrel (Fig. 7.4-12). By using only PV power plants for renewable power methane production the average cost would be slightly higher and by wind power plants slightly lower than assumed hybrid PV-Wind power plants. However the cost level might be not too high compared to typical fuel prices in industrial countries, since 200, 300 and 400 USD/barrel are equivalent to diesel prices of 0.90, 1.35 and 1.80 €/l, excluding any kind of taxation and subsidies.

The technological route of renewable power methane production offers access to highly valuable fuels in many regions in the world (Fig. 7.4-11 and 7.4-12), in contrary to today's fossil fuel resource availability (sub-chapter 1.3). Based on a more homogeneous solar resource and wind resource distribution in the world, the perspective is given for an additional more homogeneously distributed renewable sourced hydrocarbon fuel availability.

7.4.3 Economic Analysis of Hybrid Renewable Power Methane Power Plants

The previous section describes the LCOE of single components and renewable power methane production cost. This section is focussed on the LCOE dynamics of hybrid PV-Wind-RPM-CCGT power plants in a global perspective (section 7.4.3.1) and for case studies of selected regions (section 7.4.3.2).

7.4.3.1 Global Overview on Cost Trends

Renewable power methane storage offers three key features: Firstly, direct renewable energy supply can be used as much as possible, e.g. PV and wind power. Secondly, storage can be charged by surplus energy for use in periods of lower load than renewable power in the grid, in particular for seasonal balancing. Thirdly, a stable power supply can be granted for the entire year. The remaining question will be whether it might be economically feasible to run

hybrid PV-Wind-RPM-CCGT power plants as the centrepiece of such a potential fully stable and sustainable renewable electricity future.

Total LCOE of hybrid PV-Wind-RPM-CCGT power plants for 5,000 FLh are calculated on basis of Equations 7.4-1 and scenario assumptions in Table 7.4-1 for the renewable components 1-axis horizontal north-south continuous tracking PV, wind turbines on 150 meter hub height and the hybrid composition of these two sub-plants for the two CO₂ source routes, i.e. from ambient air (Fig. 7.4-13) and accessible by CCS (Fig. 7.4-14).

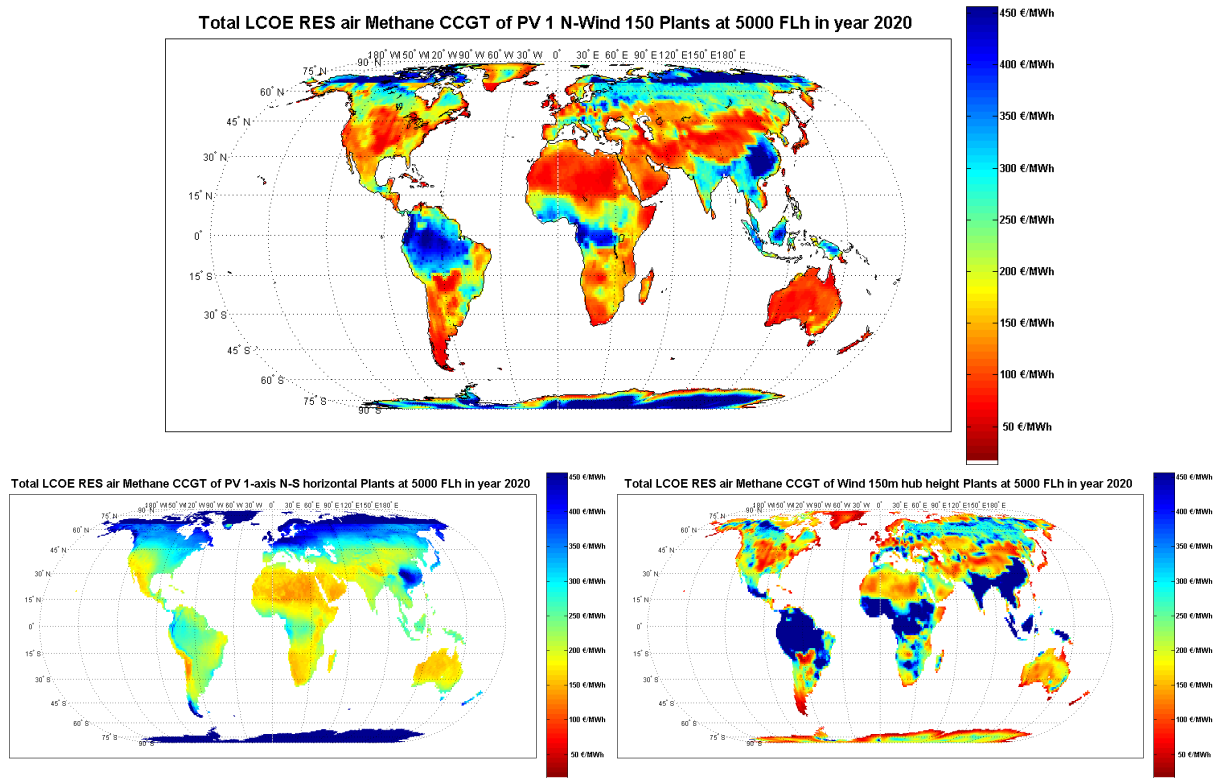
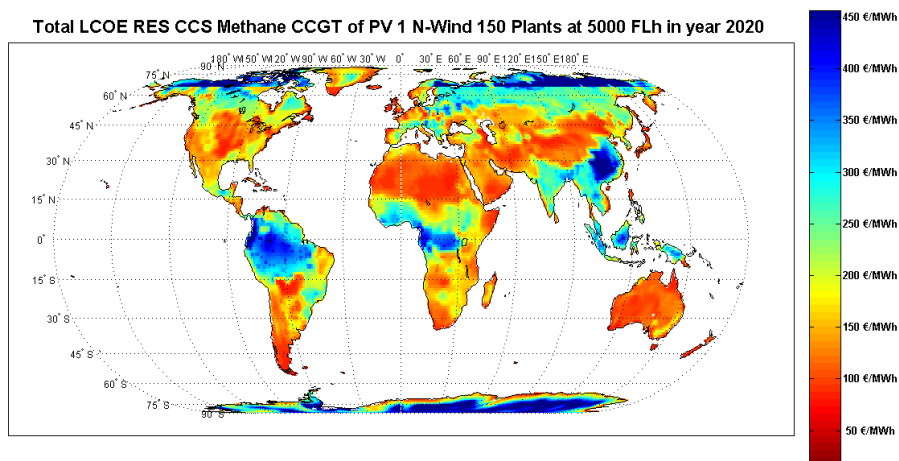


Figure 7.4-13: Total LCOE of hybrid RES-RPM-CCGT power plants for hybrid PV-Wind (top), PV (bottom, left) and wind (bottom, right) supplied by CO₂ from ambient air and operated 5,000 FLh in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). Hybrid PV-Wind component is composed by the two aforementioned PV and wind components and illustrated in Figure 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1.



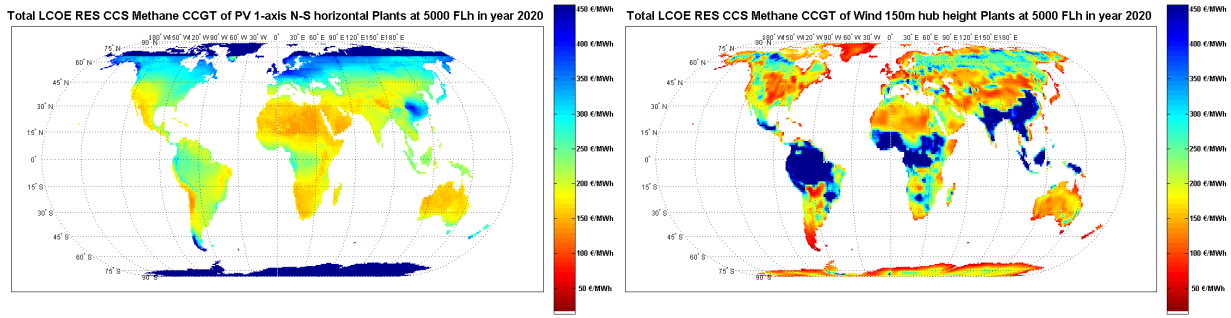


Figure 7.4-14: Total LCOE of hybrid RES-RPM-CCGT power plants for hybrid PV-Wind (top), PV (bottom, left) and wind (bottom, right) supplied by CO₂ accessible from CCS and operated 5,000 FLh in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). Hybrid PV-Wind component is composed by the two aforementioned PV and wind components and illustrated in Figure 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1.

The LCOE outcome of both CO₂ sourcing routes is nearly identical, whereas the CO₂ extraction from ambient air seems to be slightly lower in cost for the specific scenario assumptions (Fig. 7.4-13 and 7.4-14). In both cases the hybrid PV-Wind sub-plant leads to lower than the PV-only or wind-only variation for the total hybrid RES-RPM-CCGT power plant, which is caused by the beneficial effect of extended FLh on a renewable low cost basis reducing costly renewable power methane production on minimum level. Very sunny and sunny regions enable a PV-only hybrid PV-RPM-CCGT power plant on a LCOE level of 140 – 200 €/MWh for the applied scenario assumptions. In regions of good and excellent wind resource the respective LCOE can be lowered to 100 – 150 €/MWh. However, a hybrid PV-Wind power sub-plant reduces the total LCOE on a level of 60 – 100 €/MWh in regions of good and excellent solar and wind resource availability, e.g. the US, Chile, Argentina, Bolivia, some locations in Europe, nearly the entire MENA region, parts of Central Asia and Australia.

Nearly identical LCOE results for hybrid PV-Wind-RPM-CCGT power plants for both CO₂ sourcing routes (Fig. 7.4-13 and 7.4-14) is in contrast to the results of renewable power methane production costs (Fig. 7.4-11 and 7.4-12), where the CO₂ extraction from ambient air route is found to be about 40% higher in cost than the CO₂ accessible from CCS option. However, the CCS system approach is significantly higher in cost on the power plant level due to higher Capex of CCGT-CCS versus CCGT power plant component and lower respective primary energy conversion efficiency (Table 7.4-1). As a consequence higher renewable power methane production cost of the ambient air route is levelled out by beneficial power plant characteristics of the CCGT component.

This quite relevant result need to be analysed in a much deeper and broader scope than possible in this thesis. It might be possible that the enormous investments in CCS technology could end up as stranded cost on a macro economic level, in particular in case of lower total power generation system LCOE of hybrid PV-Wind-RPM-CCGT power plants using CO₂ extraction from ambient air versus fossil fuel powered CCS power plants. Enormous public financial means are needed for establishing the CCS technology and infrastructure, which might be superfluous not only in the end but right from the beginning of CCS diffusion.

An obvious evolutionary technological progress would be hybrid PV-Wind-NG-CCGT-CCS power plants for the discussed hybrid PV-Gas power plants (sub-chapter 6.3) and hybrid PV-Wind power plants (sub-chapter 7.3). Applied scenario assumptions defined in Table 7.4-1 enable calculations of hybrid PV-Wind-NG-CCGT-CCS power plants in dependence of fossil

fuel prices and for typical FLh of power plants. Results of such calculations are depicted for 1-axis horizontal north-south continuous tracking PV sub-plant (Fig. 7.4-15), wind power sub-plant (Fig. 7.4-16) and for hybrid PV-Wind sub-plant (Fig. 7.4-17) for a fossil fuel price range of 50 to 250 USD/barrel.

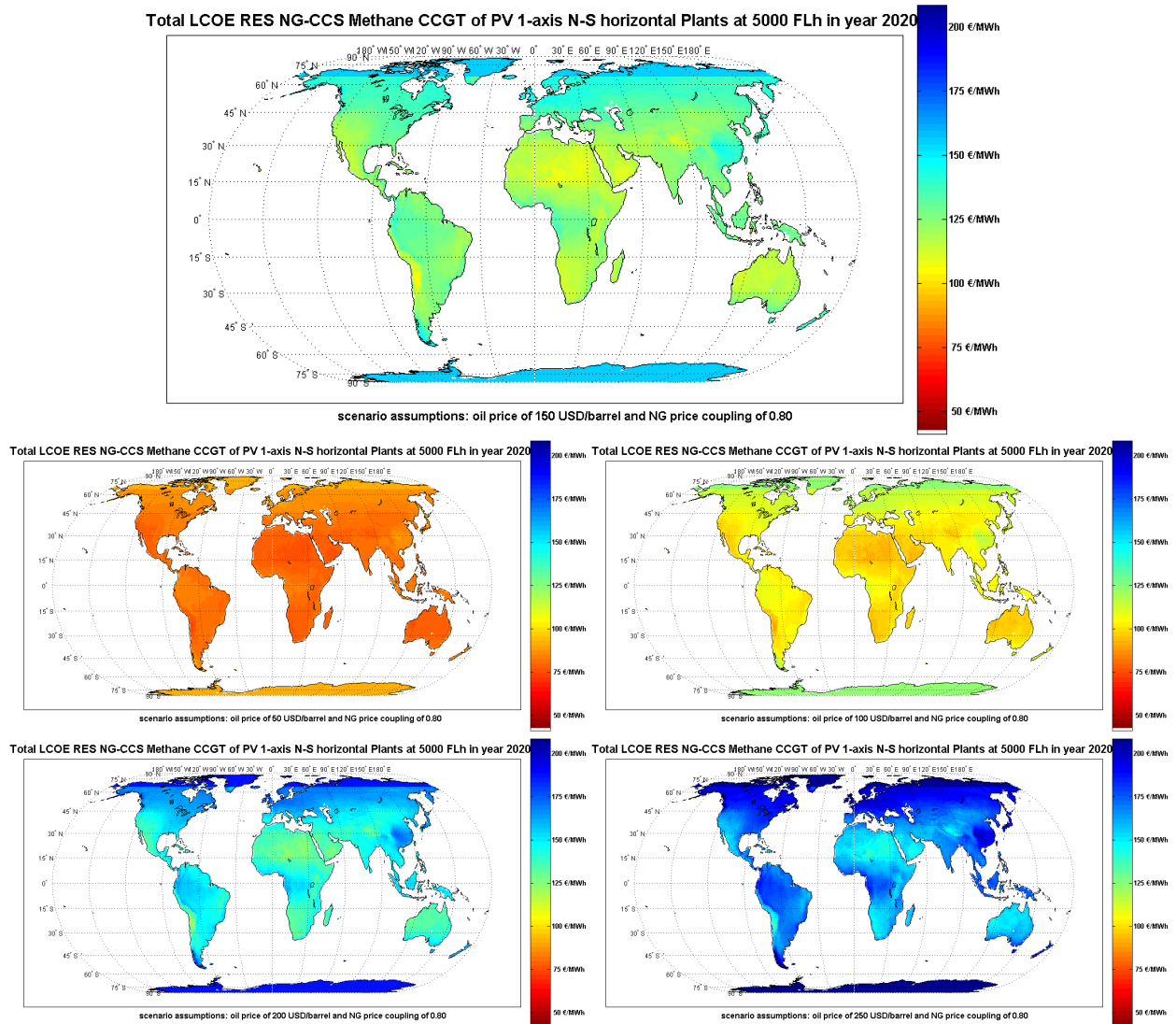


Figure 7.4-15: Total LCOE of hybrid PV-NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200 USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). Further assumptions for cost calculation are taken from Table 7.4-1.

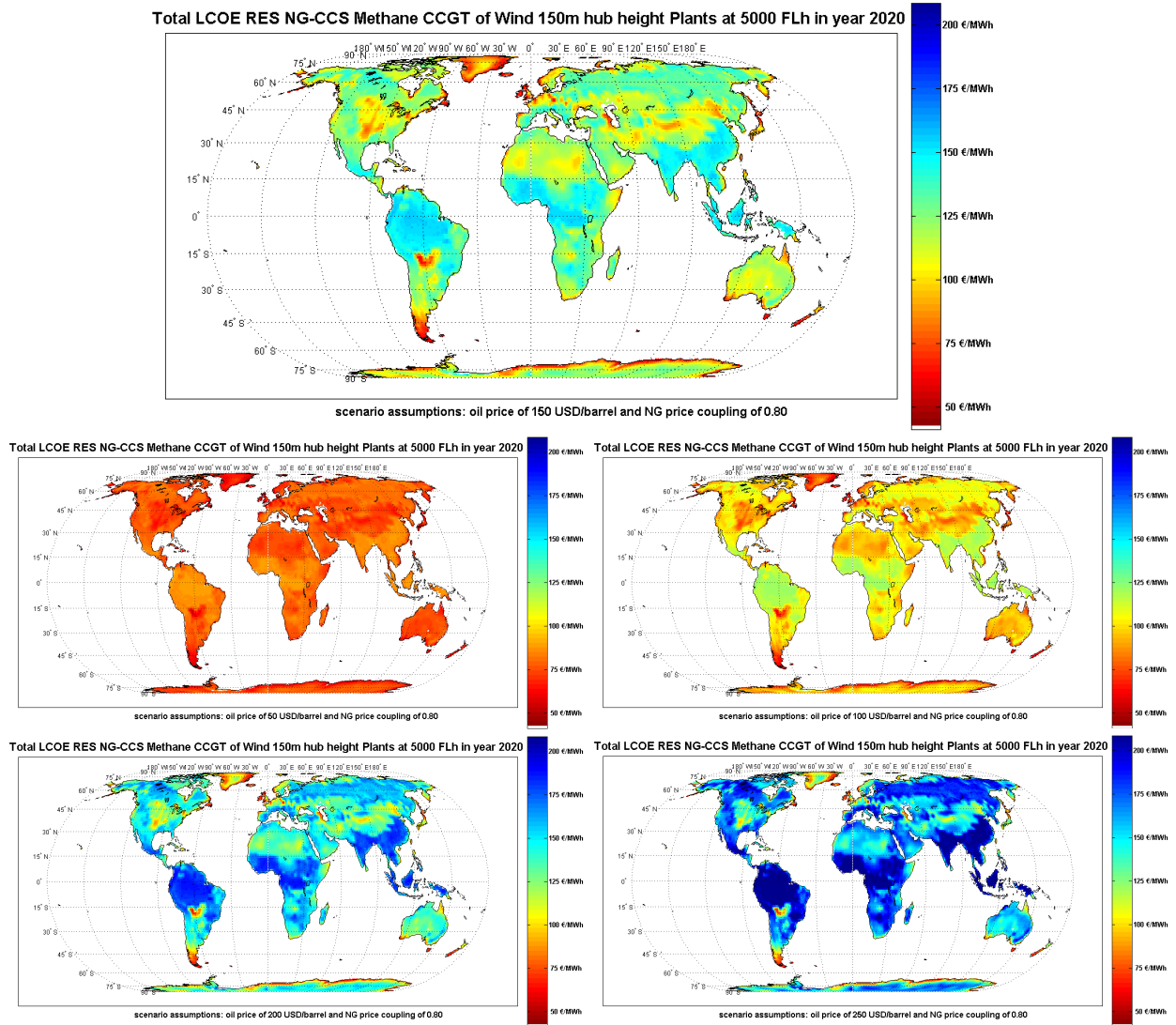
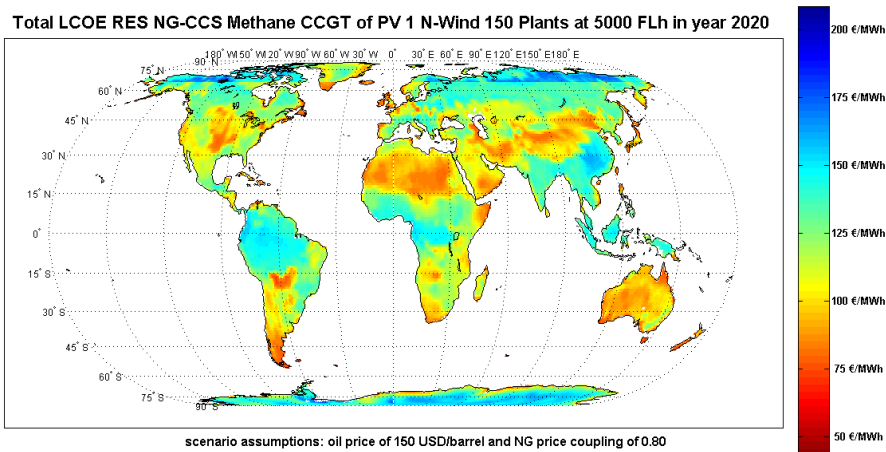


Figure 7.4-16: Total LCOE of hybrid Wind-NG-CCGT power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200 USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). Further assumptions for cost calculation are taken from Table 7.4-1.



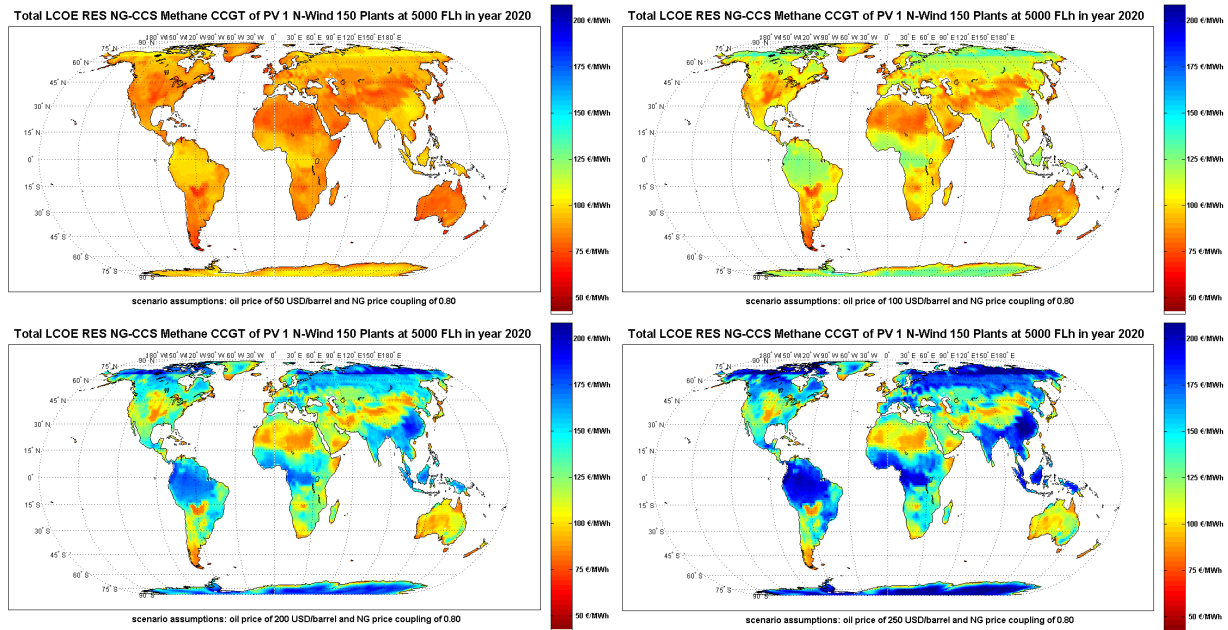


Figure 7.4-17: Total LCOE of hybrid PV-Wind-NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200 USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). The hybrid PV-Wind component is composed by the two aforementioned PV and wind components and illustrated in Figure 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1.

A steady LCOE increase for all renewable hybrid RES-NG-CCGT-CCS power plant variations is found in dependence on the fossil fuel price (Fig. 7.4-15 to 7.4-17). This result is quite similar to the findings of the hybrid PV-Fossil power plants (Fig. 6.2-12 to 6.2-15, 6.3-12 to 6.3-15 and 6.4-12 to 6.4-15). No decoupling of hybrid power plant LCOE from fossil fuel price is possible due to still used fossil fuel. The LCOE level achievable for 5,000 FLh and in regions of good to excellent resource availability is about 110 – 130 €/MWh for the PV sub-plant option (Fig. 7.4-15), about 90 – 110 €/MWh for wind sub-plant option (Fig. 7.4-16) and about 80 – 110 €/MWh for the hybrid PV-Wind sub-plant option (Fig. 7.4-17). However the favourable LCOE level for the hybrid PV-Wind sub-plant option is reached in many regions more in the world than it would be possible for the single PV or single wind sub-plant option. This outcome further confirms the highly beneficial hybridization of PV and wind power plants.

In a world where any CO₂ emissions to the atmosphere would cause an unacceptable further burden for the global climate, all fossil power plants need to be equipped with CCS technology. As a consequence hybrid RES-RPM-CCGT power plants, in particular those which extract CO₂ from ambient air, have to compete against NG-CCGT-CCS power plants. In case of lower hybrid RES-RPM-CCGT LCOE than NG-CCGT-CCS LCOE the hybrid RES-RPM-CCGT power plants would fast diffuse around the world due to better economics which are stable for the entire power plant lifetime as a consequence of no volatile cost factors.

Lower LCOE of hybrid RES-RPM-CCGT power plants extracting CO₂ from ambient air than those of NG-CCGT-CCS power plants are illustrated for 1-axis horizontal north-south continuous tracking PV sub-plant (Fig. 7.4-18), wind power sub-plant (Fig. 7.4-19) and for

hybrid PV-Wind sub-plant (Fig. 7.4-20) based on 5,000 FLh of the total power plant and for a fossil fuel price range of 50 to 250 USD/barrel in the year 2020.

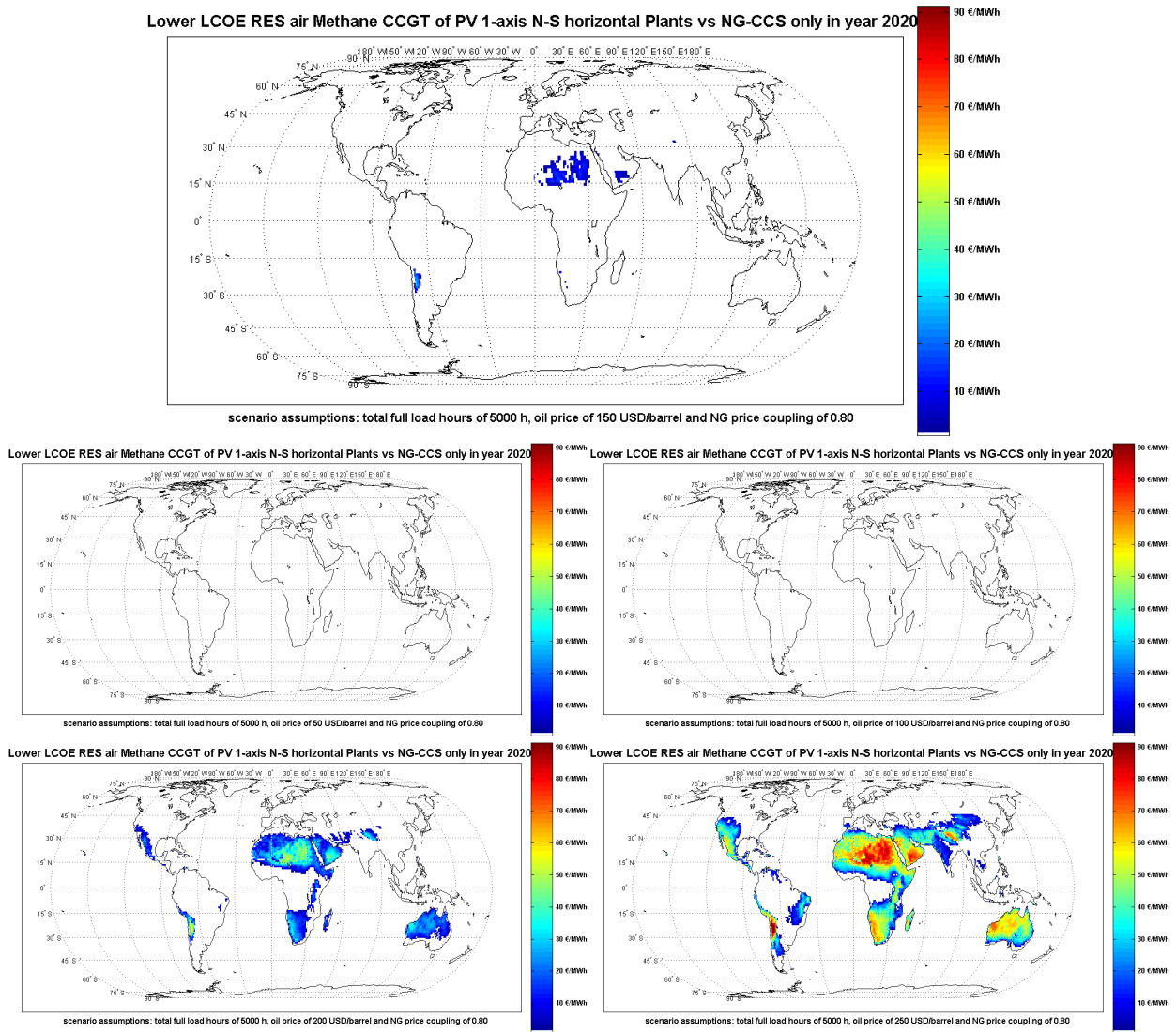


Figure 7.4-18: LCOE benefit of hybrid PV-RPM-CCGT power plants extracting CO₂ from ambient air versus NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200 USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). Further assumptions for cost calculation are taken from Table 7.4-1.

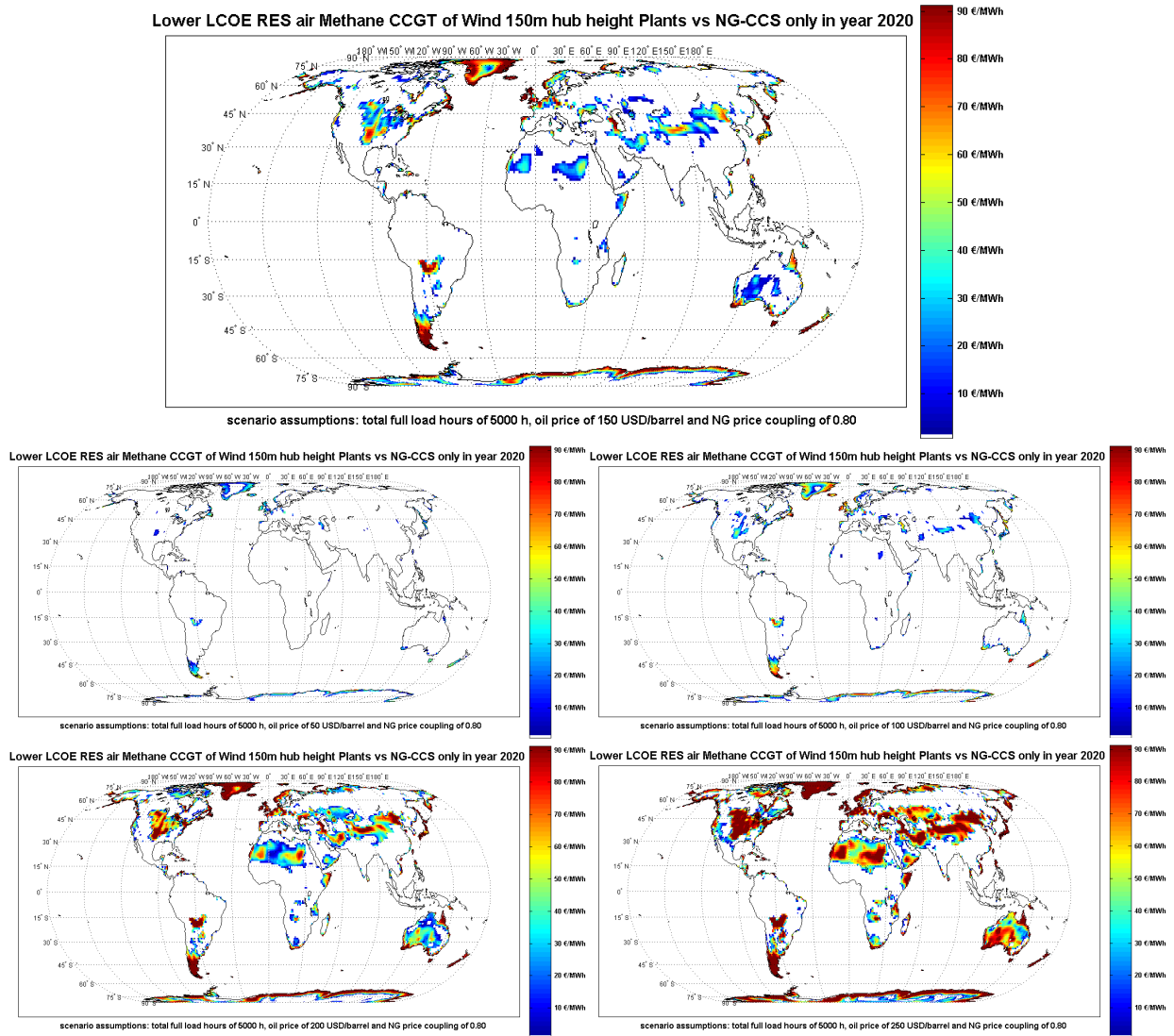
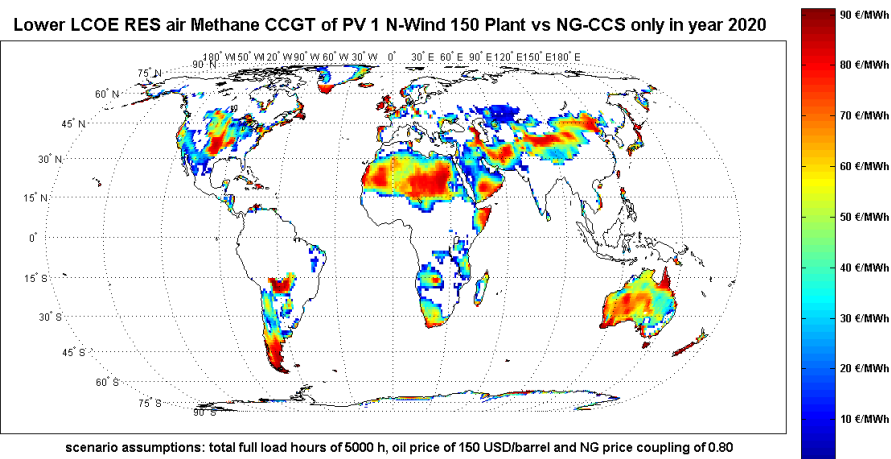


Figure 7.4-19: LCOE benefit of hybrid Wind-RPM-CCGT power plants extracting CO₂ from ambient air versus NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200 USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). Further assumptions for cost calculation are taken from Table 7.4-1.



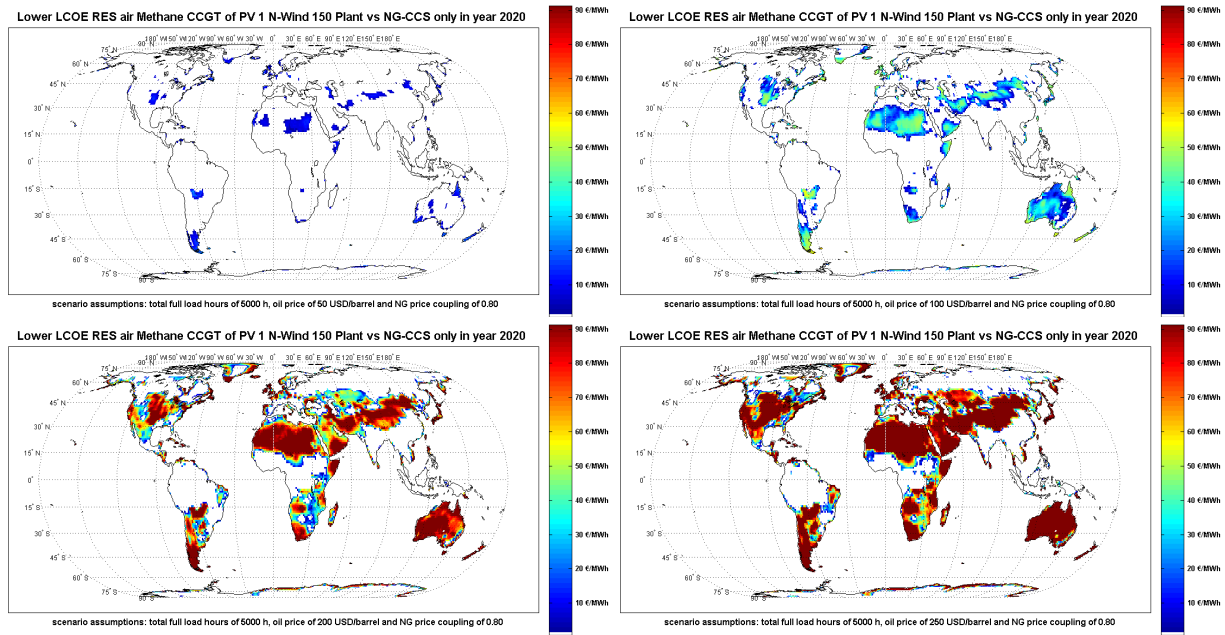


Figure 7.4-20: LCOE benefit of hybrid PV-Wind-RPM-CCGT power plants extracting CO₂ from ambient air versus NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200 USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The PV component is represented by 1-axis horizontal north-south continuous tracking PV power plants (Fig. 7.4-5). The wind component is represented by wind power plants of 150 m hub height (Fig. 7.4-6). The hybrid PV-Wind component is composed by the two aforementioned PV and wind components and illustrated in Fig. 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1.

Breakeven of hybrid RES-RPM-CCGT power plants extracting CO₂ from ambient air versus NG-CCGT-CCS power plants is given for all renewable sub-plant options for a crude oil price of at least 150 USD/barrel for at least the regions of excellent resource availability (Fig. 7.4-18 to 7.4-20). For the PV sub-plant option breakeven is reached at 150 USD/barrel for the sunniest sites in the world and for fossil fuel prices at 250 USD/barrel the 100% renewable power supply option is lower in cost of up to 80 €/MWh in regions of good and excellent solar resource (Fig. 7.4-18). The outcome for the wind power sub-plant option is similar to PV, whereas more regions in the world might have reached the breakeven and LCOE benefit is about 40 – 70 €/MWh for the regions of excellent wind resource (Fig. 7.4-19). On a fossil fuel price level of 200 – 250 USD/barrel many regions in the world show excellent economic conditions for the 100% renewable option based on the wind power sub-plant. Results for the hybrid PV-Wind-RPM-CCGT power plant show a structural cost advantage of about 50 - 100 USD/barrel (Fig. 7.4-20), i.e. the breakeven level of the single PV or single wind power sub-plant option is typically reached by the hybrid PV-Wind sub-plant at fossil fuel prices of 50 - 100 USD/barrel below. Therefore, breakeven is achieved at 50 USD/barrel in the very first regions of excellent solar and wind resource availability and at 100 USD/barrel many large regions in the world are beyond breakeven. At a fossil fuel price level of 150 USD/barrel very large regions in the world show excellent economics in comparison to gas fired CCGT-CCS power plants, i.e. the LCOE benefit of hybrid PV-Wind-RPM-CCGT power plants is up to 80 €/MWh (Fig. 7.4-20). The favourable effect of combining PV and wind power plants is confirmed in another approach of analysing relative competitiveness of renewable power plants. The fundamental reason is the complementary occurrence of solar and wind resources (sub-chapter 7.3) and the significant increase of low cost renewable FLh resulting in smaller FLh of high cost balancing renewable power methane fired CCGT power plants. The scenario definition in Table 7.4-1 is based on an overlap of 500 FLh of PV and wind power plants, however the critical overlap of hybrid PV-Wind power plants is lower (sub-chapter 7.3),

hence economics of hybrid PV-Wind-RPM-CCGT power plants are even better in reality than shown in Figure 7.4-20.

In total ten different hybrid RES-RPM-CCGT power plant variations are discussed in the sections 7.4.2 and 7.4.3.1, i.e. fixed optimally tilted PV, 1-axis horizontal north-south continuous tracking PV, wind power at 150 m hub height, hybrid fixed tilted PV-Wind and hybrid 1-axis tracking PV-Wind sub-plants for the two CO₂ source options of extracting CO₂ from ambient air and CO₂ accessible by CCS. The system combination of least local LCOE and the respective LCOE is visualised in Figure 7.4-21 for 5,000 FLh of the total hybrid power plant in the year 2020. All ten hybrid power plants have a cost structure fully decoupled from fossil fuel prices.

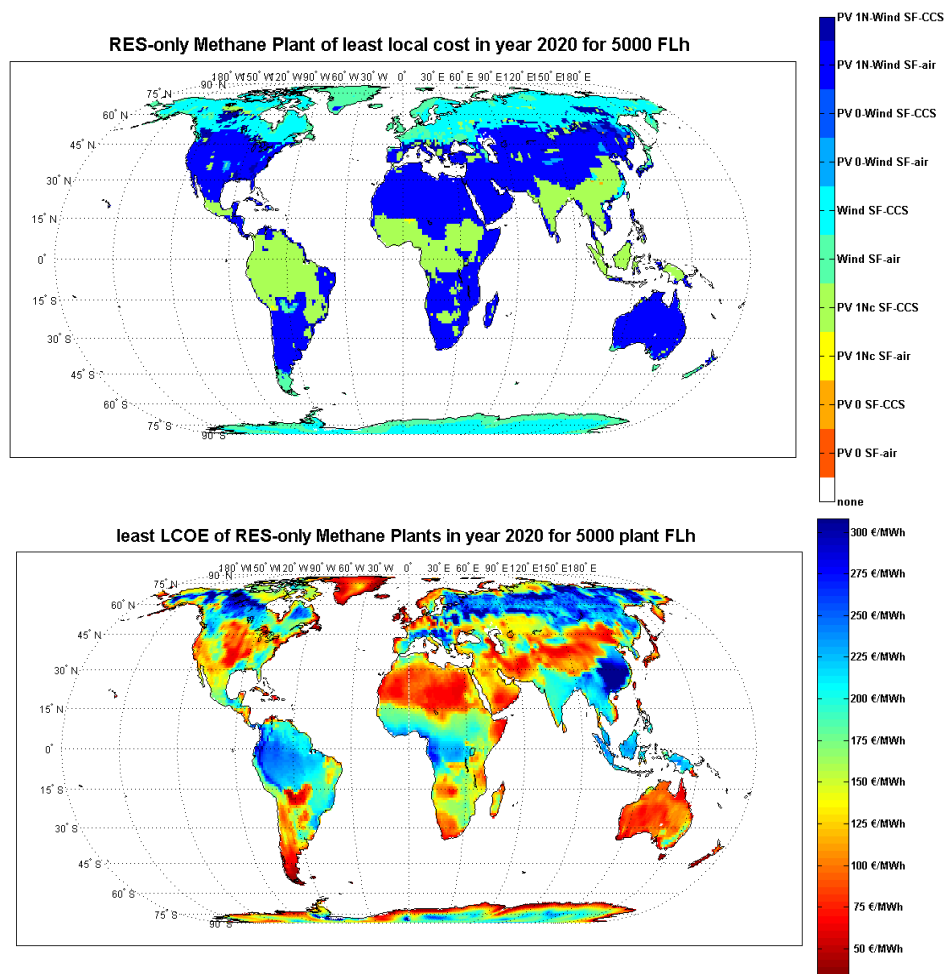


Figure 7.4-21: Hybrid RES-RPM-CCGT power plant option of least local LCOE (top) and respective absolute LCOE (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. Single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1.

In most regions of good solar and wind resources the hybrid 1-axis tracking PV-Wind sub-plant option using CO₂ extracted from ambient air generates the least LCOE of the analysed systems, typically on a LCOE level of 70 – 90 €/MWh (Fig. 7.4-21). Only very small regions achieve slightly lower LCOE for the identical hybrid power plant but based on CCS. In regions of good solar but unfavourable wind resources the best adapted system is the hybrid

1-axis tracking PV sub-plant based on a CCS CO₂ source but still on a 100% renewable basis (Fig. 7.4-21), i.e. the carbon of the methane is captured as CO₂ in the CCGT-CCS plant and used for the renewable methanation in a nearly closed cycle. In regions of only moderate solar but good wind resource quality the least cost system is the wind sub-plant, but in the regions of at least good wind resources in the variation of extracting CO₂ from ambient air whereas in regions of not such good wind resource quality the CCS option reaches a slightly lower LCOE level (Fig. 7.4-21). Within 45°S/N a PV sub-plant is in nearly all coordinates part of the least LCOE system solution, whereas in regions lower and higher than 45°S/N typically the single wind power sub-plant founds the least LCOE system design. Large parts of the world show least LCOE system levels of 70 – 130 €/MWh which might be fully competitive to fossil fired power plants in the end of the 2010s.

Full economic competitiveness of hybrid RES-RPM-CCGT power plants against fossil fired power plants could mark the beginning of a new era of sustainable power supply. As a consequence of a fast worsen climate change a drastic CCS legislation might be assumed, i.e. gas and coal fired new power plants could be only allowed in their CCS variation. Relative competitiveness of hybrid RES-RPM-CCGT power plants against gas and coal fired CCS power plants is depicted in Figure 7.4-22.

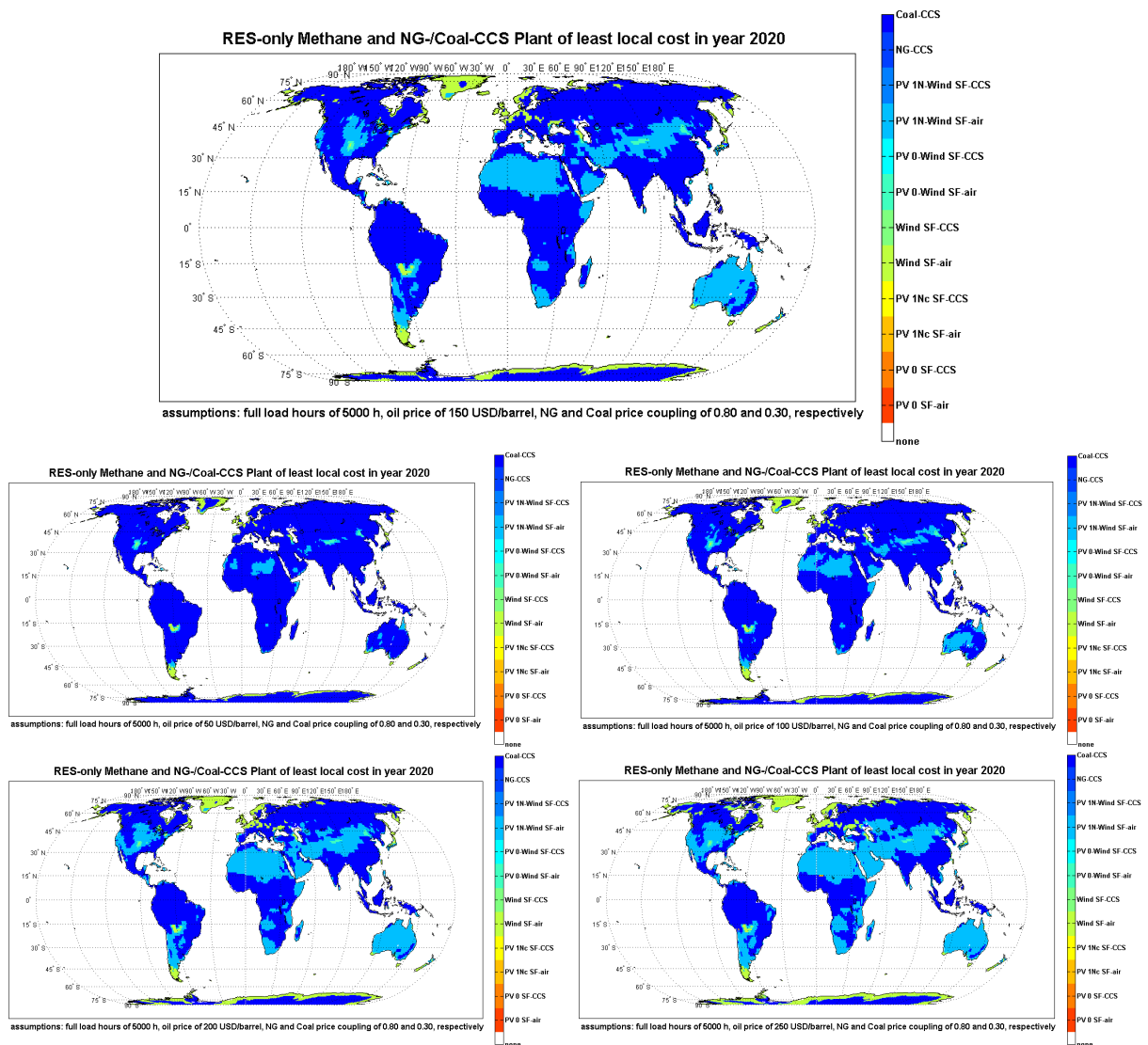


Figure 7.4-22: Least local LCOE of hybrid RES-RPM-CCGT, NG-CCGT-CCS and coal-CCS power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200

USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. The single PV, single wind and hybrid PV-Wind components are characterized in Figure 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1.

The outcome of this breakeven analysis (Fig. 7.4-22) is comparable to the results of Figure 7.4-21. In regions of good and excellent solar and wind resources the hybrid PV-Wind-RPM-CCGT power plant is very competitive against coal-CCS power plants starting at a fossil fuel price of about 100 USD/barrel (Fig. 7.4-22). Only in regions of excellent wind and only moderate solar resources the hybrid Wind-RPM-CCGT power plant is competitive against coal-CCS power plants. The CO₂ extraction from ambient air route generates lower LCOE than the renewable CCS variation in this analysis. No regions could be found in which hybrid PV-RPM-CCGT power plants are among the most competitive solutions.

Summing up, LCOE results of hybrid RES-RPM-CCGT power plants clearly indicate a growing competitiveness of 100% renewable systems. Optimised economics in regions of at least good solar and wind resources are typically achieved for hybrid PV-Wind sub-plants of a 1-axis horizontal north-south tracking PV component and a CO₂ extraction from ambient air. In regions of very good and excellent wind but only moderate solar resources a single wind power sub-plant is often found to be the best design. The renewable power methane production cost is significantly lower in cost for sourcing CO₂ from CCS, but high Capex and lower efficiencies of CCGT-CCS power plants lead to slightly better economics of power systems extracting CO₂ from the ambient air. Hybrid PV-Wind-RPM-CCGT power plants are lower in total LCOE than coal-CCS power plants in case of at least good solar and wind resource availability. This remarkable economic competitiveness might mark the beginning of a new era in sustainable power supply in the world.

7.4.3.2 Case Studies for Selected Regions

Considerations in the last section are focussed on least LCOE of respective hybrid RES-RPM-CCGT power plants in the global context. However, from the point of local view a more differentiated analysis is very helpful for understanding the local cost and technological dynamics. Key assumptions for this consideration are already defined in Table 7.4-1, which are applied for power plant configurations of 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel. The single components for establishing respective power plants are: fixed optimally tilted PV, 1-axis horizontal north-south continuous tracking PV, wind power of 150 meter hub height, conventional NG-CCGT, NG-CCGT-CCS, conventional coal without CCS, coal-CCS, renewable power methane production using CO₂ extracted from ambient air and by a cyclical CCS route. Based on these nine components a variety of 24 hybrid RES-RPM-CCGT power plants and fossil fuel fired power plants is analysed. These analyses are performed for six specific sites in the world, located in the US (section 7.4.3.2.1), Chile (section 7.4.3.2.2), Germany (section 7.4.3.2.3), Saudi Arabia (section 7.4.3.2.4), India (section 7.4.3.2.5) and China (section 7.4.3.2.6).

7.4.3.2.1 Competitiveness of Hybrid Renewable Power Methane Power Plants in the US

Dynamics of the different power plant variations are depicted for a site in the US in Figure 7.4-23. The variations are measured in LCOE but are dependent on the fossil fuel price. The selected site is characterized by very good solar and excellent wind resource conditions.

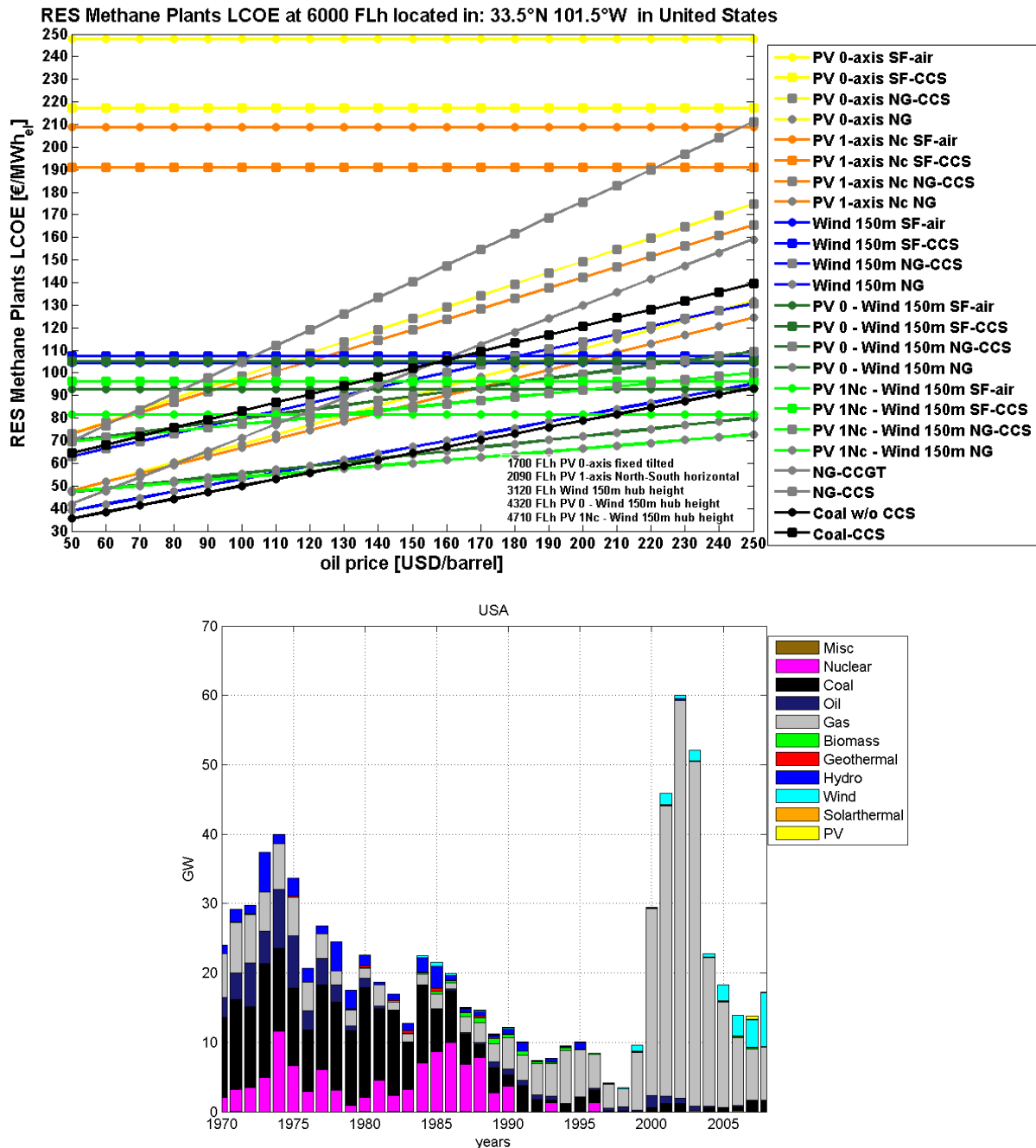


Figure 7.4-23: Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in the US (33.5°N/ 101.5°W) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 (top) and an overview on annually new installed power plant capacity in the US (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. FLh of renewable

sub-plants can be found in the figure for the site chosen. The fossil sub-plant options are natural gas (NG) fired combined cycle gas turbine (CCGT) and coal fired power plants. The single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1. Annual power plant capacity investments still in operation are sorted by power technology for the years 1970 to 2008. Data are taken from UDI World Electric Power Plants database ¹⁰⁹.

The selected site would allow a fossil fuel price decoupled power generation for LCOE of about 80 €/MWh supplied by a hybrid PV-Wind-RPM-CCGT power plant using CO₂ extracted from ambient air.

Breakeven of hybrid PV-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of 80 USD/barrel at LCOE of about 58 €/MWh. A hybrid PV-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 190 €/MWh for the CCS CO₂ sourcing option.

Breakeven of hybrid Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 50 USD/barrel at LCOE of about 40 €/MWh. A hybrid Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 160 USD/barrel and would generate electricity at a LCOE level of about 105 €/MWh for the CO₂ extraction from ambient air option.

Breakeven of hybrid PV-Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 60 USD/barrel at LCOE of about 48 €/MWh. A hybrid PV-Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 105 USD/barrel and would generate electricity at a LCOE level of about 80 €/MWh for the CO₂ extraction from ambient air option. Total LCOE parity for hybrid PV-Wind-RPM-CCGT and NG-CCGT-CCS power plants is given for a fossil fuel price of about 65 USD/barrel at a LCOE level of about 80 €/MWh and for extracting CO₂ from ambient air.

The hybrid PV-Wind-RPM-CCGT power plant achieves LCOE parity to coal-CCS power plants for a fossil fuel price of 95 USD/barrel at about 80 €/MWh LCOE for the CO₂ extracting from ambient air option. The respective parity to coal without CCS is given at a fossil fuel price of about 210 USD/barrel at about 80 €/MWh LCOE and for extracting CO₂ from ambient air.

The total power plant capacity already available in the US by end of 2008 (Fig. 7.4-23) shows massive investments in NG-CCGT capacities in the last 10 – 20 years. This matches excellent to potentially new investments in hybrid PV-Wind-RPM sub-plants upgrading the existing power plant capacity.

The hybrid PV-Wind-NG-CCGT power plant is the least LCOE power plant for a fossil fuel price of at least 130 USD/barrel at a beginning LCOE level of about 55 €/MWh. The hybrid PV-Wind-RPM-CCGT power plant LCOE is about 80 €/MWh, but cannot reach the least LCOE level below 250 USD/barrel. CCS technology is not needed for any least LCOE system design.

¹⁰⁹ Platts, UDI World Electric Power Plants data base, 2009

7.4.3.2.2 Competitiveness of Hybrid Renewable Power Methane Power Plants in Chile

Dynamics of the different power plant variations are depicted for a site in Chile in Figure 7.4-24. The variations are measured in LCOE but are dependent on the fossil fuel price. The selected site is characterized by very good solar and moderate wind resource conditions.

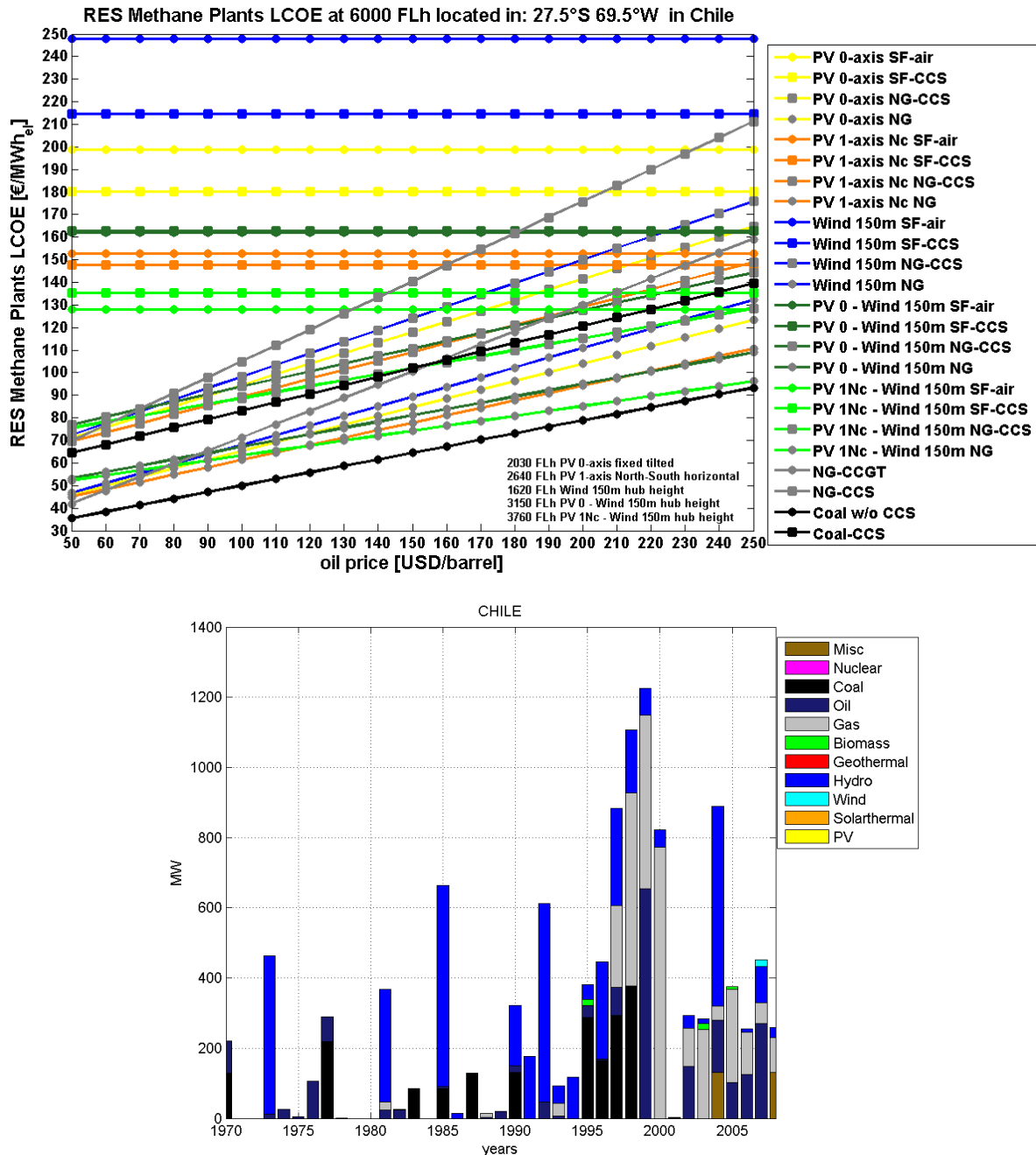


Figure 7.4-24: Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in Chile (27.5°S/ 69.5°W) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 (top) and an overview on annually new installed power plant capacity in Chile (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. FLh of renewable

sub-plants can be found in the figure for the site chosen. The fossil sub-plant options are natural gas (NG) fired combined cycle gas turbine (CCGT) and coal fired power plants. The single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1. Annual power plant capacity investments still in operation are sorted by power technology for the years 1970 to 2008. Data are taken from UDI World Electric Power Plants database ¹¹⁰.

The selected site would allow a fossil fuel price decoupled power generation for LCOE of about 128 €/MWh supplied by a hybrid PV-Wind-RPM-CCGT power plant using CO₂ extracted from ambient air.

Breakeven of hybrid PV-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of 60 USD/barrel at LCOE of about 48 €/MWh. A hybrid PV-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of about 230 - 240 USD/barrel and would generate electricity at a LCOE level of about 148 - 153 €/MWh, whereas the CCS CO₂ sourcing option would be slightly lower in LCOE than the extracting of CO₂ from ambient air.

Breakeven of hybrid Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 80 USD/barrel at LCOE of about 55 €/MWh. A hybrid Wind-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 215 €/MWh for the CCS CO₂ sourcing option.

Breakeven of hybrid PV-Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 80 USD/barrel at LCOE of about 57 €/MWh. A hybrid PV-Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 195 USD/barrel and would generate electricity at a LCOE level of about 128 €/MWh for the CO₂ extraction from ambient air option. Total LCOE parity for hybrid PV-Wind-RPM-CCGT and NG-CCGT-CCS power plants is given for a fossil fuel price of about 130 USD/barrel at a LCOE level of about 128 €/MWh and for extracting CO₂ from ambient air.

The hybrid PV-Wind-RPM-CCGT power plant achieves LCOE parity to coal-CCS power plants for a fossil fuel price of 220 USD/barrel at about 128 €/MWh LCOE for the CO₂ extracting from ambient air option. The respective parity to coal without CCS is not competitive at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 128 €/MWh for extracting CO₂ from ambient air.

The total power plant capacity already available in Chile by end of 2008 (Fig. 7.4-24) shows significant investments in NG-CCGT capacities in the last 15 years. This matches well to potentially new investments in hybrid PV-Wind-RPM sub-plants upgrading the existing power plant capacity. However, the large hydro power plant capacity should be analysed in respect to hybrid PV-Wind-Hydro power plants (sub-chapter 7.1).

The hybrid PV-Wind-NG-CCGT power plant is the least LCOE power plant for a fossil fuel price of at least 120 USD/barrel at a beginning LCOE level of about 60 €/MWh excluding coal without CCS, however respective parity would be reached by about 260 USD/barrel equalling about 98 €/MWh. The hybrid PV-Wind-RPM-CCGT power plant LCOE is about 128 €/MWh, but cannot reach the least LCOE level below 250 USD/barrel. CCS technology is not needed for a competitive least LCOE system design.

¹¹⁰ Platts, UDI World Electric Power Plants data base, 2009

7.4.3.2.3 Competitiveness of Hybrid Renewable Power Methane Power Plants in Germany

Dynamics of the different power plant variations are depicted for a site in Germany in Figure 7.4-25. The variations are measured in LCOE but are dependent on the fossil fuel price. The selected site is characterized by moderate solar and good wind resource conditions.

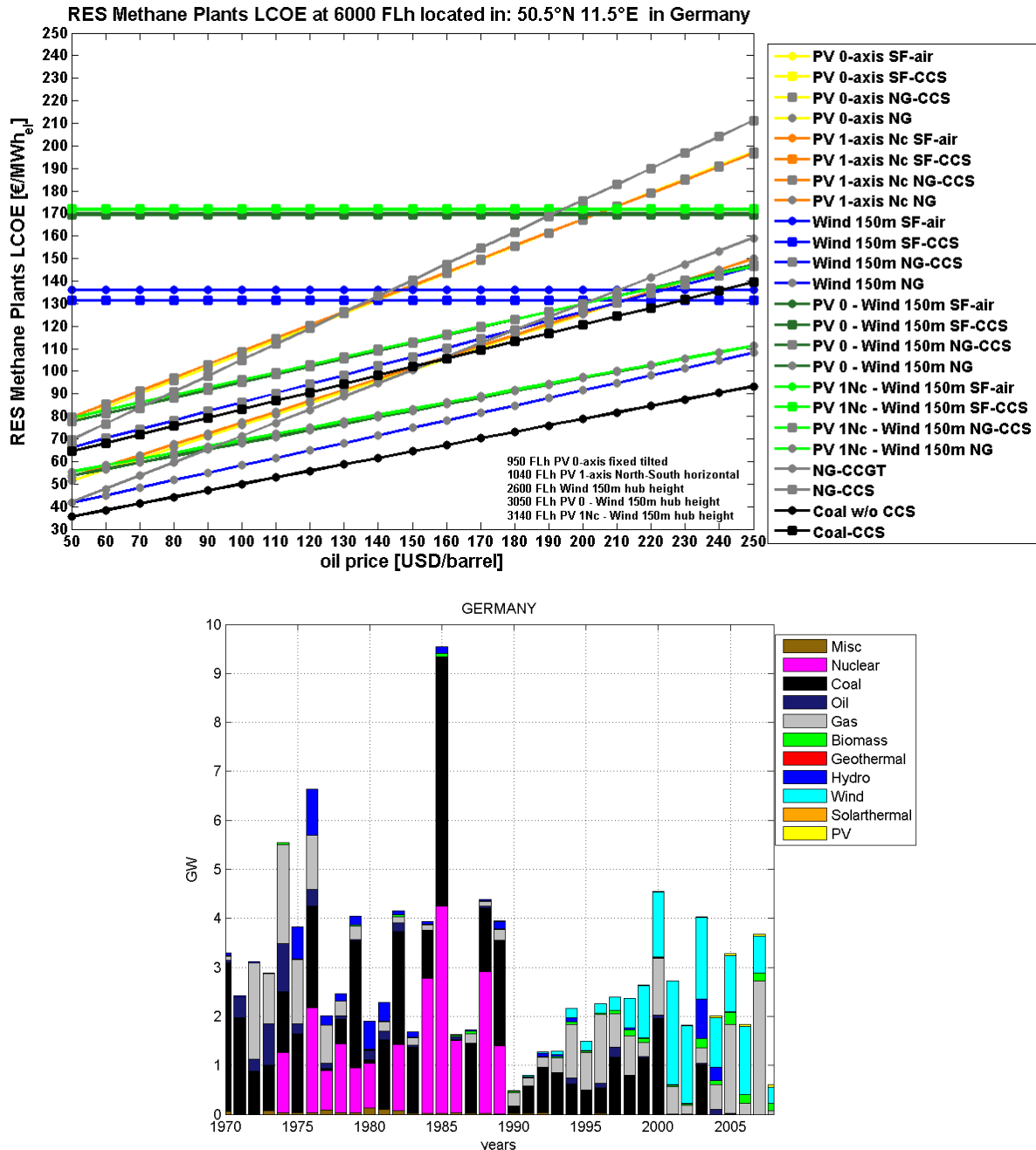


Figure 7.4-25: Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in Germany (50.5°N/ 11.5°E) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 (top) and an overview on annually new installed power plant capacity in Germany (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and

CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. FLh of renewable sub-plants can be found in the figure for the site chosen. The fossil sub-plant options are natural gas (NG) fired combined cycle gas turbine (CCGT) and coal fired power plants. The single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1. Annual power plant capacity investments still in operation are sorted by power technology for the years 1970 to 2008. The database is of very low quality for PV and limited quality for wind power. Data are taken from UDI World Electric Power Plants database ¹¹¹.

The selected site would allow a fossil fuel price decoupled power generation for LCOE of about 130 - 135 €/MWh supplied by a hybrid Wind-RPM-CCGT power plant using the CCS CO₂ sourcing option for slightly lower LCOE than CO₂ extracted from ambient air.

Breakeven of hybrid PV-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of 155 USD/barrel at LCOE of about 105 €/MWh. A hybrid PV-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of more than 250 €/MWh independent of the CO₂ sourcing option.

Breakeven of hybrid Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 50 USD/barrel at LCOE of about 42 €/MWh. A hybrid Wind-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 215 €/MWh for the CCS CO₂ sourcing option.

A hybrid Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 210 - 220 USD/barrel and would generate electricity at a LCOE level of about 130 - 135 €/MWh, whereas the CCS CO₂ sourcing option would be slightly lower in LCOE than the CO₂ extraction from ambient air option.

Breakeven of hybrid PV-Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 90 USD/barrel at LCOE of about 65 €/MWh. A hybrid PV-Wind-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 170 €/MWh for both CO₂ sourcing options. Total LCOE parity for hybrid PV-Wind-RPM-CCGT and NG-CCGT-CCS power plants is given for a fossil fuel price of about 190 USD/barrel at a LCOE level of about 170 €/MWh for both CO₂ sourcing options.

The hybrid Wind-RPM-CCGT power plant achieves LCOE parity to coal-CCS power plants for a fossil fuel price of 230 - 240 USD/barrel at about 130 - 135 €/MWh LCOE whereas the CCS CO₂ sourcing option would achieve slightly lower LCOE than the CO₂ extracting from ambient air option. The respective parity to coal without CCS is not competitive at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 130 - 135 €/MWh for both CO₂ sourcing options. The hybrid PV-Wind-RPM-CCGT power plant is higher in LCOE than without the PV sub-plant in the scenario calculations, however the assumed overlap of 500 FLh of PV and wind power plants is too conservative. The critical overlap of about 300 FLh (sub-chapter 7.3) would result in better hybrid PV-Wind sub-plant economics.

The total power plant capacity already available in Germany by end of 2008 (Fig. 7.4-25) shows significant investments in NG-CCGT capacities in the last 20 years. This matches well to potentially new investments in hybrid PV-Wind-RPM sub-plants upgrading the existing

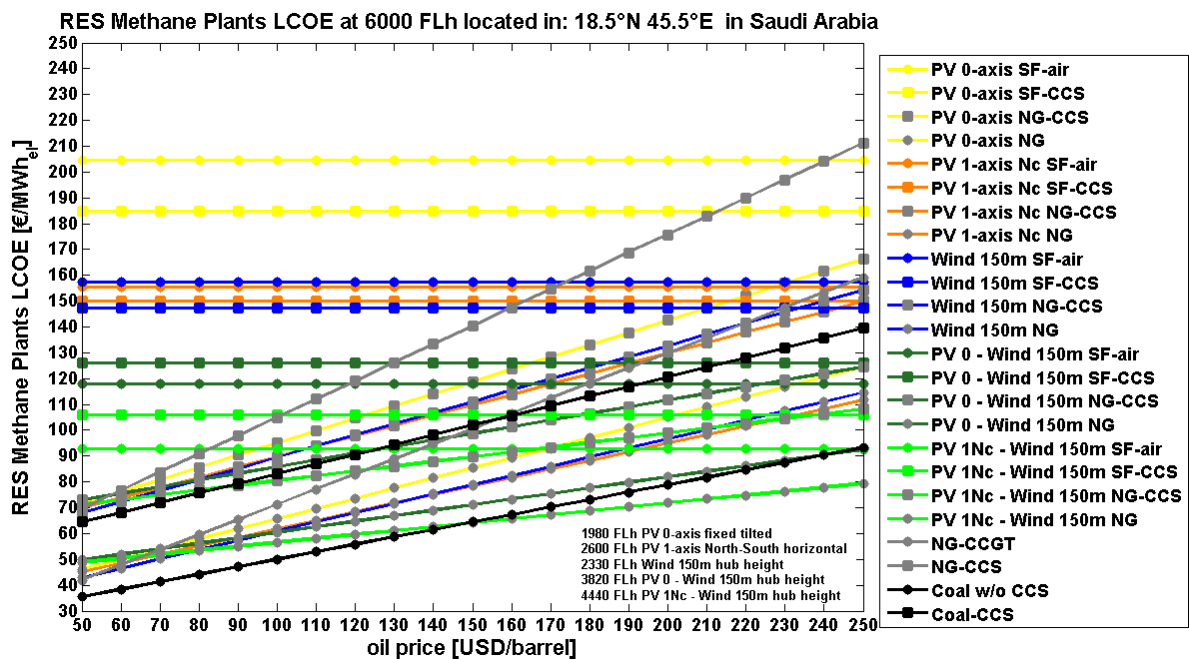
¹¹¹ Platts, UDI World Electric Power Plants data base, 2009

power plant capacity. However, the large coal power plant capacity should be taken also into account in respect to hybrid PV-Wind-Coal power plants (sub-chapter 6.4).

The hybrid Wind-NG-CCGT power plant is the least LCOE power plant for a fossil fuel price of at least 50 USD/barrel at a beginning LCOE level of about 42 €/MWh excluding coal without CCS. The hybrid Wind-RPM-CCGT power plant LCOE is about 130 - 135 €/MWh and achieves LCOE parity to coal-CCS at about 230 – 240 USD/barrel but cannot reach the least LCOE level below 250 USD/barrel. The PV sub-plant does not improve the hybrid PV-Wind power plant economics for the scenario assumptions chosen, however the real critical overlap is lower than in the scenario, hence hybrid PV-Wind power plant economics are better in reality. CCS technology is not needed for a competitive least LCOE system design.

7.4.3.2.4 Competitiveness of Hybrid Renewable Power Methane Power Plants in Saudi Arabia

Dynamics of the different power plant variations are depicted for a site in Saudi Arabia in Figure 7.4-26. The variations are measured in LCOE but are dependent on the fossil fuel price. The selected site is characterized by very good solar and good wind resource conditions.



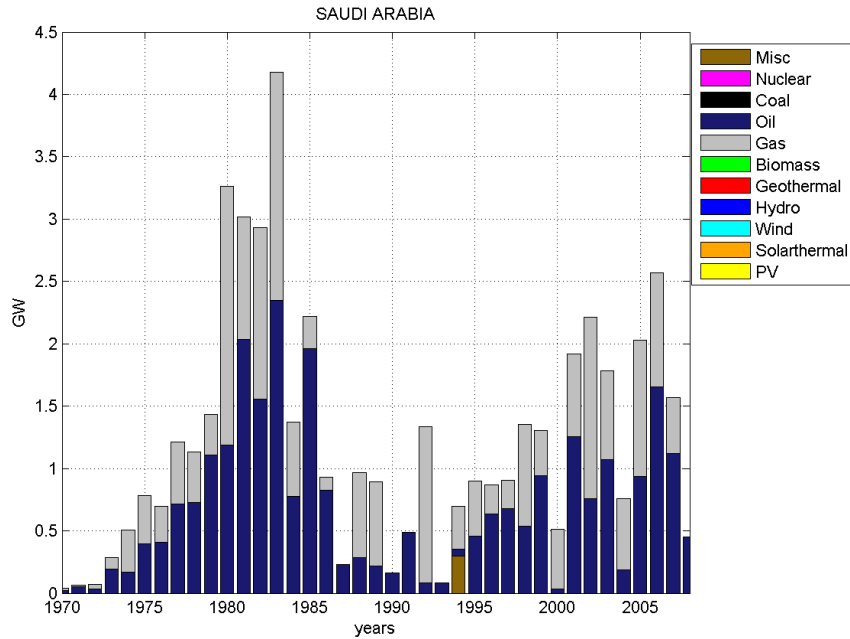


Figure 7.4-26: Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in Saudi Arabia (18.5°N/ 45.5°E) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 (top) and an overview on annually new installed power plant capacity in Saudi Arabia (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. FLh of renewable sub-plants can be found in the figure for the site chosen. The fossil sub-plant options are natural gas (NG) fired combined cycle gas turbine (CCGT) and coal fired power plants. The single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1. Annual power plant capacity investments still in operation are sorted by power technology for the years 1970 to 2008. Data are taken from UDI World Electric Power Plants database ¹¹².

The selected site would allow a fossil fuel price decoupled power generation for LCOE of about 92 €/MWh supplied by a hybrid PV-Wind-RPM-CCGT power plant using CO₂ extracted from ambient air.

Breakeven of hybrid PV-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of 60 USD/barrel at LCOE of about 48 €/MWh. A hybrid PV-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of about 235 - 245 USD/barrel and would generate electricity at a LCOE level of about 150 - 155 €/MWh, whereas the CCS CO₂ sourcing option would be slightly lower in LCOE than the extracting of CO₂ from ambient air.

Breakeven of hybrid Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 55 USD/barrel at LCOE of about 45 €/MWh. A hybrid Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of about 230 - 245 USD/barrel and would generate electricity at a LCOE level of about 148 - 158 €/MWh, whereas the CCS CO₂ sourcing option would be slightly lower in LCOE than the extracting of CO₂ from ambient air.

¹¹² Platts, UDI World Electric Power Plants data base, 2009

Breakeven of hybrid PV-Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 65 USD/barrel at LCOE of about 50 €/MWh. A hybrid PV-Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 138 USD/barrel and would generate electricity at a LCOE level of about 92 €/MWh for the CO₂ extraction from ambient air option. Total LCOE parity for hybrid PV-Wind-RPM-CCGT and NG-CCGT-CCS power plants is given for a fossil fuel price of about 82 USD/barrel at a LCOE level of about 92 €/MWh and for extracting CO₂ from ambient air.

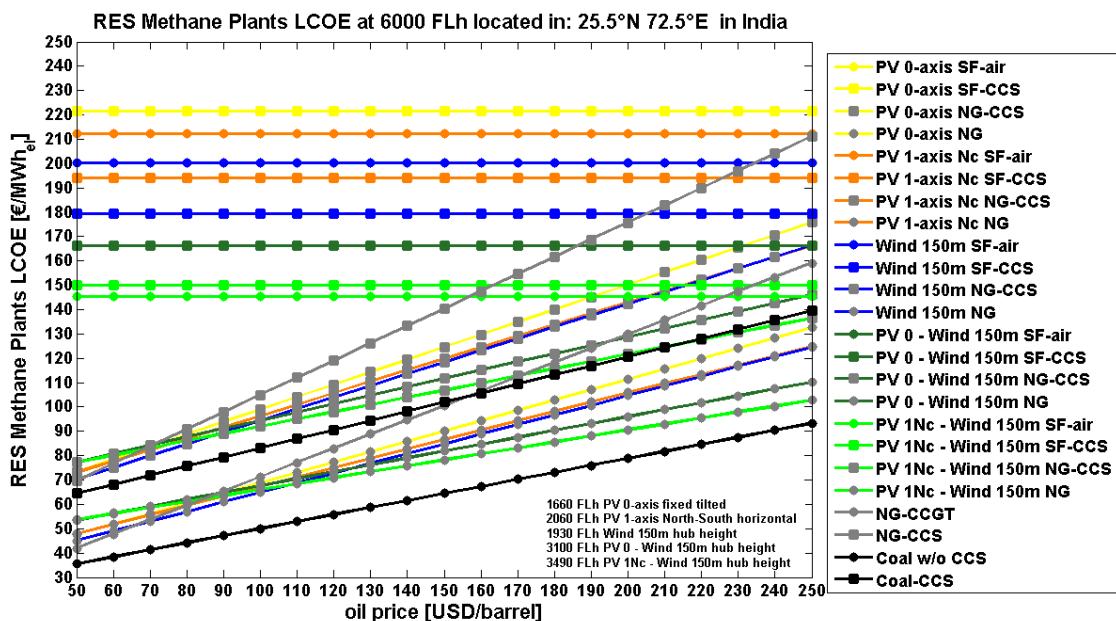
The hybrid PV-Wind-RPM-CCGT power plant achieves LCOE parity to coal-CCS power plants for a fossil fuel price of 125 USD/barrel at about 92 €/MWh LCOE for the CO₂ extracting from ambient air option. The respective parity to coal without CCS is given at a fossil fuel price of about 250 USD/barrel at about 92 €/MWh LCOE and for extracting CO₂ from ambient air.

The total power plant capacity already available in Saudi Arabia by end of 2008 (Fig. 7.4-26) shows significant investments in NG and oil fired GT and CCGT capacities in the last decades. This matches excellent to potentially new investments in hybrid PV-Wind-RPM sub-plants upgrading the existing power plant capacity.

The hybrid PV-Wind-NG-CCGT power plant is the least LCOE power plant for a fossil fuel price of at least 150 USD/barrel at a beginning LCOE level of about 62 €/MWh. The plant would be the least LCOE option at 80 USD/barrel at a beginning LCOE level of 52 €/MWh excluding coal without CCS. The hybrid PV-Wind-RPM-CCGT power plant LCOE is about 92 €/MWh, but cannot reach the least LCOE level below 250 USD/barrel. CCS technology is not needed for a competitive least LCOE system design.

7.4.3.2.5 Competitiveness of Hybrid Renewable Power Methane Power Plants in India

Dynamics of the different power plant variations are depicted for a site in India in Figure 7.4-27. The variations are measured in LCOE but are dependent on the fossil fuel price. The selected site is characterized by good solar and good wind resource conditions.



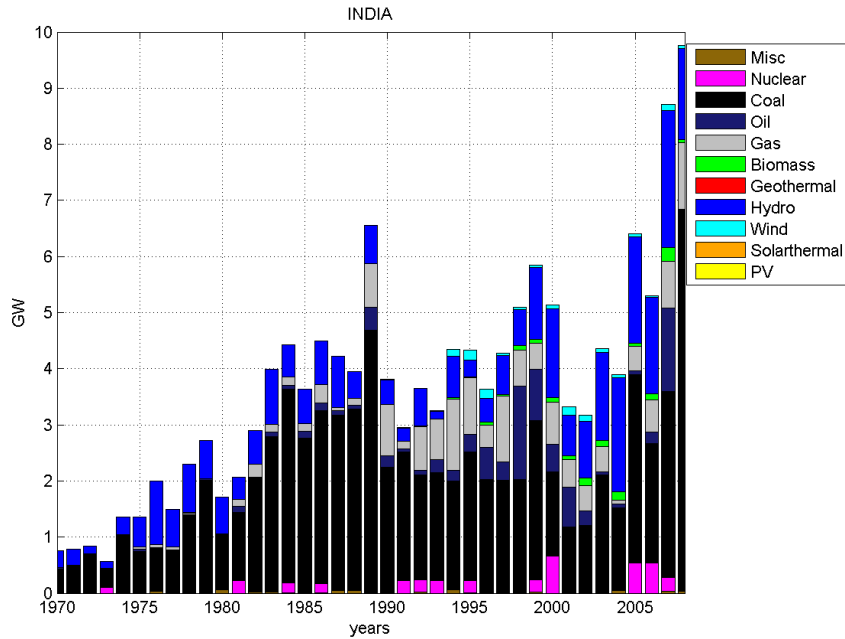


Figure 7.4-27: Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in India (25.5°N/ 72.5°E) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 (top) and an overview on annually new installed power plant capacity in India (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. FLh of renewable sub-plants can be found in the figure for the site chosen. The fossil sub-plant options are natural gas (NG) fired combined cycle gas turbine (CCGT) and coal fired power plants. The single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1. Annual power plant capacity investments still in operation are sorted by power technology for the years 1970 to 2008. Data are taken from UDI World Electric Power Plants database ¹¹³.

The selected site would allow a fossil fuel price decoupled power generation for LCOE of about 145 €/MWh supplied by a hybrid PV-Wind-RPM-CCGT power plant using CO₂ extracted from ambient air.

Breakeven of hybrid PV-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of 80 USD/barrel at LCOE of about 60 €/MWh. A hybrid PV-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 195 €/MWh for the CCS CO₂ sourcing option.

Breakeven of hybrid Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 65 USD/barrel at LCOE of about 50 €/MWh. A hybrid Wind-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 180 €/MWh for the CCS CO₂ sourcing option.

Breakeven of hybrid PV-Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 85 USD/barrel at LCOE of about 60 €/MWh. A hybrid PV-Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel

¹¹³ Platts, UDI World Electric Power Plants data base, 2009

price of 225 USD/barrel and would generate electricity at a LCOE level of about 145 €/MWh for the CO₂ extraction from ambient air option. Total LCOE parity for hybrid PV-Wind-RPM-CCGT and NG-CCGT-CCS power plants is given for a fossil fuel price of about 158 USD/barrel at a LCOE level of about 145 €/MWh and for extracting CO₂ from ambient air.

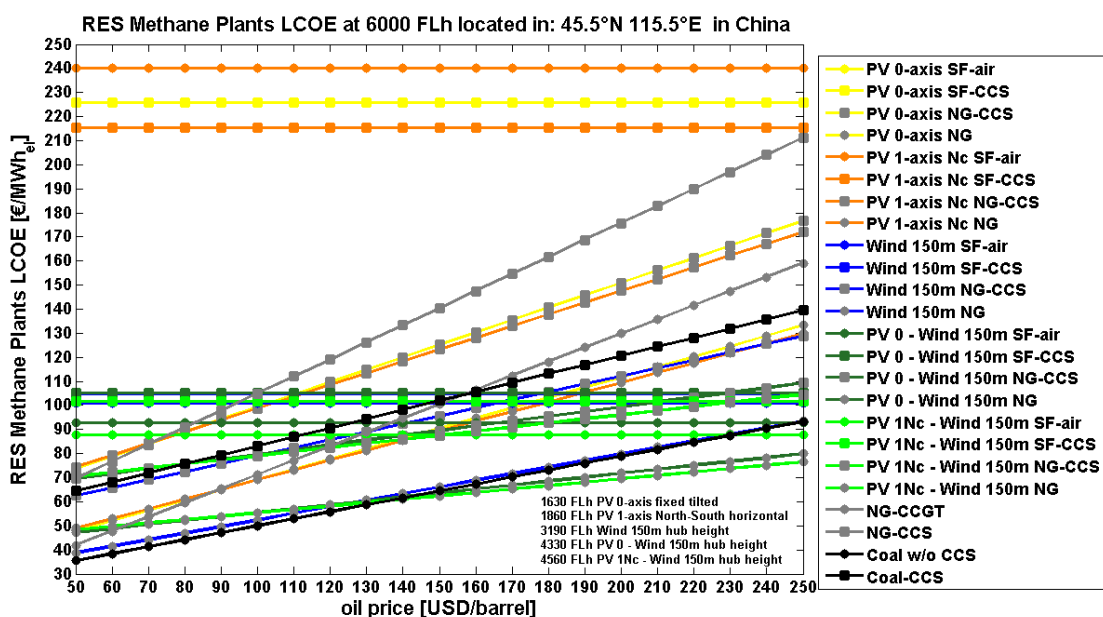
The hybrid PV-Wind-RPM-CCGT power plant achieves LCOE parity to coal-CCS power plants for a fossil fuel price of 260 USD/barrel at about 145 €/MWh LCOE for the CO₂ extracting from ambient air option. The respective parity to coal without CCS is not competitive at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 145 €/MWh for extracting CO₂ from ambient air.

The total power plant capacity already available in India by end of 2008 (Fig. 7.4-27) shows some investments in NG-CCGT capacities in the last 20 years. This matches well to potentially new investments in hybrid PV-Wind-RPM sub-plants upgrading the existing power plant capacity. However, the large coal and hydro power plant capacity should be taken also into account in respect to hybrid PV-Wind-Coal power plants (sub-chapter 6.4) and hybrid PV-Wind-Hydro power plants (sub-chapter 7.1).

The hybrid PV-Wind-NG-CCGT power plant is the least LCOE power plant for a fossil fuel price of at least 105 USD/barrel at a beginning LCOE level of about 65 €/MWh excluding coal without CCS. In the fossil fuel price range of 60 – 105 USD/barrel the least LCOE are reached by the hybrid Wind-NG-CCGT power plant, excluding coal without CCS. The hybrid PV-Wind-RPM-CCGT power plant LCOE is about 145 €/MWh, but cannot reach the least LCOE level below 250 USD/barrel. CCS technology is not needed for a competitive least LCOE system design.

7.4.3.2.6 Competitiveness of Hybrid Renewable Power Methane Power Plants in China

Dynamics of the different power plant variations are depicted for a site in China in Figure 7.4-28. The variations are measured in LCOE but are dependent on the fossil fuel price. The selected site is characterized by good solar and very good wind resource conditions.



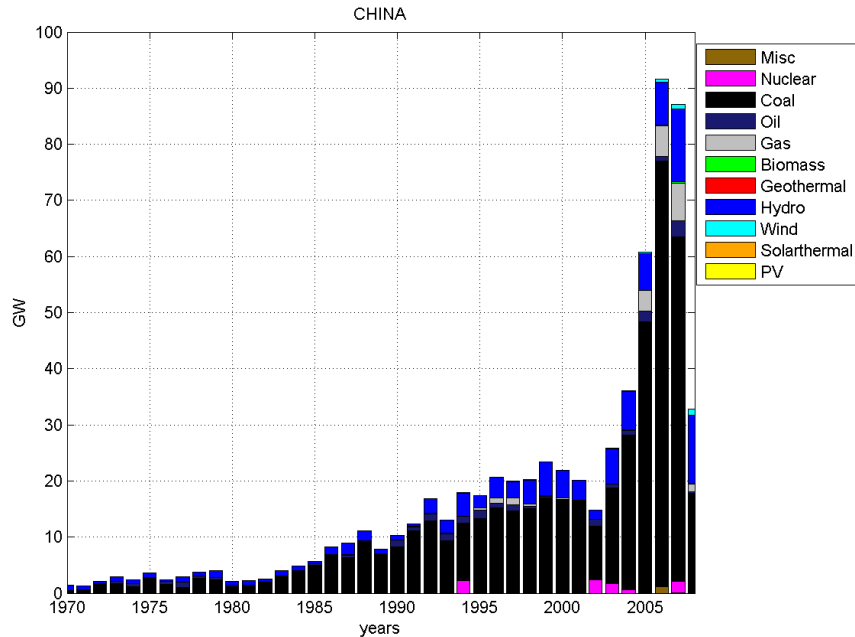


Figure 7.4-28: Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in China (45.5°N/ 115.5°W) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 (top) and an overview on annually new installed power plant capacity in China (bottom). The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. FLh of renewable sub-plants can be found in the figure for the site chosen. The fossil sub-plant options are natural gas (NG) fired combined cycle gas turbine (CCGT) and coal fired power plants. The single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1. Annual power plant capacity investments still in operation are sorted by power technology for the years 1970 to 2008. Data are taken from UDI World Electric Power Plants database ¹¹⁴.

The selected site would allow a fossil fuel price decoupled power generation for LCOE of about 88 €/MWh supplied by a hybrid PV-Wind-RPM-CCGT power plant using CO₂ extracted from ambient air.

Breakeven of hybrid PV-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of 90 USD/barrel at LCOE of about 65 €/MWh. A hybrid PV-RPM-CCGT power plant is not competitive to a NG-CCGT power plant at a fossil fuel price of 250 USD/barrel and would generate electricity at a LCOE level of about 215 €/MWh for the CCS CO₂ sourcing option.

Breakeven of hybrid Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of below 50 USD/barrel at LCOE of about 38 €/MWh. A hybrid Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel price of 150 USD/barrel and would generate electricity at a LCOE level of about 100 €/MWh for the CO₂ extraction from ambient air option.

Breakeven of hybrid PV-Wind-NG-CCGT power plant versus NG-CCGT power plant is achieved at a fossil fuel price of about 60 USD/barrel at LCOE of about 50 €/MWh. A hybrid PV-Wind-RPM-CCGT power plant is competitive to a NG-CCGT power plant at a fossil fuel

¹¹⁴ Platts, UDI World Electric Power Plants data base, 2009

price of 128 USD/barrel and would generate electricity at a LCOE level of about 88 €/MWh for the CO₂ extraction from ambient air option. Total LCOE parity for hybrid PV-Wind-RPM-CCGT and NG-CCGT-CCS power plants is given for a fossil fuel price of about 75 USD/barrel at a LCOE level of about 88 €/MWh and for extracting CO₂ from ambient air.

The hybrid PV-Wind-RPM-CCGT power plant achieves LCOE parity to coal-CCS power plants for a fossil fuel price of 110 USD/barrel at about 88 €/MWh LCOE for the CO₂ extracting from ambient air option. The respective parity to coal without CCS is given at a fossil fuel price of about 230 USD/barrel at about 88 €/MWh LCOE and for extracting CO₂ from ambient air.

The total power plant capacity already available in China by end of 2008 (Fig. 7.4-28) shows relatively little investments in NG-CCGT capacities in the last years. Therefore the upgrading potential for hybrid PV-Wind-RPM sub-plants might be limited. However, the large coal and hydro power plant capacity should be taken also into account in respect to hybrid PV-Wind-Coal power plants (sub-chapter 6.4) and hybrid PV-Wind-Hydro power plants (sub-chapter 7.1).

The hybrid PV-Wind-NG-CCGT power plant is the least LCOE power plant for a fossil fuel price of at least 140 USD/barrel at a beginning LCOE level of about 60 €/MWh. Below 140 USD the hybrid Wind-NG-CCGT power plant is only 2 – 3 €/MWh higher in LCOE than coal without CCS. The hybrid PV-Wind-RPM-CCGT power plant LCOE is about 88 €/MWh, but cannot reach the least LCOE level below 250 USD/barrel. CCS technology is not needed for a competitive least LCOE system design.

Summing up, upgrading NG-CCGT power plants by hybrid PV-Wind power plants typically lead to lower LCOE for fossil fuel prices of about 50 – 90 USD/barrel. In case of good solar and wind resource availability the hybrid PV-Wind-NG-CCGT power plant is very competitive beginning between fossil fuel prices of 70 – 90 USD/barrel onwards. The remaining natural gas fired in the NG-CCGT sub-plant still leads to CO₂ emissions but the natural gas can be replaced by renewable power methane, however it will be higher in cost than the natural gas option in nearly all regions in the world and for fossil fuel prices up to 250 USD/barrel assuming no carbon emission cost.

The hybrid PV-Wind-RPM-CCGT power plant extracting CO₂ from ambient air is an excellent centrepiece of a 100% renewable power supply, which might be established on a LCOE level of about 80 – 90 €/MWh in regions of very good solar and wind resource availability. In regions of good solar and wind resources the LCOE ranges from about 100 – 120 €/MWh and for at least one good and one moderate resource the LCOE could be about 140 – 170 €/MWh. These LCOE levels are fully fossil fuel decoupled and represent the full social cost, i.e. no further external cost create an additional financial burden. Moreover, no CCS route is needed. CO₂ extraction from air leads in most cases to lower total LCOE and in cases of lower CCS CO₂ sourcing this is only slightly lower in cost. It is not clear whether CCS technology will be really available by 2020 or even in 2030, hence waiting for this route might waste a lot of valuable time. Concluding this, hybrid PV-Wind-RPM-CCGT power plants extracting CO₂ from ambient air enable a 100% renewable power supply in many regions in the world and show favourable economic performance.

7.4.4 Global Energy Supply Potential of Hybrid Renewable Power Methane Systems

The enormous solar and wind resource potential sets the basis for analyses of their global energy supply potential. The last sections clearly emphasise that 100% renewable energy supply is technically feasible on basis of PV and wind power using renewable power methane for storage purposes, in particular for seasonal storage. Economic considerations result in total power generation cost of below 100 €/MWh in many large regions spread over the world (Fig. 7.4-21).

In reality more renewable energy sources can be used for power supply. An excellent example how such a fully renewable powered energy system could work is analysed for the DESERTEC project (Fig. 7.4-29).^{115,116,117,118} Historic roots of the DESERTEC project have been laid in the 1920s focussing hydro power^{119,120} and in the 1930s already based on first PV power concepts transmitted by power lines^{121,122} but have been changed in the 1980s to solar hydrogen^{123,124} and in the 2000s to solar thermal power generation (STEG), again transmitted by power lines^{125,126,127,128}. DESERTEC is based on all major renewable energy sources and the interconnection of centres of energy supply and centres of energy demand by high voltage direct current (HVDC) power lines. Solar PV, solar thermal and wind power are assumed to be major sources of power, whereas biomass and hydro power might act as a renewable balancing power. The EU-MENA DESERTEC project gained pace by the Desertec Industrial Initiative lead by industry giants¹²⁹ and might become a blueprint for similar interregional cooperation in other parts of the world reaching a global power grid (Fig. 7.4-29).

¹¹⁵ Knies G. (ed.), Clean Power from Deserts, 2009

¹¹⁶ Trieb F. et al., Concentrating Solar Power for the Mediterranean Region, 2005

¹¹⁷ Trieb F. et al., Trans-Mediterranean Interconnection for Concentrating Solar Power, 2006

¹¹⁸ Czisch G., Szenarien zur zukünftigen Stromversorgung - Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien, 2005

¹¹⁹ Sörgel H., Atlantropa, 1932

¹²⁰ Voigt W., Atlantropa. Weltbauen am Mittelmeer. Ein Architektentraum der Moderne, 2007

¹²¹ Schottky W., Photoelectric Generator, 1929

¹²² Dominik H., Wunschträume beim Jahreswechsel, 1930

¹²³ Winter C.J., Wasserstoff als Sekundärenergieträger, 1981

¹²⁴ Sprengel U. and Hoyer W., Solarer Wasserstoff – Energieträger der Zukunft, 1989

¹²⁵ Knies G. (ed.), Clean Power from Deserts, 2009

¹²⁶ Trieb F. et al., Concentrating Solar Power for the Mediterranean Region, 2005

¹²⁷ Trieb F. et al., Trans-Mediterranean Interconnection for Concentrating Solar Power, 2006

¹²⁸ Czisch G., Szenarien zur zukünftigen Stromversorgung - Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien, 2005

¹²⁹ Dii, Energy from deserts – Bringing the Desertec Vision into reality, 2010

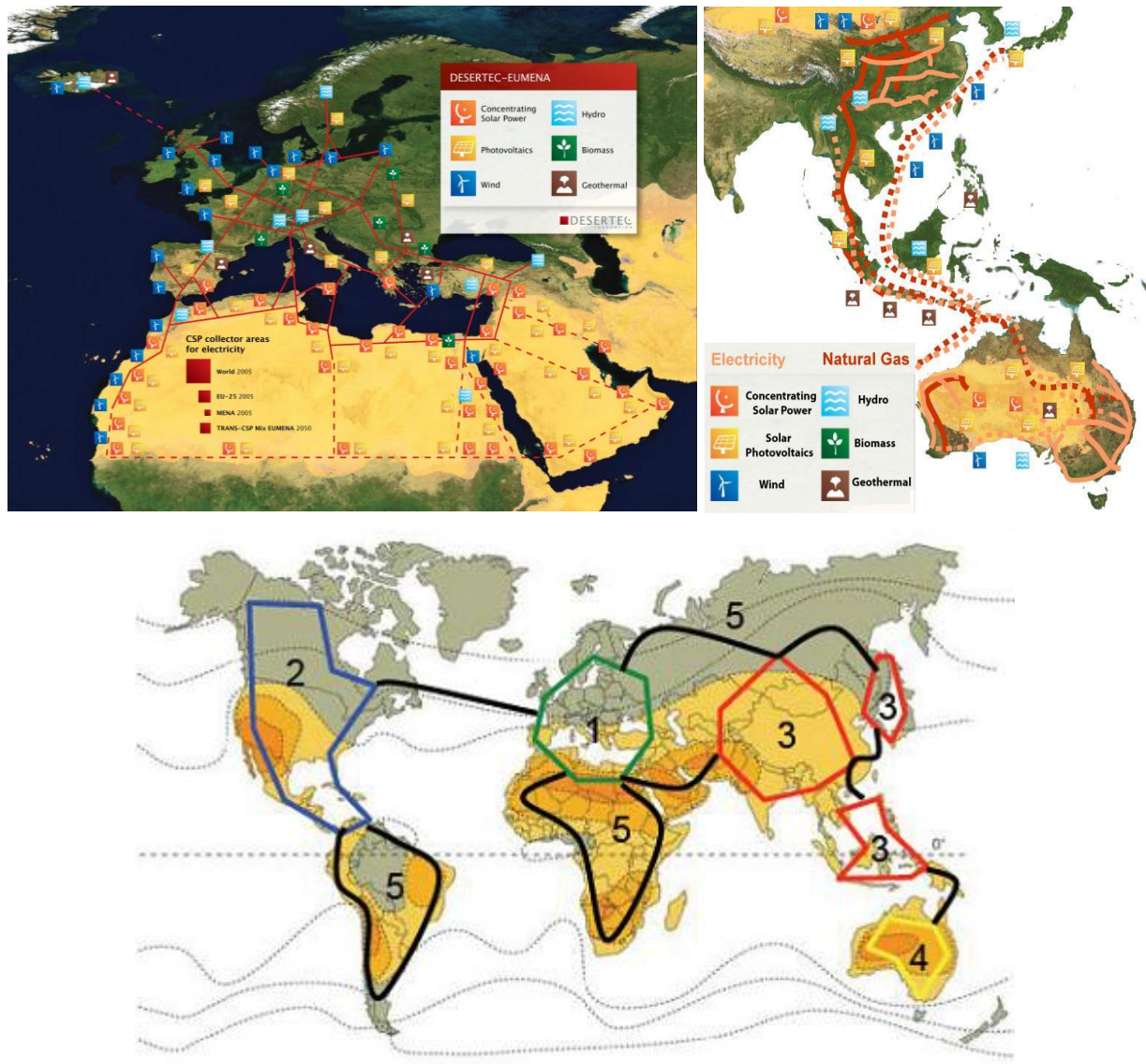


Figure 7.4-29: DESERTEC vision for the EU-MENA rim (top, left) and for Asia-Pacific (top, right) might result in a global power grid (bottom) based on renewable energies. The concept of the DESERTEC project is based on all major renewable energy sources and the interconnection of centres of energy supply and centres of energy demand by high voltage direct current (HVDC) power lines. The symbols for power sources and lines are only sketching typical locations. Regional cooperation projects, e.g. in EU-MENA (1), NAFTA (2), Asia (3) and Australia (4), might build the foundation of a global power link¹³⁰. Diagrams are taken from DESERTEC Foundation^{131,132} and EPIA¹³³.

The global energy supply potential for solar thermal power plants has already been analysed (Fig. 7.4-30).^{134,135} This analysis of global energy supply potential of solar electricity generated only in regions of excellent solar resources, i.e. at least 2,000 kWh/m²/y direct normal irradiation, clearly shows the true potential of solar power: 90% of world population could be supplied by solar power (solar PV and solar thermal) via HVDC power lines not longer than 3,000 km (Fig. 7.4-30).¹³⁶ The four major backbone technologies solar PV, solar

¹³⁰ Komoto K. et al., Energy from the Desert – Very Large Scale Photovoltaic Systems, 2009

¹³¹ Knies G. (ed.), Clean Power from Deserts, 2009

¹³² Taggart S., A Pan-Asian Energy Infrastructure, 2009

¹³³ Hoffmann W., Europe's Ambitious Goals for Making PV Solar a Mainstream Electricity Provider, 2009

¹³⁴ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

¹³⁵ Breyer Ch., Concentrating Solar Power – Global Potential and Application in the United Arab Emirates, 2007

¹³⁶ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

thermal, wind power and HVDC power lines are already available and implemented in many regions of the world.

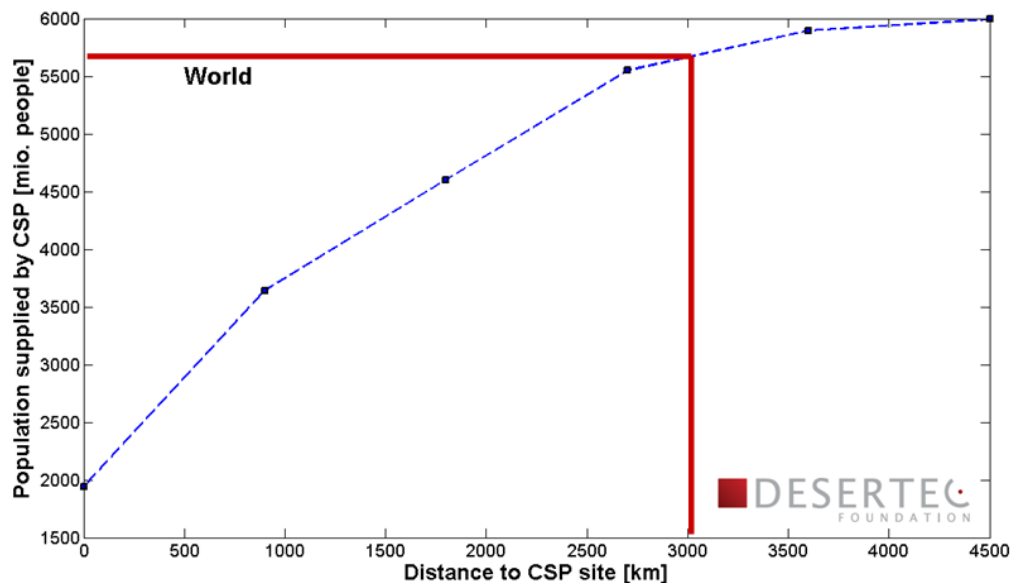


Figure 7.4-30: Population accessible by solar power in dependence on distance to sites of excellent solar conditions.¹³⁷ 90% of world population could be supplied by solar power (solar PV and solar thermal) via HVDC power lines not longer than 3,000 km. Only regions of excellent solar resource conditions have been taken into account, i.e. direct normal irradiation of at least 2,000 kWh/m²/y.

The indication is high, that based on STEGs a nearly 100% renewable power supply could be established. However, the results for STEG economics (sub-chapter 4.1) are not as favourable as the comparable ones for PV (chapter 3 and sub-chapters 4.3 and 7.2) and wind power (sub-chapters 4.2 and 4.3). Therefore it might be of very high relevance to perform a global energy supply potential for hybrid PV-Wind-RPM power plants on basis of economic competitiveness.

The last sections point out that a 100% renewable power supply is economically feasible at latest in the end of the 2010s in the regions of the world where at least good and very good solar and wind resources are available. Key question in this section is the global energy supply potential of hybrid renewable power methane systems. The three major steps for answering this are: Firstly, it needs to be identified where hybrid PV-Wind-RPM-CCGT power plants are lower in cost than natural gas and coal fired CCS power plants, which would be the major competing power plant technologies in a CO₂ constraint world. Secondly, it need to be estimated how much energy can be provided by those regions. Thirdly, it need to be evaluated how many people live in that favourable regions and more relevant depending on the distant to that regions how many further people could be supplied. The third step is quite similar to the Desertec Project being under preparation for the EU-MENA region.¹³⁸

The regions of least LCOE for 100% renewable power plants on basis of PV, wind, renewable power methane and CCGT components are shown in Figure 7.4-31 being derived on basis of cost competition against NG-CCGT-CCS and coal-CCS power plants and shown for fossil fuel prices in the range of 50 – 250 USD/barrel (Fig. 7.4-22).

¹³⁷ Breyer Ch. and Knies G., Global Energy Supply Potential of Concentrating Solar Power, 2009

¹³⁸ Knies G. (ed.), Clean Power from Deserts, 2009

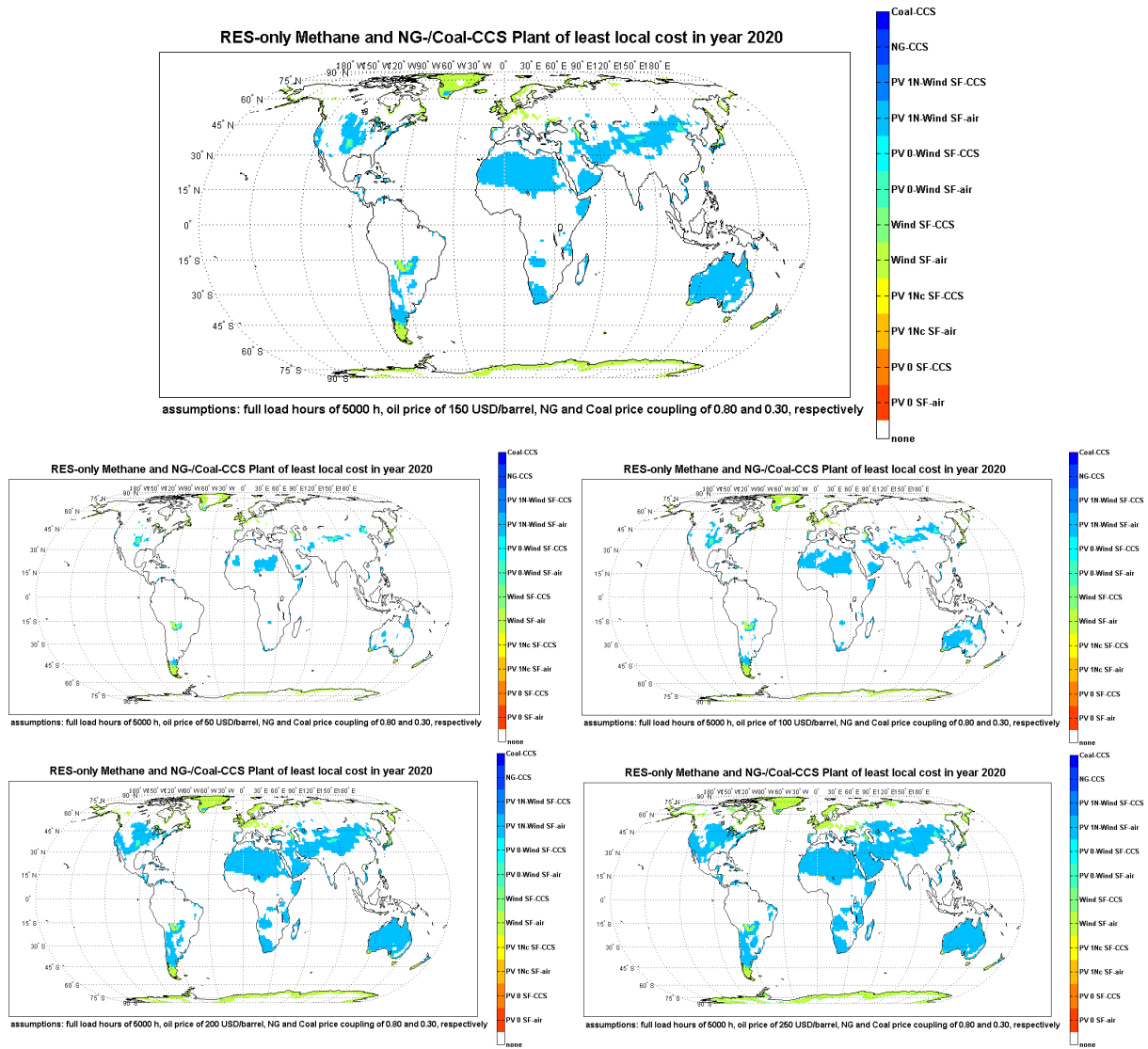


Figure 7.4-31: Hybrid RES-RPM-CCGT power plants of least local LCOE in competition to NG-CCGT-CCS and coal-CCS power plants for fossil fuel prices of 150 USD/barrel (top), 50 USD/barrel (centre, left), 100 USD/barrel (centre, right), 200 USD/barrel (bottom, left) and 250 USD/barrel (bottom, right) operated 5,000 FLh in the year 2020. The renewable sub-plant options are fixed optimally tilted PV (PV 0), 1-axis horizontal north-south continuous tracking PV (PV 1Nc), wind power at 150 m hub height (Wind), hybrid fixed tilted PV-Wind (PV 0-Wind) and hybrid 1-axis tracking PV-Wind (PV 1N-Wind) sub-plants for the two CO₂ source options of extracting CO₂ from ambient air (air) and CO₂ accessible by CCS (CCS), whereas renewable power methane is denoted as SF for solar fuel. The single PV, single wind and hybrid PV-Wind components are characterized in Figures 7.4-4 to 7.4-8. Further assumptions for cost calculation are taken from Table 7.4-1.

The regions of most competitive hybrid RES-RPM-CCGT power plants are distributed all around the world and comprise the regions of very good solar and wind resource availability.

The global energy supply potential of hybrid RES-RPM-CCGT power plants can be roughly estimated. Firstly, the maximum theoretical power generation potential of the least local LCOE areas in Figure 7.4-31 need to be estimated. The size of the areas can be derived in dependence on the crude oil price. It is known the type of least local LCOE and respective local FLh. The power generation potential of PV sub-plants is derived by assuming a reciprocal ground cover ratio of 3 (section 3.2.2.1), module efficiency of 16% and local FLh of respective least local LCOE system. The power generation potential of wind sub-plants is derived by assuming an optimal ratio of the distance of wind turbine to the rotor diameter of 5

^{139,140,141}, Enercon E-126 7.5 MW turbines and about 10% lower FLh of E-126 compared to E-82 ¹⁴² on which the FLh data are based on (section 4.2.2.2). In case of hybrid PV-Wind subplants the area is taken to 50% for PV and 50% for wind power, being the case for about 50% to 70% of all least local LCOE sites depending on the crude oil price. Secondly, the specific energy demand of the population needs to be taken into account. In 2008, the specific electricity consumption of the roughly 7 billion people in the world was 3.0 MWh_{el} per capita and for the 500 million EU citizens about 6.7 MWh_{el} per capita.^{143,144} The additional specific thermal energy demand for in particular transportation, heating and cooking was 13.8 MWh_{th} per capita (global average) and 25.3 MWh_{th} per capita (EU average).^{145,146} Thirdly, the efficiency of the full energy service of a PV and wind power based RPM energy system need to be included. For being conservative a 30% RPM-CCGT and a 70% direct PV and wind power supply is assumed. This results in total via the CO₂ from ambient air route in a factor of 1.74 for needed initial electricity for serving one electric energy unit. A thermal energy unit can be provided by two renewable electricity energy units, as a consequence of electrolysis and methanation efficiency (Table 7.4-1).

Results for the global energy supply potential of hybrid RES-RPM-CCGT power plants based on least local LCOE (Fig. 7.4-31) are summarized in Table 7.4-2 for the current situation (but for the hybrid PV-Wind-RPM-CCGT results derived for the year 2020) and also for the case some decades in the future assuming 12 billion people living on earth but all on the current energetic wealth level of the EU.

oil price	area		power generation			global energy demand		global energy demand (RPM)		required area fraction	
			theoret. potential	power	thermal	power	thermal	power	thermal	power	thermal
[USD/barrel]	[mio km ²]	[% of earth]	[TWh _{el}]	[TWh _{el}]	[TWh _{th}]	[TWh _{el}]	[TWh _{th}]	[TWh _{el}]	[TWh _{th}]	[%]	[%]
today											
50	10.0	1.97%	794,000	21,000	98,000	36,000	196,000	4.60%	24.84%		
100	22.5	4.42%	1,773,000	21,000	98,000	36,000	196,000	2.07%	11.15%		
150	37.1	7.27%	2,854,000	21,000	98,000	36,000	196,000	1.28%	6.93%		
200	56.9	11.17%	3,706,000	21,000	98,000	36,000	196,000	0.99%	5.32%		
250	59.7	11.71%	4,382,000	21,000	98,000	36,000	196,000	0.84%	4.49%		
future											
50	10.0	1.97%	794,000	84,000	300,000	146,000	601,000	18.40%	75.69%		
100	22.5	4.42%	1,773,000	84,000	300,000	146,000	601,000	8.23%	33.91%		
150	37.1	7.27%	2,854,000	84,000	300,000	146,000	601,000	5.12%	21.05%		
200	56.9	11.17%	3,706,000	84,000	300,000	146,000	601,000	3.94%	16.21%		
250	59.7	11.71%	4,382,000	84,000	300,000	146,000	601,000	3.33%	13.70%		

Table 7.4-2: Global energy supply potential of hybrid RES-RPM-CCGT power plants based on least local LCOE. Results are tabled for the current (3.0 MWh_{el}/capita and 14.0 MWh_{th}/capita and 7 billion humans) and future status (7 MWh_{el}/capita and 25 MWh_{th}/capita and 12 billion humans). The oil price dependent least local LCOE area is according to Figure 7.4-31 and put into relation to the 510 mio km² of the total earth's surface.

¹³⁹ Heier S., Windkraftanlagen – Systemauslegung, Netzintegration und Regelung, 2009, p. 393-436

¹⁴⁰ Gasch R. and Twele J., (eds.), Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb, 2010, p. 505-522

¹⁴¹ Hau E., Windkraftanlagen – Grundlagen, Technik, Einsatz, Wirtschaftlichkeit, 2008, p. 732-748

¹⁴² Enercon, Wind Turbines – Product Overview, Status 01/10, 2010

¹⁴³ IEA, World Energy Outlook 2010, 2010

¹⁴⁴ UN, World Population Prospects: The 2008 Revision Highlights, 2009

¹⁴⁵ IEA, World Energy Outlook 2010, 2010

¹⁴⁶ UN, World Population Prospects: The 2008 Revision Highlights, 2009

Core assumptions for PV sub-plants are a reciprocal GCR of 3, module efficiency of 16% and respective local FLh, whereas those for wind power sub-plants are an optimal ratio of the distance of wind turbine to the rotor diameter of 5, the characteristics of an Enercon E-126 turbine and local FLh corrected by 10% due to FLh deviations of the modelled E-82 to the E-126. The electricity fraction provided via RPM is assumed to be 30%, based on the efficiencies in Table 7.4-1.

The numbers for the thermal energy might be by a factor of four too high, according to fundamental efficiency reasons. The worst case estimate here assumes the conversion of valuable electricity to methane and then subsequent conversions for the various thermal energy services, like transportation, heating, cooking, etc. However, it would be much more efficient to use the electricity in a direct way like electric transportation, electric heating and electric cooking which would be more efficient by roughly a factor of four, or even more. Notably, good PV sites of about 2,000 FLh generate an annual electricity amount of about 107 GWh/km², whereas the good wind power sites of about 3,000 FLh generate an annual electricity of about 56 GWh/km², hence the practical specific energy generation density of PV is by a factor of two higher than that of wind power. However, the entire site need to be reserved more or less fully for a PV power plant, but the site beneath the wind turbines can be used similar to the purpose before, e.g. crop land, forests, etc.

For a crude oil price of about 150 USD/barrel, about 37 mio km² fulfil the criteria of lower hybrid PV-Wind-RPM-CCGT LCOE than comparable fossil fuel fired CCS power plants (Table 7.4-2). Only 1.3% and 6.9% of that area would be needed to cover the current power and additional thermal energy demand fully by the hybrid PV-Wind-RPM-CCGT approach. The number for the thermal energy is a worst case assumption due to previous mentioned efficiency potentials. The numbers for some decades in the future, based on a crude oil price of 200 USD/barrel would be 12 billion humans, about 57 mio km² of least local hybrid PV-Wind-RPM-CCGT LCOE, 3.9% and 16.2% of that area needed for covering the electric and thermal energy demand and similar efficiency considerations for the hybrid PV-Wind-RPM-CCGT but also for the thermal energy demand (Table 7.4-2). The area requirement might be not as high as it appears, since in the future 200 USD/barrel case only 11% of the earth's surface is classified for excellent RES-RPM economics, enormous efficiency potentials of about a factor of four in the thermal energy demand are to be realised, the energetic wealth level of the EU today might be too high for 12 billion people and all technologies for the chosen hybrid PV-Wind-RPM-CCGT approach are still significantly improvable. In total, enormous amounts of energy under least local LCOE conditions are available for powering the energy needs of the humans without relevant sustainability criteria restrictions, in particular due to the fact that several other renewable power technologies are able to complement PV and wind power, the two core power technologies in the years and decades to come.

Besides the enormous energy supply potential of the most competitive regions on LCOE basis in the world, it is of highest interest how many live in these regions and within what distance lives the other part of mankind. Depending on fossil fuel prices it is shown in Figure 7.4-32 how many people live within the least cost regions and how many further could be reached in intervals of 100 km next to these regions.

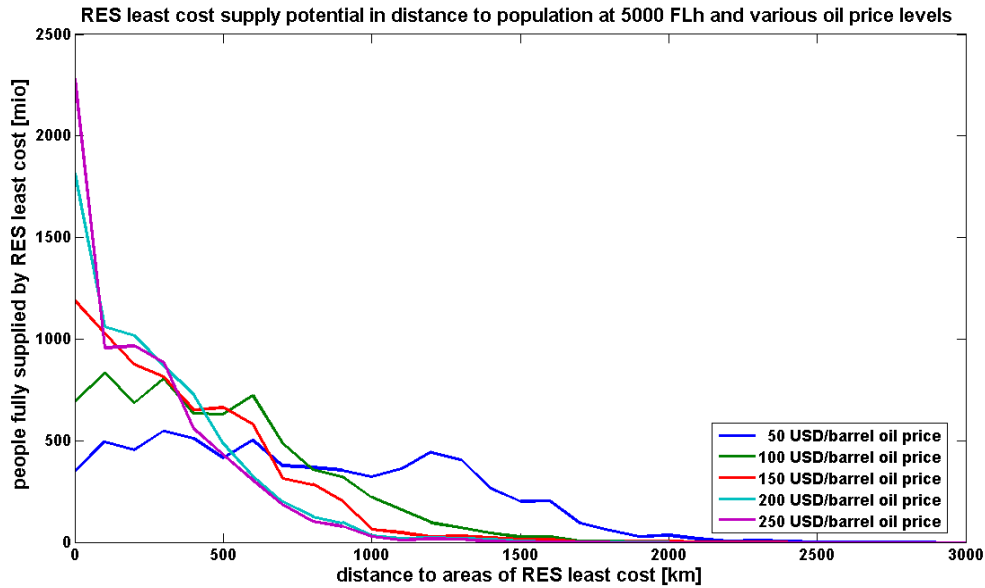


Figure 7.4-32: People living in regions of least cost 100% renewable power supply and respective distance to these regions in dependence on fossil fuel prices in the range of 50 – 250 USD/barrel in the year 2020. The evaluation is based on least cost hybrid RES-RPM-CCGT power plants (Fig. 7.4-31) and the distribution of global population density (Fig. 2.3-1).

Many people live in the regions of least cost 100% renewable power supply based on PV and wind power plants even for low fossil fuel prices. For fossil fuel prices of up to 100 USD/barrel about 500 million (50 USD/barrel) and about 800 million (100 USD/barrel) people live within 100 km next to the regions of least cost power supply. These numbers sharply rise for higher fuel prices to about 1,200 million (150 USD/barrel), 1,800 million (200 USD/barrel) and 2,200 million (250 USD/barrel).

Power lines can transmit electricity over several thousand kilometres very efficiently. Distances more than about 800 – 1,000 km are economically best interconnected by high voltage direct current (HVDC) power lines, being applied since decades for distances of 2,000 km and more. HVDC power lines show a power transmission efficiency of about 97% per 1,000 km. Below 800 – 1,000 km conventional high voltage alternating current (HVAC) power lines represent the most cost efficient power transport solution.¹⁴⁷

The aggregated population in dependence of the distance to the least cost regions is depicted in Figure 7.4-33 for various fossil fuel price levels.

¹⁴⁷ Trieb F. et al., Trans-Mediterranean Interconnection for Concentrating Solar Power, 2006

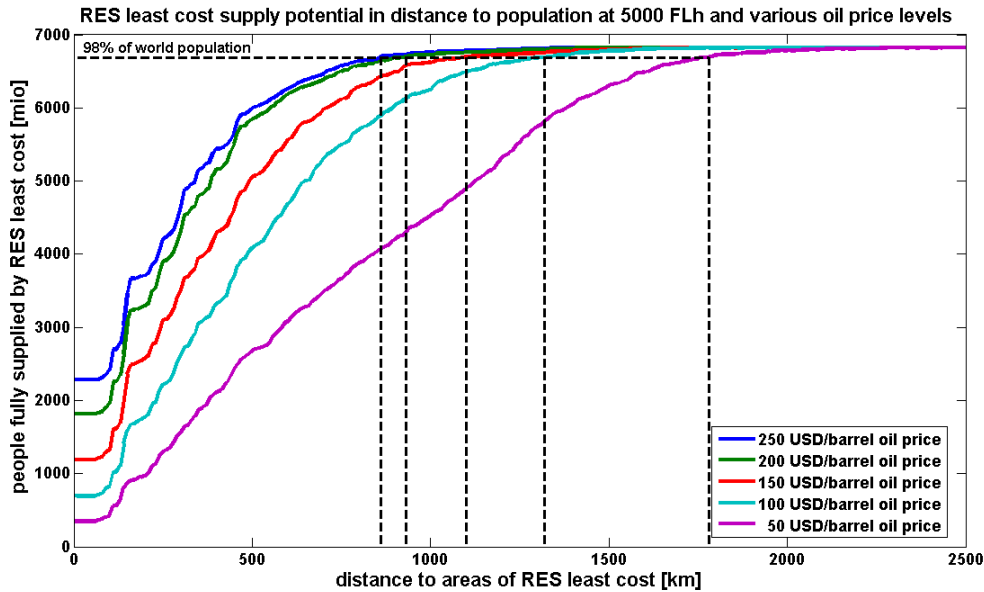


Figure 7.4-33: Aggregated people living in regions of least cost 100% renewable power supply and respective distance to these regions in dependence on fossil fuel prices in the range of 50 – 250 USD/barrel in the year 2020. The evaluation is based on least cost hybrid RES-RPM-CCGT power plants (Fig. 7.4-31) and the distribution of global population density (Fig. 2.3-1).

Within about 800 km next to the regions of least cost 100% renewable power supply most people in the world could be supplied depending on the fossil fuel prices, i.e. about 85% of world population based on the least cost situation for 100 USD/barrel, about 90% for 150 USD/barrel, about 95% for 200 USD/barrel and about 98% for 250 USD/barrel.

Comparing the results for the global energy supply potential of STEG versus hybrid PV-Wind-RPM power plants (Fig. 7.4-30 and 7.4-33) shows the beneficial consequences of good solar and wind resource potential accessible in many regions in the world. Supply potential for more than 90% of world population is lowered from 3,000 km to about 500 – 1,000 km. This reduction in distance is very important for lowering the political obstacles for the issues of transmitting large power amounts through various countries and the time consuming construction process of HVDC power lines. Moreover, the hybrid PV-Wind-RPM power plants enable the 100% renewable power supply and guarantee the least LCOE option.

Summing up, hybrid PV-Wind-RPM-CCGT power plants might represent the fundamental centrepiece of sustainable and low cost power supply in the years to come. By the year 2020 about 90% of mankind might be in reach to be supplied by 100% renewable power fully competitive to fossil fuel prices of about 150 USD/barrel and for practically not limited amounts of sustainably provided energy. The renewable power methane approach enables long-term cost stability due to a fully decoupled cost structure from fossil fuels, no net CO₂ emissions and enormous power supply potential offering long-term sustainable economic growth.

Appendix

Table 1: Global Overview on Solar Resources (Population Weighted)

Table 2: Global Overview on PV Capacities Installed and Social Progress Indicators

Table 3: Global Overview on Grid-Parity

Table 4: Global Country Codes of Top Level Web Domain

Appendix Table 1

Global Overview on Solar Resources (Population Weighted)

Country	Popula- tion	Area	fixed tilted	horiz. E-W	1-axis		optimally tilted N-S	2-axis		GHI	
					horiz. N-S	vertical		GNI	DNI	total	diffuse
Data source	1		2	3	4	5	6	7	8	9	10
	[mio people]	[1000 km ²]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]	[kWh/m ² /y]
Afghanistan	29.1	579.5	2164	2335	2693	2898	2940	3031	2326	1887	516
Albania	3.2	57.1	1923	2077	2372	2600	2639	2702	2034	1647	499
Algeria	35.4	2,383.5	1993	2143	2468	2641	2683	2757	2046	1765	549
Angola	19.0	1,316.8	2084	2212	2601	2617	2642	2747	1959	2015	678
Argentina	40.7	2,953.8	1962	2104	2411	2557	2595	2673	1940	1762	587
Armenia	3.1	19.0	1830	1964	2177	2406	2434	2503	1786	1538	544
Australia	21.5	9,113.1	1914	2050	2333	2484	2520	2594	1867	1709	586
Austria	8.4	67.2	1389	1490	1550	1748	1765	1801	1088	1169	605
Azerbaijan	8.9	114.0	1685	1806	1978	2177	2203	2260	1562	1443	566
Bahamas, The	0.3	260.6	2198	2352	2778	2869	2917	3017	2266	2037	590
Bangladesh	164.4	148.7	1908	2007	2227	2349	2375	2455	1691	1709	654
Belarus	9.6	200.8	1264	1373	1399	1612	1627	1657	980	1040	571
Belgium	10.7	31.6	1203	1299	1336	1509	1522	1545	906	1036	574
Belize	0.3	35.6	1807	1905	2207	2217	2250	2323	1507	1754	729
Benin	9.2	98.0	1895	2001	2332	2327	2347	2435	1611	1861	736
Bhutan	0.7	33.2	1943	2059	2274	2429	2454	2538	1774	1712	639
Bolivia	10.0	1,041.3	2037	2164	2527	2567	2599	2697	1918	1940	665
Bosnia- Herzegovina	3.8	72.4	1548	1663	1811	2013	2038	2082	1426	1316	538
Botswana	2.0	549.3	2302	2462	2887	2990	3031	3145	2411	2118	579
Brazil	195.4	8,927.9	1883	1995	2296	2337	2365	2449	1653	1792	696
Brunei	0.4	12.4	1915	2030	2409	2376	2399	2493	1651	1911	749
Bulgaria	7.5	110.2	1606	1722	1883	2085	2111	2159	1486	1368	549
Burkina Faso	16.3	279.2	2164	2306	2754	2759	2792	2903	2105	2105	667

¹ UN, World Population Prospects: The 2008 Revision Highlights, 2009

² Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

³ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

⁴ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

⁵ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

⁶ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

⁷ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

⁸ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

⁹ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

¹⁰ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

Burma (Myanmar)	50.5	816.2	1939	2034	2297	2386	2413	2495	1735	1774	656
Burundi	8.5	12.4	1803	1898	2207	2187	2205	2285	1449	1791	761
Cambodia	15.1	206.3	1937	2050	2384	2396	2421	2512	1693	1879	719
Cameroon	20.0	444.5	1875	1980	2304	2298	2306	2403	1589	1845	731
Canada	33.9	10,592.0	1554	1668	1776	2014	2035	2082	1347	1269	575
Cape Verde	0.5	107.6	2283	2444	2957	2968	3014	3131	2364	2208	616
Central African Republic	4.5	591.7	2031	2155	2550	2538	2550	2662	1849	2000	708
Chad	11.5	1,256.1	2222	2368	2835	2841	2874	2989	2211	2158	645
Chile	17.1	1,188.8	2124	2294	2704	2862	2913	2996	2320	1909	506
China	1,354.7	9,759.7	1631	1723	1849	2009	2026	2087	1359	1414	625
Colombia	46.3	1,210.5	1732	1825	2110	2093	2108	2185	1354	1722	766
Comoros	0.7	60.4	2287	2449	2980	2966	3007	3131	2362	2241	624
Congo, DR	67.8	2,383.1	1848	1950	2275	2258	2277	2362	1532	1830	750
Congo, R	3.8	371.6	1638	1717	1966	1946	1960	2027	1199	1634	777
Costa Rica	4.6	73.4	1735	1819	2095	2090	2112	2182	1369	1705	747
Croatia	4.4	88.5	1586	1706	1851	2081	2105	2150	1497	1322	524
Cuba	11.2	416.4	1987	2111	2456	2508	2545	2633	1834	1879	676
Cyprus	0.9	20.6	2244	2426	2866	3054	3108	3197	2530	1989	478
Czech Republic	10.4	64.6	1251	1346	1386	1565	1579	1607	946	1067	583
Denmark	5.5	87.4	1287	1422	1474	1711	1727	1752	1088	1061	554
Djibouti	0.9	12.2	2318	2482	3012	3008	3046	3172	2404	2262	620
Dominica	0.1	36.0	2386	2561	3124	3133	3182	3310	2569	2308	579
Dominican Republic	10.2	117.6	1995	2122	2478	2513	2548	2640	1833	1908	688
Ecuador	13.8	384.3	1660	1743	2010	1986	2003	2070	1244	1660	771
Egypt	84.5	1,087.9	2242	2412	2871	2993	3047	3143	2443	2054	525
El Salvador	6.2	12.1	2206	2355	2811	2825	2859	2975	2187	2134	651
Equatorial Guinea	0.7	49.6	1632	1710	1949	1934	1941	2012	1191	1624	771
Eritrea	5.2	179.5	2215	2366	2835	2852	2892	3005	2222	2137	641
Estonia	1.3	71.4	1298	1457	1525	1791	1809	1835	1154	1042	535
Ethiopia	85.0	1,115.7	2205	2348	2816	2814	2844	2960	2174	2151	656
Falkland Islands Federated States of Micronesia	0.0	60.6	1458	1588	1688	1917	1938	1968	1249	1228	596
Fiji	0.1	98.6	2016	2142	2564	2534	2566	2664	1835	2003	719
Fiji	0.9	117.8	1976	2103	2471	2488	2523	2616	1813	1911	690
Finland	5.3	406.9	1181	1347	1402	1668	1684	1708	1079	931	483
France	63.1	732.3	1441	1549	1656	1853	1874	1908	1240	1228	567
French Guiana	0.2	111.4	1785	1877	2205	2172	2196	2274	1440	1781	761
Gabon	1.5	322.4	1667	1751	2015	1991	2007	2076	1239	1666	781
Gambia, The	1.8	36.3	2129	2267	2705	2709	2745	2851	2049	2071	674
Georgia	4.2	83.5	1678	1795	1939	2164	2187	2246	1541	1396	557
Germany	82.1	398.0	1222	1320	1356	1534	1548	1573	926	1046	575
Ghana	24.3	283.1	1852	1954	2272	2264	2278	2367	1539	1826	746
Greece	11.2	325.9	1753	1885	2143	2314	2350	2406	1721	1546	548
Grenada	0.1	12.1	2317	2481	3029	3017	3062	3186	2420	2266	615
Guadeloupe	0.5	47.6	2344	2514	3052	3068	3117	3240	2489	2261	591
Guam	0.2	24.1	2212	2367	2851	2851	2889	3006	2225	2157	642
Guatemala	14.4	156.0	1997	2118	2478	2497	2527	2621	1810	1927	701
Guinea	10.3	244.1	2046	2168	2560	2562	2590	2689	1883	1994	696
Guinea - Bissau	1.6	60.8	2089	2222	2636	2641	2672	2776	1975	2033	682
Guyana	0.8	247.1	1784	1875	2193	2165	2190	2265	1425	1776	767
Haiti	10.2	70.5	2146	2294	2719	2755	2795	2901	2115	2050	646
Honduras	7.6	155.9	1932	2045	2413	2409	2446	2531	1714	1888	714
Hong Kong	7.1	23.1	1506	1584	1735	1784	1799	1857	1095	1428	710
Hungary	10.0	102.1	1445	1550	1644	1841	1861	1894	1185	1233	604

India	1,214.5	3,751.2	2032	2150	2450	2559	2591	2680	1918	1848	634
Indonesia	233.7	4,510.2	1809	1904	2219	2200	2222	2300	1470	1793	755
Iran	75.1	1,798.3	2041	2194	2516	2695	2734	2816	2099	1801	552
Iraq	31.5	470.5	2073	2232	2593	2756	2801	2882	2171	1853	544
Ireland	4.6	136.2	1055	1143	1134	1294	1303	1321	729	907	552
Israel	7.3	32.0	2247	2422	2877	3023	3077	3171	2482	2035	508
Italy	60.1	597.9	1720	1851	2039	2272	2300	2354	1680	1443	527
Ivory Coast	21.6	344.4	1818	1916	2221	2211	2224	2310	1481	1794	752
Jamaica	2.7	59.1	2132	2274	2703	2732	2774	2877	2084	2044	654
Japan	127.0	999.7	1578	1665	1771	1935	1953	2007	1298	1364	616
Jordan	6.5	85.3	2103	2264	2674	2806	2857	2939	2234	1916	539
Kazakhstan	15.8	2,851.7	1709	1843	2006	2272	2297	2350	1591	1393	567
Kenya	40.9	619.6	2124	2268	2760	2713	2748	2859	2040	2123	695
Kiribati	0.1	62.0	2178	2333	2855	2807	2842	2961	2159	2178	670
Korea, DPR	24.0	220.5	1874	1969	2063	2360	2377	2449	1719	1465	555
Korea, R	48.5	212.3	1770	1865	1971	2199	2217	2283	1562	1464	592
Kuwait	3.1	10.8	2134	2290	2719	2823	2876	2963	2248	1972	554
Kyrgyzstan	5.6	205.3	1840	1975	2200	2442	2471	2539	1831	1532	523
Laos	6.4	200.1	1829	1919	2168	2226	2252	2327	1535	1712	701
Latvia	2.2	89.1	1307	1448	1505	1753	1771	1798	1117	1062	551
Lebanon	4.3	31.2	2159	2327	2754	2909	2961	3045	2362	1945	508
Liberia	4.1	172.7	1781	1872	2162	2151	2167	2246	1416	1758	759
Libya	6.5	1,734.2	2110	2269	2686	2809	2860	2944	2238	1932	542
Lithuania	3.3	71.5	1277	1399	1436	1664	1680	1707	1035	1048	561
Macedonia	2.0	28.1	1718	1848	2048	2257	2286	2341	1659	1470	543
Madagascar	20.1	874.2	2091	2222	2604	2655	2692	2790	2013	1976	650
Malawi	15.7	60.3	2088	2213	2620	2633	2668	2767	1973	2016	675
Malaysia	27.9	668.0	1766	1859	2171	2142	2164	2240	1401	1763	769
Mali	13.3	1,292.6	2185	2330	2791	2798	2836	2946	2157	2121	655
Malta	0.4	10.2	2188	2364	2780	2973	3024	3108	2435	1933	486
Mauritania	3.4	1,070.7	2202	2355	2841	2850	2898	3006	2230	2133	632
Mauritius	1.3	23.2	2244	2404	2879	2920	2967	3079	2321	2136	606
Mexico	110.6	2,603.0	2136	2275	2663	2735	2774	2873	2105	1997	630
Moldova	3.6	34.5	1492	1603	1716	1919	1941	1979	1276	1268	586
Mongolia	2.7	1,587.6	1910	2032	2149	2491	2511	2576	1691	1472	622
Morocco	32.4	463.4	2153	2316	2682	2863	2907	2995	2283	1904	536
Mozambique	23.4	952.5	2026	2150	2512	2552	2587	2680	1884	1927	676
Namibia	2.2	925.5	2352	2520	2992	3067	3108	3231	2505	2201	571
Nepal	29.9	142.4	2176	2310	2602	2786	2819	2915	2188	1896	577
Netherlands	17.0	53.1	1242	1352	1409	1596	1612	1635	985	1063	569
New Caledonia	0.3	149.9	2129	2276	2717	2749	2797	2897	2124	2038	632
New Zealand	4.3	598.2	1644	1756	1914	2094	2119	2173	1468	1424	590
Nicaragua	5.8	205.9	2016	2137	2523	2526	2558	2653	1844	1962	699
Niger	15.9	1,220.5	2382	2556	3111	3118	3162	3292	2550	2309	585
Nigeria	158.3	979.3	1978	2095	2462	2462	2483	2580	1775	1935	705
Norway	4.9	624.8	1103	1247	1284	1514	1528	1549	954	891	482
Oman	2.9	408.0	2239	2397	2837	2915	2960	3068	2313	2090	597
Pakistan	184.8	982.6	2135	2284	2609	2785	2822	2914	2174	1883	573
Palestine	4.4	10.6	2056	2213	2604	2724	2772	2854	2133	1884	562
Panama	3.5	221.0	1728	1809	2083	2074	2097	2165	1349	1701	751
Papua New Guinea	6.9	1,279.2	1825	1928	2260	2234	2258	2340	1502	1817	758
Paraguay	6.5	409.5	1898	2023	2339	2403	2440	2520	1740	1786	663
Peru	29.5	1,608.1	2006	2133	2531	2522	2551	2650	1844	1971	699
Philippines	93.6	1,021.2	1842	1943	2271	2265	2295	2374	1559	1806	729
Poland	38.0	329.3	1235	1338	1366	1558	1572	1598	942	1041	575

Portugal	10.7	144.8	1891	2037	2309	2532	2568	2631	1950	1620	517
Puerto Rico	4.0	82.8	2142	2286	2715	2746	2787	2892	2101	2051	651
Qatar	1.5	22.5	2065	2211	2616	2680	2728	2818	2062	1947	613
Palau	0.0	36.9	2020	2142	2562	2535	2569	2665	1840	2000	715
Romania	21.2	235.1	1500	1609	1712	1924	1944	1987	1301	1256	566
Russia	140.4	19,145.0	1403	1529	1593	1846	1864	1901	1184	1125	562
Rwanda	10.3	24.8	1831	1935	2265	2238	2258	2342	1498	1827	763
Saudi Arabia	26.2	2,145.8	2296	2465	2953	3022	3073	3184	2451	2158	568
Senegal	12.9	216.5	2126	2266	2713	2714	2754	2858	2059	2071	669
Serbia	10.5	135.6	1573	1689	1837	2042	2067	2114	1447	1334	544
Seychelles	0.1	12.4	2168	2313	2822	2777	2815	2928	2120	2161	679
Sierra Leone	5.8	122.9	1861	1959	2278	2273	2295	2377	1557	1825	737
Slovakia	5.4	65.7	1286	1381	1420	1604	1619	1649	975	1092	590
Slovenia	2.0	17.2	1483	1586	1662	1872	1890	1930	1200	1244	610
Solomon Island	0.5	220.3	1953	2074	2467	2442	2473	2566	1740	1937	725
Somalia	9.4	874.5	2100	2234	2697	2661	2691	2801	1983	2088	699
South Africa	50.5	1,483.2	2166	2315	2644	2804	2840	2939	2207	1925	579
Spain	45.3	814.4	1886	2029	2287	2506	2541	2606	1919	1616	527
Sri Lanka	20.4	135.4	1813	1907	2238	2211	2240	2315	1482	1802	755
Sudan	43.2	2,558.1	2271	2427	2923	2932	2971	3090	2320	2200	627
Suriname	0.5	198.0	1872	1976	2338	2305	2329	2418	1577	1866	754
Swaziland	1.2	11.1	1982	2104	2351	2491	2519	2607	1844	1767	637
Sweden	9.3	608.5	1218	1363	1408	1657	1673	1696	1059	981	515
Switzerland	7.6	59.8	1467	1576	1671	1872	1892	1930	1206	1245	606
Syria	22.5	204.5	2026	2185	2554	2715	2762	2837	2141	1815	531
Taiwan	n/a	136.9	1632	1725	1951	1990	2017	2079	1309	1560	697
Tajikistan	7.1	175.6	1996	2152	2469	2688	2728	2801	2115	1718	506
Tanzania	45.0	1,057.7	2043	2171	2600	2571	2600	2702	1887	2027	706
Thailand	68.1	709.8	1903	2005	2306	2339	2365	2449	1644	1816	708
Togo	6.8	86.1	1931	2041	2388	2383	2404	2495	1670	1896	731
Trinidad and Tobago	1.3	36.6	2136	2274	2742	2722	2761	2868	2058	2102	682
Tunisia	10.4	266.6	1916	2063	2382	2535	2576	2646	1937	1719	558
Turkey	75.7	1,104.2	1839	1980	2257	2446	2483	2545	1858	1606	534
Turkmenistan	5.2	503.9	1894	2036	2297	2505	2540	2607	1904	1634	545
Uganda	33.8	248.0	1980	2105	2512	2477	2501	2601	1764	1977	734
Ukraine	45.4	727.9	1398	1506	1583	1784	1802	1837	1130	1181	595
United Arab Emirates	4.7	124.7	2261	2426	2883	2970	3020	3127	2390	2103	572
United Kingdom	62.3	531.4	1128	1225	1238	1411	1422	1442	827	966	560
United States	317.8	11,063.0	1796	1921	2137	2324	2353	2418	1702	1556	575
Uruguay	3.4	227.6	1853	1988	2256	2399	2434	2505	1769	1664	600
Uzbekistan	27.8	467.9	1976	2129	2413	2657	2694	2764	2076	1672	506
Venezuela	29.0	1,155.3	1934	2048	2412	2399	2427	2517	1687	1905	733
Vietnam	89.0	597.0	1665	1750	1993	2005	2027	2093	1298	1620	731
Yemen	24.3	611.5	2295	2456	2952	2973	3011	3133	2367	2211	618
Zambia	13.3	805.8	2201	2334	2765	2794	2828	2937	2172	2104	638
Zimbabwe	12.6	397.5	2221	2364	2784	2847	2887	2995	2234	2084	619
EU	420.4	6,122.3	1391	1502	1591	1789	1808	1842	1182	1181	561
Europe	736.5	28,835.0	1448	1565	1671	1878	1899	1938	1260	1221	560
MENA	435.5	12,995.0	2086	2243	2618	2765	2810	2895	2184	1880	546
Europe-MENA	1,171.9	40,727.0	1685	1817	2023	2208	2238	2293	1603	1466	555
Africa	976.1	32,492.0	2067	2201	2599	2629	2660	2759	1975	1985	661
Asia	3,909.0	58,038.0	1834	1943	2170	2300	2325	2400	1651	1643	631
Pacific Rim	2,004.3	31,718.0	1678	1771	1939	2063	2082	2147	1398	1501	650
North America	303.0	21,655.0	1776	1900	2108	2298	2327	2391	1673	1533	575

Latin America	170.2	4,638.3	2087	2221	2603	2656	2693	2790	2008	1973	652
South America	368.8	19,724.0	1890	2006	2321	2363	2391	2475	1683	1802	688
Americas	841.9	46,017.0	1889	2011	2301	2399	2429	2508	1745	1740	640
World	6,898.1	161,930.0	1846	1961	2217	2331	2358	2434	1685	1677	630

Appendix Table 1: Dataset of population weighted mean irradiation values of various solar resources for all countries, continents and major regions in the world.¹¹ Solar resources are for fixed optimally tilted, 1-axis horizontal east-west continuous tracking, 1-axis horizontal north-south continuous tracking, 1-axis vertical optimally tilted continuous tracking, 1-axis optimally tilted north-south continuous tracking, 2-axes non-concentrating continuous tracking (GNI) and 2-axes concentrating continuous tracking (DNI). Core data for calculations are total global horizontal irradiation (GHI) and diffuse part of GHI, provided by NASA SSE 6.0.^{12,13} The methodology of solar resource derivation is presented and discussed in chapter 2. Data are complemented by population and area data for further analyses. Solar resource data are also tabled for area weighted, maximum and minimum resource per geographic entity in the referenced publication.

Appendix Table 2

Global Overview on PV Capacities Installed and Social Progress Indicators

Country	final electricity consumption													
	Populat ion	GDP	PV cumulat ive end of 2010	GDP/ capita	electrifi cation rate	per				adult illiterac y rate	diesel prices	corru ption index	improv ed water source	undern ourishe d
						total	per capita	per electrifi ed capita	fertility					
Data source	14	15	16	17,18	19,20	21	22	23,24,25,26	27	28	29	30	31	32
	[mio. pop]	[bnUSD]	[MWp]	[USD/ capita]	[% of pop]	[GWh]	[kWh/ capita]	[kWh/ capita]	[child/ woman]	[% aged 15 and older]	[USDct/ l]	[0..... 10]	[% of pop]	[% of pop]
Afghanistan	29.1	10.2	1.30	349	2.0%	n/a	n/a	n/a	6.63	n/a	96	1.5	n/a	n/a
Albania	3.2	12.3	0.03	3880	99.5%	2744	866	870	1.87	n/a	131	3.4	96.0%	6.0%
Algeria	35.4	173.9	7.10	4909	98.5%	26456	747	758	2.38	30.1%	20	3.2	85.0%	4.0%

¹¹ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

¹² Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy (SSE) release 6.0, 2008

¹³ Stackhouse P.W. and Whitlock C.H., Surface meteorology and Solar Energy release 6.0 Methodology, 2009

¹⁴ UN, World Population Prospects: The 2008 Revision Highlights, 2009

¹⁵ World Bank, Gross domestic product 2008, 2009

¹⁶ Werner C. et al., Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, 2011

¹⁷ World Bank, Gross domestic product 2008, 2009

¹⁸ UN, World Population Prospects: The 2008 Revision Highlights, 2009

¹⁹ UNDP, Human Development Report 2007/2008, 2007

²⁰ IEA, World Energy Outlook 2006, 2006

²¹ IEA, Key World Energy Statistics 2009, 2009

²² IEA, Key World Energy Statistics 2009, 2009

²³ IEA, Key World Energy Statistics 2009, 2009

²⁴ UNDP, Human Development Report 2007/2008, 2007

²⁵ IEA, World Energy Outlook 2006, 2006

²⁶ UN, World Population Prospects: The 2008 Revision Highlights, 2009

²⁷ UN, World Population Prospects: The 2006 Revision Highlights, 2007

²⁸ UNDP, Human Development Report 2007/2008, 2008

²⁹ Ebert S. et al., International Fuel Prices 2009 6th Edition, 2009

³⁰ TI, Global Corruption Report 2009: Corruption and the Private Sector, 2009

³¹ WHO, Progress on Sanitation and Drinking-water: 2010 Update, 2010

³² WHO, Progress on Sanitation and Drinking-water: 2010 Update, 2010

Andorra	0.1	n/a	0.05	n/a	99.0%	n/a	n/a	n/a	n/a	n/a	106	n/a	n/a	n/a
Angola	19.0	83.4	2.90	4390	10.0%	2372	125	1249	5.79	32.6%	39	1.9	53.0%	35.0%
Antigua and Barbuda	0.1	1.2	0.09	13834	87.0%	n/a	n/a	n/a	n/a	14.2%	134	n/a	91.0%	n/a
Argentina	40.7	328.4	11.70	8075	95.0%	98681	2427	2554	2.25	2.8%	58	2.9	96.0%	3.0%
Armenia	3.1	11.9	0.07	3856	99.5%	4528	1465	1473	1.74	n/a	111	2.9	92.0%	24.0%
Australia	21.5	1015.2	532.00	47193	100.0%	209634	9745	9745	1.83	1.5%	94	8.7	100.0%	2.5%
Austria	8.4	416.4	101.00	49643	100.0%	58655	6993	6993	1.38	1.5%	143	8.1	100.0%	2.5%
Azerbaijan	8.9	46.3	0.18	5178	99.5%	19952	2233	2245	2.16	1.5%	56	1.9	77.0%	7.0%
Bahamas	0.3	6.9	0.21	20059	87.0%	n/a	n/a	n/a	2.02	1.5%	n/a	n/a	97.0%	8.0%
Bahrain	0.8	15.8	0.05	19610	99.5%	9102	11277	11339	2.29	13.5%	13	5.4	n/a	n/a
Bangladesh	164.4	79.0	34.70	480	29.2%	21501	131	449	2.36	52.5%	70	2.1	74.0%	30.0%
Barbados	0.3	3.4	0.14	13288	87.0%	n/a	n/a	n/a	1.53	0.3%	103	7	100.0%	2.5%
Belarus	9.6	60.3	2.10	6289	99.5%	28460	2968	2983	1.28	n/a	106	2	100.0%	4.0%
Belgium	10.7	497.6	796.00	46514	100.0%	82606	7722	7722	1.77	1.5%	134	7.3	n/a	2.5%
Belize	0.3	1.4	0.03	4368	87.0%	n/a	n/a	n/a	2.94	24.9%	53	2.9	91.0%	4.0%
Benin	9.2	6.7	0.55	725	23.4%	602	65	279	5.48	65.3%	103	3.1	67.0%	12.0%
Bermuda	0.1	5.9	0.22	90084	87.0%	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0%	0.0%
Bhutan	0.7	1.4	0.02	1918	80.0%	n/a	n/a	n/a	2.68	53.0%	87	5.2	62.0%	n/a
Bolivia	10.0	16.7	3.10	1662	64.6%	4488	447	693	3.50	13.3%	53	3	85.0%	23.0%
Bosnia-Herzegovina	3.8	18.5	0.13	4908	99.5%	7787	2071	2082	1.21	n/a	118	3.2	97.0%	9.0%
Botswana	2.0	13.0	2.70	6558	32.7%	2544	1286	3934	2.90	18.8%	102	5.8	95.0%	32.0%
Brazil	195.4	1612.5	26.60	8252	95.8%	375379	1921	2005	1.90	11.4%	103	3.5	90.0%	7.0%
Brunei	0.4	11.5	0.01	28181	99.1%	3000	7370	7437	2.11	n/a	21	n/a	n/a	4.0%
Bulgaria	7.5	49.9	17.40	6656	99.5%	26888	3586	3604	1.40	n/a	137	3.6	99.0%	8.0%
Burkina Faso	16.3	7.9	1.80	488	8.5%	n/a	n/a	n/a	5.94	n/a	133	3.5	61.0%	15.0%
Burma	50.5	n/a.0	0.71	n/a	8.0%	4410	87	1092	2.32	10.1%	52	1.3	78.0%	5.0%
Burundi	8.5	1.2	0.19	137	23.5%	n/a	n/a	n/a	4.66	40.7%	123	1.9	79.0%	66.0%
Cambodia	15.1	9.6	2.10	636	19.2%	1194	79	414	2.96	26.4%	89	1.8	41.0%	33.0%
Cameroon	20.0	23.4	0.98	1172	43.9%	3374	169	386	4.67	32.1%	104	2.3	66.0%	26.0%
Canada	33.9	1400.1	240.00	41313	100.0%	498977	14724	14724	1.57	1.5%	90	8.7	100.0%	2.5%
Cape Verde	0.5	1.7	7.90	3375	23.5%	n/a	n/a	n/a	2.76	18.8%	143	5.1	80.0%	n/a
Central African Republic	4.5	2.0	0.15	437	23.5%	n/a	n/a	n/a	4.85	51.4%	144	2	75.0%	44.0%
Chad	11.5	8.4	0.54	727	23.5%	n/a	n/a	n/a	6.20	74.3%	132	1.6	42.0%	35.0%
Chile	17.1	169.5	3.70	9890	98.0%	50646	2956	3016	1.94	4.3%	95	6.9	95.0%	4.0%
China	1354.7	4344.8	861.00	3207	99.0%	2316812	1710	1727	1.77	9.1%	101	3.6	77.0%	12.0%
Colombia	46.3	242.3	6.90	5233	88.1%	40625	877	996	2.45	7.2%	73	3.8	93.0%	13.0%
Comoros	0.7	0.5	0.16	767	23.5%	n/a	n/a	n/a	4.00	43.2%	n/a	2.5	86.0%	60.0%
Congo, DR	67.8	11.6	0.99	171	7.2%	3030	45	625	6.07	32.8%	121	1.7	46.0%	74.0%
Congo, Republic	3.8	10.7	1.70	2846	19.8%	381	101	512	4.41	15.3%	57	1.9	58.0%	33.0%
Costa Rica	4.6	29.8	1.00	6430	98.0%	7812	1684	1718	1.96	5.1%	110	5.1	97.0%	5.0%
Croatia	4.4	69.3	11.30	15723	99.5%	15046	3412	3429	1.42	n/a	137	4.4	100.0%	7.0%
Cuba	11.2	n/a	2.10	n/a	95.9%	12985	1159	1208	1.50	n/a	151	4.3	91.0%	2.5%
Cyprus	0.9	21.3	6.20	24186	100.0%	4168	4738	4738	1.52	3.2%	125	6.4	100.0%	2.5%
Czech Republic	10.4	216.5	1950.00	20794	99.5%	57016	5477	5504	1.41	1.5%	145	5.2	100.0%	2.5%
Denmark	5.5	342.7	6.00	61955	100.0%	34076	6161	6161	1.84	1.5%	154	9.3	100.0%	2.5%
Djibouti	0.9	0.9	1.40	995	23.5%	n/a	n/a	n/a	3.95	29.7%	124	3	73.0%	24.0%

Dominica	0.1	0.4	0.04	5472	87.0%	n/a	n/a	n/a	n/a	12.0%	n/a	6	97.0%	8.0%
Dominican Republic	10.2	45.8	1.90	4478	92.7%	12173	1190	1285	2.67	13.0%	94	3	95.0%	29.0%
Ecuador	13.8	52.6	1.20	3817	89.9%	9561	694	772	2.58	9.0%	27	2	94.0%	6.0%
Egypt	84.5	162.8	5.50	1927	97.9%	98443	1165	1191	2.89	28.6%	20	2.8	98.0%	4.0%
El Salvador	6.2	22.1	0.32	3570	78.5%	4663	753	960	2.35	19.4%	81	3.9	84.0%	11.0%
Equatorial Guinea	0.7	18.5	0.54	26717	23.5%	n/a	n/a	n/a	5.36	13.0%	n/a	1.7	43.0%	n/a
Eritrea	5.2	1.7	0.41	317	19.2%	220	42	219	4.68	39.5%	107	2.6	60.0%	75.0%
Estonia	1.3	23.1	3.00	17238	99.5%	6473	4833	4857	1.64	n/a	130	6.6	100.0%	2.5%
Ethiopia	85.0	26.5	6.90	312	8.8%	2567	30	343	5.38	64.1%	89	2.6	22.0%	46.0%
Micronesia	0.1	n/a	0.15	n/a	80.0%	n/a	n/a	n/a	3.62	n/a	n/a	n/a	n/a	n/a
Fiji	0.9	3.5	0.47	4130	80.0%	n/a	n/a	n/a	2.75	5.6%	104	n/a	47.0%	5.0%
Finland	5.3	271.3	26.10	50747	100.0%	85772	16045	16045	1.83	1.5%	139	9	100.0%	2.5%
France	63.1	2853.1	1050.00	45205	100.0%	429913	6812	6812	1.89	1.5%	145	6.9	100.0%	2.5%
Gabon	1.5	14.4	0.17	9615	48.0%	1294	862	1798	3.35	16.0%	90	3.1	88.0%	5.0%
Gambia	1.8	0.8	0.69	447	23.5%	n/a	n/a	n/a	5.10	57.5%	75	1.9	82.0%	29.0%
Georgia	4.2	12.8	0.36	3032	99.5%	5669	1344	1350	1.58	n/a	116	3.9	82.0%	9.0%
Germany	82.1	3652.8	17210.0	44516	100.0%	525804	6408	6408	1.32	1.5%	156	7.9	100.0%	2.5%
Ghana	24.3	16.1	0.84	663	48.8%	6519	268	550	4.31	42.1%	90	3.9	75.0%	11.0%
Greece	11.2	356.8	206.00	31904	99.8%	52523	4697	4708	1.38	1.5%	141	4.7	n/a	2.5%
Grenada	0.1	0.6	0.10	6115	99.5%	n/a	n/a	n/a	2.30	4.0%	134	n/a	95.0%	7.0%
Guatemala	14.4	39.0	1.80	2711	81.7%	6847	476	583	4.15	30.9%	82	3.1	95.0%	22.0%
Guinea	10.3	4.3	1.20	413	80.0%	n/a	n/a	n/a	5.45	70.5%	102	1.6	50.0%	24.0%
Guinea - Bissau	1.6	0.4	0.47	261	23.5%	n/a	n/a	n/a	5.73	55.2%	n/a	1.9	59.0%	39.0%
Guyana	0.8	1.2	1.50	1521	87.0%	n/a	n/a	n/a	2.33	1.0%	85	2.6	83.0%	8.0%
Haiti	10.2	7.0	0.86	682	34.8%	339	33	96	3.55	45.2%	89	1.4	54.0%	46.0%
Honduras	7.6	14.1	1.10	1848	61.1%	4431	582	953	3.31	20.0%	80	2.6	87.0%	23.0%
Hong Kong	7.1	215.4	0.14	30463	100.0%	40338	5706	5706	1.02	1.5%	116	8.1	n/a	n/a
Hungary	10.0	154.7	1.80	15508	99.5%	33238	3333	3349	1.35	n/a	138	5.1	99.0%	2.5%
Iceland	0.3	16.7	0.33	50589	100.0%	9038	27448	27448	2.10	1.5%	131	8.9	100.0%	2.5%
India	1214.5	1217.5	177.00	1002	50.2%	505577	416	829	2.76	39.0%	70	3.4	86.0%	20.0%
Indonesia	233.7	514.9	9.20	2203	53.3%	112609	482	905	2.19	9.6%	42	2.6	77.0%	6.0%
Iran	75.1	385.1	4.30	5130	98.1%	150753	2008	2047	1.83	17.6%	3	2.3	94.0%	4.0%
Iraq	31.5	n/a	2.20	n/a	95.4%	31105	989	1036	4.11	n/a	n/a	1.3	n/a	n/a
Ireland	4.6	281.8	5.00	61402	100.0%	25879	5639	5639	1.96	1.5%	164	7.7	n/a	2.5%
Israel	7.3	199.5	40.20	27385	98.5%	45625	6263	6358	2.81	1.5%	170	6	100.0%	2.5%
Italy	60.1	2294.7	3490.00	38163	100.0%	308777	5135	5135	1.38	1.5%	163	4.8	n/a	2.5%
Ivory Coast	21.6	23.4	0.93	1085	50.4%	3307	153	304	4.65	51.3%	120	2	84.0%	13.0%
Jamaica	2.7	15.1	0.43	5520	87.0%	6519	2388	2745	2.40	20.1%	84	3.1	93.0%	9.0%
Japan	127.0	4909.3	3610.00	38657	100.0%	980872	7724	7724	1.27	1.5%	130	7.3	100.0%	2.5%
Jordan	6.5	20.0	0.79	3092	97.8%	9489	1466	1500	3.13	8.9%	61	5.1	97.0%	6.0%
Kazakhstan	15.8	132.2	0.29	8394	99.5%	49053	3114	3129	2.31	n/a	72	2.2	86.0%	6.0%
Kenya	40.9	34.5	8.70	844	11.6%	5296	130	1122	4.96	26.4%	114	2.1	61.0%	31.0%
Kiribati	0.1	0.1	0.15	1316	80.0%	n/a	n/a	n/a	n/a	n/a	n/a	3.1	n/a	n/a
Korea, DPR	24.0	n/a	2.20	n/a	20.0%	16762	699	3493	1.86	n/a	95	n/a	n/a	n/a
Korea, Republic	48.5	929.1	655.00	19157	100.0%	371354	7657	7657	1.22	1.0%	140	5.6	92.0%	2.5%
Kuwait	3.1	112.1	1.80	36750	100.0%	30131	9877	9877	2.18	6.7%	20	4.3	n/a	5.0%
Kyrgyzstan	5.6	4.4	0.02	796	99.5%	10345	1864	1873	2.56	n/a	88	1.8	77.0%	4.0%

Laos	6.4	5.4	0.68	844	80.0%	n/a	n/a	n/a	3.54	31.3%	76	2	51.0%	19.0%
Latvia	2.2	33.8	0.11	15080	99.5%	6128	2735	2749	1.40	n/a	123	5	99.0%	3.0%
Lebanon	4.3	28.7	0.71	6736	98.0%	8684	2041	2083	1.86	11.7%	76	3	100.0%	3.0%
Lesotho	2.1	1.6	0.01	778	8.0%	n/a	n/a	n/a	3.37	17.8%	93	3.2	79.0%	13.0%
Liberia	4.1	0.9	0.36	212	23.5%	n/a	n/a	n/a	5.14	n/a	103	2.4	n/a	n/a
Libya	6.5	99.9	2.20	15266	98.4%	21573	3296	3349	2.72	n/a	12	2.6	n/a	2.5%
Lithuania	3.3	47.3	0.62	14543 11033	99.5%	8432	2590	2603	1.34	n/a	122	4.6	n/a	2.5%
Luxembourg	0.5	54.3	30.10	0	100.0%	6508	13234	13234	1.66	1.5%	133	8.3	100.0%	2.5%
Macedonia	2.0	9.5	0.38	4659	99.5%	6439	3151	3167	1.44	n/a	112	3.6	n/a	5.0%
Madagascar	20.1	9.0	1.50	445	11.7%	n/a	n/a	n/a	4.78	29.3%	143	3.4	50.0%	38.0%
Malawi	15.7	4.3	0.37	272	6.4%	n/a	n/a	n/a	5.59	35.9%	167	2.8	73.0%	35.0%
Malaysia	27.9	194.9	11.30	6983	97.6%	86772	3109	3187	2.58	11.3%	53	5.1	99.0%	3.0%
Maldives	0.3	1.3	0.23	4014	80.0%	n/a	n/a	n/a	2.06	3.7%	n/a	2.8	50.0%	29.0%
Mali	13.3	8.7	3.00	656	23.5%	n/a	n/a	n/a	5.49	76.0%	110	3.1	83.0%	10.0%
Malta	0.4	7.4	1.10	18168	100.0%	1853	4520	4520	1.26	1.5%	156	5.8	100.0%	2.5%
Mauritania	3.4	2.9	0.91	849	23.5%	n/a	n/a	n/a	4.52	48.8%	106	2.8	53.0%	10.0%
Mauritius	1.3	8.7	1.30	6672	97.0%	n/a	n/a	n/a	1.78	15.7%	n/a	5.5	100.0%	5.0%
Mexico	110.6	1086.0	30.30	9815	87.0%	190837	1725	1982	2.21	8.4%	54	3.6	97.0%	5.0%
Moldova	3.6	6.0	0.16	1691	99.5%	5145	1439	1446	1.50	n/a	104	2.9	92.0%	11.0%
Mongolia	2.7	5.3	3.10	1947	77.5%	2724	1008	1301	2.02	2.2%	142	3	62.0%	27.0%
Morocco	32.4	86.3	16.80	2666	81.2%	19260	595	732	2.38	47.7%	83	3.5	81.0%	6.0%
Mozambique	23.4	9.7	1.20	416	7.4%	9418	402	5475	5.11	61.3%	137	2.6	43.0%	44.0%
Namibia	2.2	8.6	2.30	3872	34.4%	3163	1430	4163	3.40	15.0%	88	4.5	87.0%	24.0%
Nepal	29.9	12.6	3.20	423	29.5%	2051	69	233	2.94	51.4%	82	2.7	90.0%	17.0%
Netherlands	17.0	860.3	86.10	50724	100.0%	106942	6305	6305	1.74	1.5%	145	8.9	100.0%	2.5%
New Caledonia	0.3	n/a	2.80	n/a	80.0%	n/a	n/a	n/a	2.10	n/a	n/a	n/a	n/a	n/a
New Zealand	4.3	130.7	5.50	30369	100.0%	38433	8931	8931	2.02	1.5%	85	9.3	n/a	2.5%
Nicaragua	5.8	6.6	2.20	1132	57.8%	2077	357	617	2.76	23.3%	82	2.5	79.0%	27.0%
Niger	15.9	5.4	0.80	337	23.5%	n/a	n/a	n/a	7.15	71.3%	97	2.8	46.0%	32.0%
Nigeria	158.3	212.1	11.60	1340	45.5%	16250	103	226	5.32	30.9%	113	2.7	48.0%	9.0%
Norway	4.9	450.0	7.30	92681	100.0%	107907	22225	22225	1.89	1.5%	163	7.9	100.0%	2.5%
Oman	2.9	35.7	0.70	12299	95.3%	10888	3748	3933	3.09	18.6%	38	5.5	n/a	n/a
Pakistan	184.8	168.3	4.00	911	53.5%	72712	394	736	4.00	50.1%	77	2.5	91.0%	24.0%
Palau, Republic	0.0	0.2	0.14	8865	80.0%	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Palestine	4.4	n/a	0.00	n/a	n/a	n/a	n/a	n/a	5.09	7.6%	125	n/a	92.0%	16.0%
Panama	3.5	23.1	0.78	6581	85.1%	4884	1392	1637	2.56	8.1%	68	3.4	90.0%	23.0%
Papua New Guinea	6.9	8.2	1.00	1186	80.0%	n/a	n/a	n/a	4.10	42.7%	90	2	39.0%	n/a
Paraguay	6.5	16.0	0.06	2473	85.7%	5138	795	929	3.08	6.5%	96	2.4	86.0%	15.0%
Peru	29.5	127.4	10.20	4320	73.9%	24383	827	1119	2.60	12.1%	99	3.6	83.0%	12.0%
Philippines	93.6	166.9	12.30	1783	85.1%	45720	488	574	3.11	7.4%	81	2.3	85.0%	18.0%
Poland	38.0	527.0	1.80	13854	99.5%	103396	2718	2732	1.27	1.5%	140	4.6	n/a	2.5%
Portugal	10.7	242.7	126.00	22613	100.0%	47763	4450	4450	1.38	1.5%	147	6.1	n/a	2.5%
Puerto Rico	4.0	n/a	1.90	n/a	99.5%	n/a	n/a	n/a	1.83	n/a	86	5.8	n/a	n/a
Qatar	1.5	52.7	1.20	34954	83.3%	12763	8462	10158	2.43	11.0%	20	6.5	100.0%	n/a
Romania	21.2	200.1	5.50	9442	99.5%	40965	1933	1943	1.32	n/a	122	3.8	57.0%	2.5%
Russia	140.4	1607.8	35.70	11454	99.5%	681401	4854	4879	1.37	1.5%	86	2.1	97.0%	3.0%
Rwanda	10.3	4.5	0.75	434	23.5%	n/a	n/a	n/a	5.43	35.1%	137	3	74.0%	33.0%

Sao Tome and Principe	0.2	0.2	0.01	1058	n/a	n/a	n/a	n/a	3.85	15.1%	n/a	2.7	79.0%	10.0%
Saudi Arabia	26.2	467.6	9.10	17816	97.7%	143481	5467	5595	3.17	17.1%	9	3.5	n/a	4.0%
Senegal	12.9	13.2	4.70	1027	32.2%	1757	137	424	5.04	60.7%	126	3.4	76.0%	20.0%
Serbia	10.5	54.6	0.48	5208	99.5%	26253	2505	2517	1.62	n/a	114	n/a	n/a	n/a
Seychelles	0.1	0.8	0.05	9846	80.0%	n/a	n/a	n/a	n/a	8.2%	91	4.8	88.0%	9.0%
Sierra Leone	5.8	2.0	0.30	335	23.5%	n/a	n/a	n/a	5.22	65.2%	115	1.9	57.0%	51.0%
Singapore	4.8	181.9	3.00	37618	100.0%	33626	6952	6952	1.27	7.5%	90	9.2	100.0%	n/a
Slovakia	5.4	95.0	145.00	17547	100.0%	23654	4371	4371	1.28	1.5%	168	5	100.0%	7.0%
Slovenia	2.0	54.6	36.30	26971	100.0%	13165	6502	6502	1.36	1.5%	126	6.7	n/a	3.0%
Solomon Island	0.5	0.6	0.32	1208	80.0%	n/a	n/a	n/a	3.92	23.4%	n/a	2.9	70.0%	21.0%
Somalia	9.4	n/a	0.08	n/a	7.0%	n/a	n/a	n/a	6.40	n/a	95	1	n/a	n/a
South Africa	50.5	276.8	39.50	5481	68.6%	198114	3924	5724	2.55	17.6%	45	4.9	88.0%	2.5%
Spain	45.3	1604.2	3840.00	35399	100.0%	249733	5511	5511	1.43	1.5%	128	6.5	100.0%	2.5%
Sri Lanka	20.4	40.7	6.70	1995	65.8%	7768	381	579	2.33	9.3%	75	3.2	79.0%	22.0%
Sudan	43.2	58.4	2.10	1353	30.5%	3553	82	270	4.23	39.1%	125	1.6	70.0%	26.0%
Suriname	0.5	2.9	0.48	5494	87.0%	n/a	n/a	n/a	2.42	10.4%	110	3.6	92.0%	8.0%
Swaziland	1.2	2.6	0.34	2178	23.5%	n/a	n/a	n/a	3.57	20.4%	93	3.6	62.0%	22.0%
Sweden	9.3	480.0	11.20	51654	100.0%	130806	14076	14076	1.87	1.5%	152	9.3	100.0%	2.5%
Switzerland	7.6	488.5	90.70	64318	100.0%	57782	7608	7608	1.45	1.5%	152	9	100.0%	2.5%
Syria	22.5	55.2	0.84	2453	88.3%	24195	1075	1218	3.29	19.2%	53	2.1	93.0%	4.0%
Taiwan	n/a.0	n/a	23.00	n/a	98.8%	206973	n/a	n/a	n/a	1.5%	69	5.7	n/a	n/a
Tajikistan	7.1	5.1	0.33	726	99.5%	14708	2079	2089	3.45	n/a	100	2	59.0%	56.0%
Tanzania	45.0	20.5	2.90	455	10.1%	2213	49	486	5.58	30.6%	130	3	62.0%	44.0%
Thailand	68.1	260.7	46.50	3826	95.1%	127811	1876	1973	1.81	7.4%	64	3.5	99.0%	22.0%
Togo	6.8	2.8	0.93	416	17.0%	623	92	541	4.30	46.8%	88	2.7	52.0%	24.0%
Trinidad and Tobago	1.3	23.9	0.14	17785	99.0%	6390	4755	4803	1.64	1.6%	24	3.6	91.0%	10.0%
Tunisia	10.4	40.2	3.20	3873	97.0%	13021	1255	1294	1.86	25.7%	84	4.4	93.0%	2.5%
Turkey	75.7	794.2	6.20	10491	99.5%	141400	1868	1877	2.13	12.6%	140	4.6	96.0%	3.0%
Turkmenistan	5.2	18.3	0.13	3529	99.5%	7943	1534	1542	2.50	n/a	20	1.8	72.0%	7.0%
Uganda	33.8	14.5	4.90	430	6.5%	n/a	n/a	n/a	6.38	33.2%	122	2.6	60.0%	19.0%
Ukraine	45.4	180.4	8.70	3970	99.5%	129645	2854	2868	1.31	n/a	96	2.5	96.0%	2.5%
United Arab Emirates	4.7	163.3	15.50	34690	94.7%	59261	12589	13294	1.95	11.3%	62	5.9	100.0%	2.5%
United Kingdom	62.3	2660.5	72.00	42736	100.0%	342923	5508	5508	1.84	1.5%	165	7.7	100.0%	2.5%
United States	317.8	14204	2520.00	44701	100.0%	3722254	11714	11714	2.09	1.5%	78	7.3	100.0%	2.5%
Uruguay	3.4	32.2	2.00	9544	97.0%	6631	1966	2027	2.12	3.2%	117	6.9	100.0%	2.5%
Uzbekistan	27.8	27.9	0.23	1004	99.5%	40661	1463	1470	2.29	n/a	75	1.8	82.0%	25.0%
Venezuela	29.0	313.8	2.60	10804	96.5%	80773	2781	2882	2.55	7.0%	5	1.9	83.0%	18.0%
Vietnam	89.0	90.7	7.20	1019	81.8%	48744	548	669	2.08	9.7%	77	2.7	85.0%	16.0%
Western Sahara	0.5	n/a	0.25	n/a	23.5%	n/a	n/a	n/a	2.70	n/a	n/a	n/a	n/a	n/a
Yemen	24.3	26.6	0.29	1096	43.2%	3625	149	346	5.30	45.9%	17	2.3	67.0%	38.0%
Zambia	13.3	14.3	1.30	1080	18.7%	8312	627	3353	5.87	32.0%	161	2.8	58.0%	46.0%
Zimbabwe	12.6	3.4	3.00	270	37.5%	11559	914	2441	3.47	10.6%	105	1.8	81.0%	47.0%
World	6904	59820	39529	8664	73.4%	15625125	2263	3082	2.60	20.7%	108	3.7	82.6%	14.2%

Appendix Table 2: Global overview on PV capacities installed, general and social progress indicators. The general indicator is population. The social progress indicators are: gross domestic product (GDP), GDP per

capita, electrification rate, total final electricity consumption, final electricity consumption per capita, final electricity consumption per electrified population, child per woman, adult illiteracy rate, diesel price, corruption index, access to improved water and undernourishment.

Appendix Table 3 Global Overview on Grid-Parity

Country	Grid-Parity		Electricity prices 2010		Irradiation fixed optimally tilted				Popula- tion	GDP	GHG	Electricity total Generation	Electrification rate	
	RES	IND	RES	IND	Pop weigh	Area weigh	max	min					40	41
Data source	33		34			35			36	37	38	39		
	[year]		[€/kWh]			[kWh/m ² /y]			[mio pop]	[bn USD]	[mio t CO ₂]	[GWh]		[% of pop]
Afghanistan	2011	2011	0.139	0.116	2164	2165	2298	1966	29.1	10.2	0.7	n/a	n/a	0.020
Albania			0.000	0.000	1923	1959	2069	1791	3.2	12.3	4.3	5094	n/a	0.995
Algeria	2019	2018	0.046	0.048	1993	2260	2488	1856	35.4	173.9	132.7	35226	n/a	0.985
Angola	2020+	2020+	0.034	0.022	2084	2128	2398	1677	19.0	83.4	10.6	2959	0.150	0.050
Argentina	2015	2017	0.086	0.051	1962	1947	2681	974	40.7	328.4	173.5	115197	0.950	0.950
Armenia	2019		0.056	0.000	1830	1789	1856	1723	3.1	11.9	4.4	5941	n/a	0.995
Australia	2014	2017	0.102	0.058	1914	2215	2570	1429	21.5	1015.2	372.0	251659	1.000	1.000
Austria	2012	2015	0.197	0.106	1389	1395	1476	1324	8.4	416.4	71.8	63505	1.000	1.000
Azerbaijan	2020+	2019	0.020	0.050	1685	1695	1968	1482	8.9	46.3	35.1	23611	n/a	0.995
Bangladesh	2015	2018	0.086	0.047	1908	1907	2022	1820	164.4	79.0	41.6	24334	0.320	0.263
Belarus	2020	2020+	0.067	0.061	1264	1269	1320	1229	9.6	60.3	68.8	31811	n/a	0.995
Belgium	2013	2016	0.194	0.103	1203	1243	1364	1200	10.7	497.6	107.2	85617	1.000	1.000
Belize	2013	2012	0.130	0.132	1807	1893	2094	1757	0.3	1.4	0.8	n/a	n/a	0.870
Benin	2013		0.112	0.000	1895	2008	2135	1809	9.2	6.7	3.1	127	0.220	0.248
Bolivia	2017	2019	0.058	0.041	2037	1983	2690	1625	10.0	16.7	7.0	5293	0.640	0.651
Bosnia			0.000	0.000	1548	1696	2025	1447	3.8	18.5	27.4	13346	n/a	0.995
Botswana	2017	2020+	0.056	0.027	2302	2315	2363	2237	2.0	13.0	4.8	1042	0.390	0.264
Brazil	2011	2013	0.162	0.104	1883	1881	2353	1545	195.4	1612.5	352.5	419337	0.970	0.946
Brunei Darussalam	2015	2015	0.087	0.072	1915	1915	1915	1915	0.4	11.5	5.9	3298	0.990	0.992
Bulgaria	2016	2018	0.086	0.061	1606	1607	1703	1569	7.5	49.9	48.1	45843	n/a	0.995
Burkina Faso	2010	2010	0.172	0.181	2164	2166	2352	2081	16.3	7.9	0.8	n/a	0.070	0.100
Burma (Myanmar)	2015	2014	0.088	0.088	1939	1917	2047	1625	50.5	n/a	10.0	6164	0.110	0.050
Burundi	2020+	2012	0.029	0.131	1803	1803	1803	1803	8.5	1.2	0.2	n/a	n/a	0.235
Cambodia	2011	2010	0.153	0.157	1937	1933	2006	1757	15.1	9.6	4.1	1235	0.200	0.183
Cameroon	2015	2013	0.087	0.099	1875	1889	2157	1580	20.0	23.4	3.6	3954	0.470	0.407
Canada	2018	2020	0.069	0.049	1554	1095	1702	1102	33.9	1400.1	544.7	612594	1.000	1.000
Central African Republic	2012	2013	0.127	0.089	2031	2080	2237	1840	4.5	2.0	0.2	n/a	n/a	0.235
Chad	2010	2010	0.188	0.145	2222	2366	2592	2107	11.5	8.4	0.4	n/a	n/a	0.235
Chile	2012	2013	0.118	0.094	2124	1775	2769	916	17.1	169.5	60.1	57555	0.990	0.970
China	2018	2014	0.064	0.102	1631	1911	2615	1087	1354.7	4344.8	6105.7	2864204	0.990	0.990
China Central	2020	2015	0.061	0.103	1381				315.3					
China East	2018	2014	0.066	0.099	1689				950.7					

³³ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

³⁴ Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 2010

³⁵ Breyer Ch. and Schmid J., Population Density and Area weighted Solar Irradiation, 2010

³⁶ UN, World Population Prospects: The 2008 Revision Highlights, 2009

³⁷ World Bank, Gross domestic product 2008, 2009

³⁸ UN, Carbon Dioxide Emissions (CO₂), 2009

³⁹ IEA, Key World Energy Statistics 2009, 2009

⁴⁰ UNDP, Human Development Report 2007/2008, 2007

⁴¹ IEA, World Energy Outlook 2006, 2006

China West	2019	2012	0.048	0.111	2071				88.8					
Colombia	2016	2015	0.085	0.085	1732	1725	2454	1375	46.3	242.3	63.4	54301	0.860	0.902
Congo DR	2020+	2015	0.029	0.074	1848	1872	2216	1571	67.8	11.6	2.2	7886	0.060	0.083
Congo R	2020	2019	0.050	0.057	1638	1724	1897	1517	3.8	10.7	1.5	453	0.200	0.196
Costa Rica	2018	2016	0.065	0.065	1735	1899	2222	1537	4.6	29.8	7.9	8698	0.990	0.970
Cote d'Ivoire	2012	2012	0.141	0.123	1818	1891	2100	1708	21.6	23.4	6.9	5530	0.500	0.507
Croatia	2014	2016	0.122	0.082	1586	1652	1906	1490	4.4	69.3	23.7	12430	n/a	0.995
Cuba	2011	2015	0.170	0.076	1987	2198	2386	1950	11.2	n/a	29.6	16469	0.960	0.958
Cyprus	2010	2010	0.169	0.143	2244	2248	2259	2237	0.9	21.3	7.8	4651	n/a	1.000
Czech Republic	2015	2016	0.146	0.103	1251	1259	1293	1197	10.4	216.5	117.0	84361	n/a	0.995
Denmark	2011	2016	0.263	0.095	1287	1240	1378	975	5.5	342.7	54.6	45716	1.000	1.000
Djibouti			0.000	0.000	2318	2318	2318	2318	0.9	0.9	0.5	n/a	n/a	0.235
Dominican Republic	2011	2010	0.157	0.169	1995	2115	2393	1930	10.2	45.8	20.4	14150	0.930	0.923
Ecuador	2016	2018	0.079	0.054	1660	1807	2384	1368	13.8	52.6	31.3	15406	0.900	0.897
Egypt	2020+	2020+	0.012	0.024	2242	2374	2589	1964	84.5	162.8	166.8	115407	0.980	0.977
El Salvador	2013	2012	0.132	0.103	2206	2206	2206	2206	6.2	22.1	6.5	5597	0.800	0.769
Eritrea			0.000	0.000	2215	2239	2389	2049	5.2	1.7	0.6	269	0.200	0.184
Estonia	2017	2019	0.097	0.060	1298	1318	1414	1262	1.3	23.1	17.5	9731	n/a	0.995
Ethiopia	2020	2020	0.038	0.034	2205	2183	2365	1927	85.0	26.5	6.0	3269	0.150	0.026
Fiji	2012	2010	0.140	0.163	1976	2030	2131	1803	0.9	3.5	1.6	n/a	n/a	0.800
Finland	2015	2019	0.135	0.070	1181	849	1394	1167	5.3	271.3	66.7	82304	1.000	1.000
France	2015	2018	0.119	0.065	1441	1521	2065	1239	63.1	2853.1	384.0	574473	1.000	1.000
Gabon	2016	2013	0.086	0.125	1667	1657	1880	1531	1.5	14.4	2.1	1726	0.480	0.479
Gambia	2013	2010	0.113	0.201	2129	2118	2159	2081	1.8	0.8	0.3	n/a	n/a	0.235
Georgia			0.000	0.000	1678	1684	1840	1605	4.2	12.8	5.5	7287	n/a	0.995
Germany	2012	2016	0.236	0.106	1222	1223	1475	1140	82.1	3652.8	805.1	636761	1.000	1.000
Ghana	2018	2013	0.059	0.105	1852	1921	2087	1709	24.3	16.1	9.2	8429	0.490	0.485
Greece	2014	2015	0.108	0.085	1753	1983	2330	1680	11.2	356.8	96.4	60789	1.000	0.995
Grenada	2010	2010	0.178	0.160	2317	2317	2317	2317	0.1	0.6	0.2	n/a	n/a	0.995
Guatemala	2014	2012	0.102	0.106	1997	2061	2355	1778	14.4	39.0	11.8	7916	0.790	0.844
Guinea	2016	2013	0.065	0.093	2046	2063	2139	1953	10.3	4.3	1.4	n/a	n/a	0.800
Guyana	2010	2010	0.197	0.226	1784	1844	1948	1749	0.8	1.2	1.5	n/a	n/a	0.870
Haiti	2016	2010	0.063	0.144	2146	2276	2435	2062	10.2	7.0	1.8	570	0.360	0.335
Honduras	2017	2014	0.068	0.090	1932	1959	2181	1789	7.6	14.1	7.2	5982	0.620	0.601
Hong Kong (China)	2016		0.093	0.000	1506	1605	1703	1506	7.1	215.4	39.0	38616	n/a	1.000
Hungary	2013	2014	0.164	0.120	1445	1448	1500	1339	10.0	154.7	57.6	35859	n/a	0.995
India	2017	2014	0.064	0.079	2032	2027	2446	1615	1214.4	1217.5	1510.4	744078	0.560	0.444
India East	2016	2015	0.069	0.077	1975				338.6					
India West	2015	2014	0.080	0.085	2051				875.8					
Indonesia	2019	2017	0.053	0.059	1809	1916	2415	1616	233.7	514.9	333.7	133108	0.540	0.525
Iran	2020	2020+	0.038	0.031	2041	2121	2459	1569	75.1	385.1	467.0	201029	0.970	0.992
Iraq	2020+	2020+	0.012	0.012	2073	2096	2190	2022	31.5	n/a	92.6	31869	n/a	0.954
Ireland	2014	2017	0.191	0.102	1055	1151	1331	1032	4.6	281.8	43.8	28046	1.000	1.000
Israel	2013	2015	0.105	0.068	2247	2258	2320	2205	7.3	199.5	70.4	51811	0.970	1.000
Italy	2010	2012	0.206	0.129	1720	1855	2186	1568	60.1	2294.7	474.1	314121	1.000	1.000
Jamaica	2010	2010	0.203	0.160	2132	2257	2353	2132	2.7	15.1	12.2	7473	0.870	0.870
Japan	2012	2014	0.163	0.099	1578	1603	1999	1362	127.0	4909.3	1293.4	1100364	1.000	1.000
Jordan	2014	2017	0.084	0.054	2103	2194	2298	2084	6.5	20.0	20.7	11560	1.000	0.955
Kazakhstan	2020+	2020+	0.036	0.024	1709	1704	1954	1508	15.8	132.2	193.5	71653	n/a	0.995
Kenya	2013	2016	0.101	0.054	2124	2117	2313	1929	40.9	34.5	12.2	6477	0.140	0.091
Korea, North (DR)			0.000	0.000	1874	1892	2001	1780	24.0	n/a	79.1	22436	n/a	0.200
Kuwait	2020+	2020+	0.015	0.016	2134	2134	2134	2134	3.1	112.1	86.6	47607	1.000	1.000
Kyrgyzstan	2020+	2020+	0.016	0.016	1840	1880	2007	1698	5.6	4.4	5.6	17082	n/a	0.995
Lao PDR	2020+	2017	0.036	0.057	1829	1827	1949	1656	6.4	5.4	1.4	n/a	n/a	0.800
Latvia	2016	2018	0.105	0.067	1307	1331	1418	1259	2.2	33.8	7.5	4891	n/a	0.995
Lebanon	2014	2020+	0.088	0.022	2159	2262	2334	2159	4.3	28.7	15.3	9287	1.000	0.960
Liberia	2010	2010	0.250	0.250	1781	1788	1915	1696	4.1	0.9	0.8	n/a	n/a	0.235
Libya	2020+	2020+	0.011	0.018	2110	2341	2575	1899	6.6	99.9	55.5	23992	0.970	0.998

Lithuania	2017	2018	0.097	0.070	1277	1286	1381	1218	3.3	47.3	14.2	12482	n/a	0.995
Luxembourg	2013	2016	0.194	0.098					0.5	54.3	11.3	4333	1.000	1.000
Macedonia			0.000	0.000	1718	1713	1774	1636	2.0	9.5	10.9	7006	n/a	0.995
Madagascar	2010	2010	0.169	0.166	2091	2168	2531	1654	20.1	9.0	2.8	n/a	0.150	0.083
Malawi	2020+	2014	0.028	0.074	2088	2103	2176	2041	15.7	4.3	1.0	n/a	0.070	0.058
Malaysia	2018	2017	0.063	0.056	1766	1844	2148	1636	27.9	194.9	187.9	91563	0.980	0.971
Mali	2011	2010	0.148	0.145	2185	2270	2497	2106	13.3	8.7	0.6	n/a	n/a	0.235
Malta	2011	2013	0.156	0.090	2188	2188	2188	2188	0.4	7.4	2.5	2296	n/a	1.000
Mauretania			0.000	0.000	2202	2267	2443	2098	3.4	2.9	1.7	n/a	n/a	0.235
Mauritius	2015	2013	0.075	0.080	2244	2248	2273	2222	1.3	8.7	3.9	n/a	0.940	1.000
Mexico	2014	2013	0.083	0.093	2136	2194	2530	1696	110.6	1086.0	436.2	249648	n/a	0.870
Moldova	2020+	2020+	0.037	0.037	1492	1497	1577	1445	3.6	6.0	7.8	3829	n/a	0.995
Mongolia			0.000	0.000	1910	1996	2333	1701	2.7	5.3	9.4	3649	0.650	0.900
Morocco	2013	2013	0.101	0.092	2153	2194	2410	1938	32.4	86.3	45.3	23192	0.850	0.774
Mozambique	2015	2016	0.077	0.061	2026	2053	2339	1943	23.4	9.7	2.0	14737	0.060	0.087
Namibia	2013	2014	0.091	0.069	2352	2355	2521	1952	2.2	8.6	2.8	1606	0.340	0.347
Nepal			0.000	0.000	2176	2191	2276	2082	29.9	12.6	3.2	2684	0.330	0.259
Netherlands	2013	2015	0.191	0.106	1242	1259	1325	1153	17.0	860.3	175.1	99664	1.000	1.000
New Zealand	2013	2018	0.133	0.056	1644	1644	2017	1309	4.3	130.7	30.5	43519	1.000	1.000
Nicaragua	2013	2014	0.119	0.087	2016	1907	2387	1621	5.8	6.6	4.3	2958	0.690	0.466
Niger	2014	2015	0.084	0.062	2382	2450	2599	2170	15.9	5.4	0.9	n/a	n/a	0.235
Nigeria	2020+	2016	0.023	0.060	1978	2037	2370	1523	158.3	212.1	97.3	23110	0.460	0.449
Norway	2015	2019	0.161	0.071	1103	575	1378	994	4.9	450.0	40.2	121663	1.000	1.000
Oman			0.000	0.000	2239	2336	2511	2167	2.9	35.7	41.4	13585	0.960	0.946
Pakistan	2018	2013	0.052	0.086	2135	2137	2468	1863	184.8	168.3	142.7	98350	0.540	0.530
Palestine	2012	2011	0.125	0.125	2056	2056	2056	2056	4.4	n/a	3.0	n/a	n/a	n/a
Panama	2013	2013	0.136	0.119	1728	1758	1921	1523	3.5	23.1	6.4	5989	0.850	0.851
Paraguay	2018	2020	0.055	0.037	1898	1891	1930	1850	6.5	16.0	4.0	53784	0.860	0.853
Peru	2013	2016	0.105	0.057	2006	1868	2422	1448	29.5	127.4	38.6	27358	0.720	0.757
Philippines	2012	2012	0.151	0.125	1842	1977	2219	1689	93.6	166.9	68.3	56730	0.810	0.891
Poland	2015	2017	0.136	0.088	1235	1236	1326	1173	38.0	527.0	318.2	161742	n/a	0.995
Portugal	2011	2014	0.164	0.087	1891	1947	2222	1769	10.7	242.7	60.0	49041	1.000	1.000
Puerto Rico	2013	2017	0.097	0.049	2142	2295	2367	2142	4.0	n/a	n/a	n/a	n/a	0.995
Qatar	2020+	2020+	0.018	0.018	2065	2223	2381	2065	1.5	52.7	46.2	15325	0.710	0.956
Romania	2015	2017	0.103	0.075	1500	1492	1625	1364	21.2	200.1	98.5	62697	n/a	0.995
Russian Federation	2020+	2020+	0.034	0.039	1403	993	1998	1012	140.4	1607.8	1564.7	995794	n/a	0.995
Rwanda	2014	2013	0.104	0.104	1831	1819	1854	1783	10.3	4.5	0.8	n/a	n/a	0.235
Saudi Arabia	2020+	2020+	0.014	0.014	2296	2327	2621	2149	26.2	467.6	381.6	179782	0.970	0.984
Senegal	2012	2010	0.133	0.151	2126	2160	2329	2039	12.9	13.2	4.3	2439	0.330	0.314
Serbia	2020	2018	0.053	0.058	1573	1585	1820	1512	10.5	54.6	53.3	36481	n/a	0.995
Seychelles	2020+	2010	0.021	0.213	2168	2168	2168	2168	0.1	0.8	0.7	n/a	n/a	0.800
Sierra Leone			0.000	0.000	1861	1888	1994	1757	5.8	2.0	1.0	n/a	n/a	0.235
Slovakia	2014	2014	0.155	0.133	1286	1296	1363	1240	5.4	95.0	37.5	31418	n/a	1.000
Slovenia	2014	2016	0.141	0.084	1483	1484	1485	1482	2.0	54.6	15.2	15115	n/a	1.000
Somalia			0.000	0.000	2100	2188	2538	1970	9.4	n/a	0.2	n/a	n/a	0.070
South Africa	2020+	2020+	0.035	0.021	2166	2238	2455	1784	50.5	276.8	414.6	253798	0.700	0.671
South Korea	2015	2019	0.091	0.047	1770	1779	1912	1672	48.5	929.1	475.2	404021	1.000	1.000
Spain	2011	2013	0.173	0.098	1886	1967	2479	1450	45.3	1604.2	352.2	303051	1.000	1.000
Sri Lanka	2018	2014	0.057	0.085	1813	1944	2146	1765	20.4	40.7	11.9	9389	0.660	0.655
Sudan	2015	2019	0.074	0.037	2271	2294	2574	1938	43.2	58.4	10.8	4209	0.300	0.310
Suriname	2012	2012	0.156	0.116	1872	1934	2270	1856	0.5	2.9	2.4	n/a	n/a	0.870
Swaziland			0.000	0.000	1982	1982	1982	1982	1.2	2.6	1.0	n/a	n/a	0.235
Sweden	2014	2019	0.170	0.063	1218	927	1458	1045	9.3	480.0	50.9	143299	1.000	1.000
Switzerland	2015	2017	0.112	0.074	1467	1482	1511	1423	7.6	488.5	41.8	64038	1.000	1.000
Syria	2014	2018	0.098	0.047	2026	2068	2269	1991	22.5	55.2	68.5	37283	0.900	0.866
Taiwan	2018	2019	0.065	0.053	1632	1628	1920	1407	n/a	n/a	n/a	235371	n/a	0.988
Tajikistan	2020+	2020+	0.007	0.007	1996	1987	2238	1777	7.1	5.1	6.4	16924	n/a	0.995
Tanzania	2016	2015	0.067	0.074	2043	2049	2284	1805	45.0	20.5	5.4	2776	0.110	0.092

Thailand	2017	2016	0.066	0.060	1903	1899	2007	1728	68.1	260.7	272.5	138742	0.990	0.911
Togo	2014	2012	0.102	0.112	1931	1991	2079	1849	6.8	2.8	1.2	221	0.170	0.170
Trinidad and Tobago	2020	2019	0.036	0.040	2136	2242	2320	2136	1.3	23.9	33.6	7045	0.990	0.990
Tunisia	2016	2016	0.075	0.065	1916	2062	2306	1819	10.4	40.2	23.1	14122	0.990	0.950
Turkey	2013	2013	0.124	0.109	1839	1883	2274	1520	75.7	794.2	269.5	176299	n/a	0.995
Turkmenistan	2020+	2020+	0.025	0.025	1894	1888	2033	1712	5.2	18.3	44.1	13650	n/a	0.995
Uganda	2010	2017	0.182	0.053	1980	2015	2179	1815	33.8	14.5	2.7	n/a	0.090	0.040
Ukraine	2020+	2020+	0.022	0.022	1398	1424	1697	1259	45.4	180.4	319.2	193381	n/a	0.995
United Arab Emirates	2020	2019	0.035	0.035	2261	2311	2453	2191	4.7	163.3	139.6	66768	0.920	0.974
United Kingdom	2015	2017	0.148	0.095	1128	1153	1456	984	62.3	2660.5	569.0	398478	1.000	1.000
United States	2016	2020+	0.083	0.034	1796	1657	2442	1067	317.8	14204.7	5752.9	4300100	1.000	1.000
United States East	2015	2019	0.097	0.049	1598				176.9					
United States North West	2016	2020+	0.084	0.039	1618				55.9					
United States South West	2017	2017	0.067	0.053	1953				88.0					
Uruguay	2012	2017	0.136	0.060	1853	1860	1915	1778	3.4	32.2	6.9	5619	0.950	0.990
Uzbekistan	2020+	2020+	0.015	0.015	1976	1907	2080	1787	27.8	27.9	115.7	49299	n/a	0.995
Venezuela	2020+	2020+	0.039	0.028	1934	1951	2463	1582	29.0	313.8	171.6	110357	0.990	0.940
Vietnam	2019	2015	0.055	0.084	1665	1744	2054	1387	89.0	90.7	106.1	56494	0.840	0.796
Yemen			0.000	0.000	2295	2375	2525	2162	24.3	26.6	21.2	5337	0.360	0.503
Zambia	2020+	2019	0.015	0.035	2201	2214	2315	2114	13.3	14.3	2.5	9385	0.190	0.184
Zimbabwe	2020+	2020+	0.011	0.011	2221	2220	2331	2072	12.6	3.4	11.1	9776	0.340	0.409
World					1846	1776	2769	772	6883.1	59557	28313	18913638		

Appendix Table 3: List of 161 countries and respective data for grid-parity events, electricity prices, irradiation on fixed optimally tilted module surface, population, gross domestic product, greenhouse gas emissions, electricity generation and electrification rate.

Appendix Table 4

Global Country Codes of Top Level Web Domain

ccTLD	Country	ccTLD	Country
ad	Andorra	kr	Korea, Republic of
ad	Area under dispute	kw	Kuwait
ae	United Arab Emirates	kz	Kazakhstan
af	Afghanistan	la	Laos
ag	Antigua and Barbuda	lb	Lebanon
al	Albania	lc	St. Lucia
am	Armenia	lk	Sri Lanka
ao	Angola	lr	Liberia
aq	Antarctica	ls	Lesotho
ar	Argentina	lt	Lithuania
at	Austria	lu	Luxembourg
au	Australia	lv	Latvia
az	Azerbaijan	ly	Libya
ba	Bosnia-Herzegovina	ma	Morocco
bb	Barbados	md	Moldova
bd	Bangladesh	mg	Madagascar
be	Belgium	mk	Macedonia
bf	Upper Volta - Burkina Faso	ml	Mali

bg	Bulgaria	mm	Burma
bh	Bahrain	mn	Mongolia
bi	Burundi	mp	Northern Mariana Islands
bj	Benin	mq	Martinique
bm	Bermuda	mr	Mauritania
bn	Brunei	mt	Malta
bo	Bolivia	mu	Mauritius
br	Brazil	mv	Maldives
bs	Bahamas, The	mw	Malawi
bt	Bhutan	mx	Mexico
bv	Bouvet Island	my	Malaysia
bw	Botswana	mz	Mozambique
by	Belarus	na	Namibia
bz	Belize	nc	New Caledonia
ca	Canada	ne	Niger
cf	Central African Republic	nf	Norfolk Island
cg	Congo, Republic of the	ng	Nigeria
ch	Switzerland	ni	Nicaragua
ci	Crozet Islands (France)	nl	Netherlands
ci	Ivory Coast	no	Norway
cl	Chile	np	Nepal
cm	Cameroon	nz	New Zealand
cn	China	om	Oman
co	Colombia	pa	Panama
cr	Costa Rica	pdw	Prince Edward Islands (South Africa)
cu	Cuba	pe	Peru
cv	Cape Verde	ph	Philippines
cy	Cyprus	pk	Pakistan
cz	Czech Republic	pl	Poland
de	Germany	pq	Papua New Guinea
dj	Djibouti	pr	Puerto Rico
dk	Denmark	pt	Portugal
dm	Dominica	pw	Republic of Palau
do	Dominican Republic	py	Paraguay
dz	Algeria	qa	Qatar
ec	Ecuador	re	Reunion
ee	Estonia	ro	Romania
eg	Egypt	ru	Russia
eh	Western Sahara	rw	Rwanda
er	Eritrea	sa	Saudi Arabia
es	Spain	sb	Solomon Island
et	Ethiopia	sc	Seychelles
fi	Finland	sd	Sudan
fj	Fiji	se	Sweden
fk	Falkland Islands (Islas Malvinas)	sg	Singapore
fm	Federated States of Micronesia	sh	St. Helena
fr	France	si	Slovenia
ga	Gabon	sk	Slovakia
gd	Grenada	sl	Sierra Leone
ge	Georgia	sn	Senegal
gf	French Guiana	so	Somalia
gh	Ghana	sr	Suriname
gl	Greenland	st	Sao Tome and Principe
gm	Gambia, The	sv	El Salvador
gn	Guinea	sy	Syria
gp	Guadeloupe	sz	Swaziland

gq	Equatorial Guinea	td	Chad
gr	Greece	tf	Kerguelen Islands (France)
gt	Guatemala	tg	Togo
gu	Guam	th	Thailand
gw	Guinea - Bissau	tj	Tajikistan
gy	Guyana	tm	Turkmenistan
hat	Haiti	tn	Tunisia
hk	Hong Kong	tr	Turkey
hn	Honduras	tt	Trinidad and Tobago
hr	Croatia	tw	Taiwan
hu	Hungary	tz	Tanzania, United Republic of
ia	Ile Amsterdam (France)	ua	Ukraine
id	Indonesia	ug	Uganda
ie	Ireland	uk	United Kingdom
il	Israel	us	United States
in	India	uy	Uruguay
iq	Iraq	vc	St. Vincent and the Grenadines
ir	Iran	ve	Venezuela
is	Iceland	vi	Virgin Islands
it	Italy	vn	Vietnam
jm	Jamaica	vu	New Hebrides
jo	Jordan	wb	West Bank
jp	Japan	ye	Yemen
ke	Kenya	yu	Yugoslavia
kg	Kyrgyzstan	za	South Africa
kh	Cambodia (Formerly Kampuchea)	zm	Zambia
ki	Kiribati	zr	Congo, Democratic Republic of the (Formerly Zaire)
km	Comoros	zu	Uzbekistan
kp	Korea, Democratic Peoples Republic	zw	Zimbabwe

Appendix Table 4: List of country codes of top level web domain.

Bibliography

A

- Adams J.G.J., Browne B.C., Chan N.L.A., Barnham K.W.J., Ekins-Daukes N.J., 2010. Recent Progress in Quantum Well Solar Cells, Proceedings 25th European Photovoltaic Solar Energy Conference, Valencia, September, 6-10
- Adelmann P., 2009. Wireless Power, Maputo Workshop for SSA Electrification Experts, Maputo, June, 9-12
- Adelmann P., 2011. Pico PV – An Overview, Proceedings 2nd Symposium Small PV-Applications, Ulm, June 6-7
- Afgan N.H. and Carvalho M.G., 2008. Sustainability assessment of a hybrid energy system, *Energy Policy*, 36, 2903-2910
- Alcamo J., Döll P., Henrichs T., Lehner B., Rösch T., Siebert S., 2001. The Global Integrated Water Model WaterGAP 2.1, in: *EuroWasser – Model-based assessment of European water resources and hydrology in the face of global change*, Center for Environmental Systems Research, University of Kassel, www.usf.uni-kassel.de/usf/archiv/dokumente/kwws5.en.htm
- Almeida de P. and Silva P.D., 2009. The peak of oil production – Timings and market recognition, *Energy Policy*, 37, 1267-1276
- Alsema E.A., Frankl P., Kato K., 1998. Energy pay-back time of photovoltaic energy systems: present status and prospectus, Proceedings 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, July 6-10
- Alsema E.A., 2000. Energy Pay-back Time and CO₂ Emissions of PV Systems, Progress in Photovoltaics: Research and Applications, 8, 17-25
- Alsema E.A., Wild-Scholten de M.J., Fthenakis V.M., 2006. Environmental impacts of PV electricity generation a critical comparison of energy supply options, Proceedings 21st European Photovoltaic Solar Energy Conference, Dresden, September 4-8
- Alsema E.A. and Wild-Scholten de M.J., 2007. Reduction of the Environmental Impacts in Crystalline Silicon Module Manufacturing, Proceedings 22nd European Photovoltaic Solar Energy Conference, Milan, September 3-7
- Alsema E.A., 2009. Life-cycle assessment of crystalline silicon PV module production by REC, Proceedings 24th European Photovoltaic Solar Energy Conference, Hamburg, September 21-25
- Andersson B.A., 2000. Materials Availability for Large-scale Thin-film Photovoltaics, Progress in Photovoltaics: Research and Applications, 8, 61-76
- Andersson B.A. and Jacobsson S., 2000. Monitoring and assessing technology choice: the case of solar cells, *Energy Policy*, 28, 1037-1047
- [ARE] – Alliance for Rural Electrification, 2010. Hybrid Mini-Grids for Rural Electrification: Lessons Learned, study prepared for USAID by ARE, Brussels, 2010, www.ruralelec.org/fileadmin/DATA/Documents/06_Publications/Position_papers/ARE_Mini-grids.pdf
- Argaw N., 1998. The role of institutions for sustainable development of rural communities using PV systems, Proceedings 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, July 6-10
- Arkesteijn K.M. and Maaskant A.E., 2007. Small is beautiful: Solar product and market development should be scaled to the actual needs of end-users in the developing world, Proceedings 22nd European Photovoltaic Solar Energy Conference, Milan, June 3-7
- Asali K., 2010. Value of PV for Large Scale Solar Power Plants in MENA, First Solar, Hannover Messe, SOLAR XXL – Solar solutions to power the Middle East and North Africa, April 22
- Astolfi M., Xodo L., Romano M.C., Macchi E., 2011. Technical and economical analysis of a solar-geothermal hybrid plant based on an Organic Rankine Cycle, *Geothermics*, 40, 58-68
- Aulich H.A., Schulze F.W., Strake B., 1985. Energy pay-back time for crystalline silicon photovoltaic modules using new technologies, Proceedings 18th IEEE PV Specialists Conference, Las Vegas, October 21-25

- Aulich H.A., Raptis F., Schmid J., 1998. Rural Electrification with Photovoltaic Hybrid Plants – State of the Art and Future Trends, *Progress in Photovoltaics: Research and Applications*, 6, 325-339
- Auth S., Huber I., Schnatz K., 2008. Uranium - is it a country? Eine Spurensuche nach der Herkunft von Atomstrom, Initiative Strahlendes Klima, Berlin, <http://strahlendesklima.de>
- Awerbuch S., 2000. Investing in photovoltaics: risk, accounting and the value of new technology, *Energy Policy*, 28, 1023-1035
- Awerbuch S. and Berger M., 2003. Applying Portfolio Theory to EU Electricity Planning and Policymaking, IEA/EET working paper EET/2003/03, International Energy Agency (IEA), www.ieo.org/textbase/papers/2003/port.pdf
- Awerbuch S., 2006. Portfolio-based electricity generation planning: policy implications for renewables and energy security, *Mitigation and Adaption Strategies for Global Change*, 11, 693-710
- Ayclcek E., Schneider W., Bohlen A.-K., Jeggle B., Seeliger W., 2010. Sector Analysis Photovoltaics 2010: From vertical to horizontal integration – Renewables and Grid Integration, Landesbank Baden-Württemberg (LBBW), Stuttgart, April 27

B

- Bachmann M., 2008. Morning Note on First Solar, Pacific Crest Securities, Portland, December 16
- Bailat J., Fesquet L., Orhan J., Djeridane Y., Wolf B., Madliger P., Steinhauser J., Benagli S., Borrello D., Castens L., Monteduro G., Marmelo M., Dehbozorgi B., Vallat-Sauvain E., Multone X., Romang D., Boucher J., Meier J., Kroll U., 2010. Recent developments of high-efficiency micromorph tandem solar cells in Kai-M PECVD reactors, *Proceedings 25th European Photovoltaic Solar Energy Conference*, Valencia, September 21-25
- Balk D. and Yetman G., 2005. The Global Distribution of Population: Gridded Population of the World Version 3 (GPWv3), Center for International Earth Science Information Network (CIESIN), New York, <http://sedac.ciesin.columbia.edu/gpw>
- Bandi A., Specht M., Weimer T., Schaber K., 1995. CO₂ Recycling for Hydrogen Storage and Transportation – Electrochemical CO₂ Removal and Fixation, *Energy Conversion and Management*, 36, 899-902
- Bard J., 2007. Meeresenergie, Presentation at University of Munich, March 1, www.seniorenstudium.uni-muenchen.de/forschung/publikationen/pub_pdf/senior_2007_03_01.pdf
- Bardi U., 2005. The mineral economy: a model for the shape of oil production curves, *Energy Policy*, 33, 53-61
- Bardi U., 2009. Peak oil: The four stages of a new idea, *Energy*, 34, 323-326
- Barnaby F. and Kemp J., (eds.), 2007. *Secure Energy? – Civil Nuclear Power, Security and Global Warming*, Oxford Research Group, London, www.oxfordresearchgroup.org.uk/sites/default/files/secureenergy.pdf
- Bartle A., 2002. Hydropower potential and development activities, *Energy Policy*, 30, 1231-1239
- [BCG] – Boston Consulting Group, 1972. *Perspectives on experience*, Boston
- Beaucarne G. And Slaoui A., 2006. Thin Film Polycrystalline Silicon Solar Cells, in: Poortmans J. and Arkhipov V., (eds.), *Thin Film Solar Cells: Fabrication, Characterization and Applications*, John Wiley & Sons, Chichester
- Beckel O., 2010. Grid Parity in Asian Photovoltaic Markets, First Asia Solar Energy Forum, Manila, July 5-6
- Becquerel E., 1839. Recherches sur les effets de la radiation chimique de la lumière solaire au moyen des courants électriques, *Compte Rendu des Séances de l'Académie des Sciences*, 9, 145-149
- Bélanger C. and Gagnon L., 2002. Adding wind energy to hydropower, *Energy Policy*, 30, 1279-1284
- Beluco A., Souza de P.K., Krenzinger A., 2001. Hybrid Plants Based on Complementary Hydro and Photovoltaic Energy Resources, *Proceedings 17th European Photovoltaic Solar Energy Conference*, Munich, October 22-26
- Beneking A., 2011. Kratzen an der 20-Prozent-Marke, *Photon – Das Solarstrom-Magazin*, 2011(3), 128-129
- Beneking A., 2011. Europas größte Solarbremser – So reibungslos wie in Deutschland läuft es nirgends, *Photon – Das Solarstrom-Magazin*, 2011(4), 104-105

- Bertani R. and Thain I., 2002. Geothermal Power Generating Plant CO₂ Emission Survey, International Geothermal Association (IGA), Pisa, IGA News No. 49, 2002, <http://iga.igg.cnr.it/documenti/IGA/newsletter/n49.pdf>
- Bett A.W. and Lerchenmüller H., 2007. The FLATCON System from Concentrix Solar, in: Luque A.L. and Andreev V.M., (eds.), *Concentrator Photovoltaics*, Springer-Verlag, Berlin
- Beyer H.G., Hammer A., Luther J., Poplawska J., Stolzenburg K., Wieting P., 1994. Analysis and Synthesis of Cloud Pattern for Radiation Field Studies, *Solar Energy*, 52, 379-390
- Beyer H.G., Degner T., Gabler H., 1995. Operational behaviour of wind diesel systems incorporating short-term storage: an analysis via simulation calculations, *Solar Energy*, 54, 429-439
- Beyer H.G. and Degner T., 1997. Assessing the maximum fuel savings obtainable in simple wind-diesel systems, *Solar Energy*, 61, 5-10
- Beyer H.G., Lorenz E., Bofinger S., 2006. Zeitlich/ räumliche Eigenschaften meteorologischer Felder zur Charakterisierung einer verteilten Erzeugung aus regenerativen Quellen, Workshop Energiemeteorologie, ForschungsVerbund Sonnenenergie (FVS), Berlin, November 2, www.fvee.de/fileadmin/publikationen/Workshopbaende/ws2006/ws_2006.pdf
- Bhandari R., 2010. Role of Grids for Electricity and Water Supply with Decreasing Costs for Photovoltaics, PhD thesis, University of Kassel, Faculty of Electrical Engineering and Computer Science, www.uni-kassel.de/upress/online/frei/978-3-89958-958-0.volltext.frei.pdf
- Birnbaum L., Hartmann A., Malorny C., Riese J., Vahlenkamp T., Hein J., Mittelbach K., Schröder M., 2007. Kosten und Potenziale der Vermeidung von Treibhausgasemissionen in Deutschland, study on behalf of Bundesverband der Deutschen Industrie (BDI), McKinsey & Company, Berlin, www.mckinsey.de/downloads/presse/2007/070925_Kosten_und_Potenziale_der_Vermeidung_von_Treibhausgasemissionen_in_Deutschland.pdf
- Blackburn J.O. and Cunningham S., 2010. Solar and Nuclear Costs: The Historic Crossover - Solar Energy is Now the Better Buy, Duke University, http://www.ncwarn.org/wp-content/uploads/2010/07/NCW-SolarReport_final1.pdf
- Blankenship R.E., *Molecular Mechanisms of Photosynthesis*, Blackwell Science, Oxford, UK 2002
- Blankenship R.E., *Natural Organic Photosynthetic Solar Energy Transduction*, in: *Organic Photovoltaics Mechanisms, Materials and Devices*, in: Sun S.-S. and Sariciftci N.S., (eds.), *Organic Photovoltaics: Mechanisms, Materials and Devices*, CRC Press, Boca Raton
- [BMU] – Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2006. *Renewable Energies: Innovations for the Future*, BMU, Berlin, www.erneuerbare-energien.de/files/english/renewable_energy/downloads/application/pdf/broschuere_ee_innovation_eng.pdf
- [BMU] – Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 2009. *Renewable Energy Sources in Figures – National and international development*, BMU, Berlin, www.bmu.de/files/english/renewable_energy/downloads/application/pdf/broschuere_ee_zahlen_en.pdf
- [BMU] – Federal Ministry for the Environment; Nitsch J., Pregger T., Scholz Y., Naegler T., Sterner M., Gerhardt N., Oehsen von, A., Pape C., Saint-Drenan Y.-M., Wenzel B., 2010. *Leitstudie 2010 – Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global*, study prepared by German Aerospace Center (DLR), Fraunhofer Institute for Wind Energy and Energy System Technology (FhG-IWES) and Ingenieurbüro für neue Energien (IFNE), Berlin, Stuttgart, Kassel and Teltow, www.bmu.de/files/pdfs/allgemein/application/pdf/leitstudie2010_bf.pdf
- [BMW] – Bundesministerium für Wirtschaft und Technologie, 2010. *Energieszenarien für ein Energiekonzept der Bundesregierung*, study prepared by EWI, GWS and Prognos on behalf of BMWi, Berlin, www.bmu.de/files/pdfs/allgemein/application/pdf/energieszzenarien_2010.pdf
- Bofinger S. and Heilscher G., 2006. *Solar Electricity Forecast – Approaches and First Results*, Proceedings 21st European Photovoltaic Solar Energy Conference, Dresden, September 4-8
- Bolin B. (ed.), 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual (Volume 3)*, Intergovernmental Panel on Climate Change (IPCC), Geneva, www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch1ref1.pdf
- Bolman C., Boas R., Farber M., Meyers M., Porter C., Rogol M., Song J., Tracy P., Trangucci R., Zuboff G., 2011. *Solar Annual 2010-2011: Cash In*, Photon Consulting, Boston
- Bolton J.R., 1978. *Solar Fuels*, Science, 202, 705-711

- Bonnet D. and Rabenhorst H., 1972. New results on the development of a thin film p-CdTe/n-CdS heterojunction solar cell, Proceedings 9th IEEE Photovoltaic Specialists Conference, Silver Springs, May 2-4
- Bopp G. and Lippkau A., 2008. World-wide overview about design and simulation tools for hybrid PV systems, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Borges Neto M.R., Carvalho P.C.M., Carioca J.O.B., Canafistula F.J.F., 2010. Biogas/photovoltaic hybrid power system for decentralized energy supply of rural areas, Energy Policy, doi:10.1016/j.enpol.2010.04.004
- Borsukiewicz-Gozdur A., 2010. Dual-fluid-hybrid power plant co-powered by low-temperature geothermal water, Geothermics, 39, 170-176
- Bossel U., 2005. On the Way to a Sustainable Energy Future, International Conference Intelec '05, Berlin, September 18-22, www.efcf.com/reports/
- Bosworth M. and San Segundo J.R., 2011. Intermediate-Band-Solarzellen: Brücke über die Lücke, Photon – Das Solarstrom-Magazin, 2011(2), 62-63
- [BP] – British Petroleum, 2009. BP Statistical Review of World Energy, BP, London, www.bp.com/statisticalreview
- [BP] – British Petroleum, 2010. BP Statistical Review of World Energy, BP, London, www.bp.com/statisticalreview
- [BP] – British Petroleum, 2011. BP Statistical Review of World Energy, BP, London, www.bp.com/statisticalreview
- BP Solar, BP Solar's EnergyMax solar electric ground systems, BP Solar, London, www.bp.com/sectiongenericarticle.do?categoryId=9019614&contentId=7036810
- Boulton W., Lepage M., Coulson B., Martin T., Hanna E., Victor P., Miller E., Spencer S., Lourie B., Hanna R., 2005. Cost Benefit Analysis: Replacing Ontario's Coal-Fired Electricity Generation, study on behalf of Ontario Ministry of Energy prepared by DSS Management Consultants and RWDI Air, Toronto, April, www.mei.gov.on.ca/en/pdf/electricity/coal_cost_benefit_analysis_april2005.pdf
- Boyce M.P., 2010. Handbook for Cogeneration and Combined Cycle Power Plants, 2nd ed., ASME Press
- Brakmann G., 2007. Integrated Solar Combined Cycle Power Plants in Egypt and Morocco, Clean Energy Power, Berlin, January 24-25
- Braun J.E. and Mitchell J.C., 1983. Solar Geometry for Fixed and Tracking Surfaces, Solar Energy, 31, 439-444
- Braun M., Degner T., Glotzbach T., Saint-Drenan Y.-M., 2008. Value of PV Energy in Germany - Benefit from the Substitution of Conventional Power Plants and Local Power Generation, Proceedings 23rd European Photovoltaic Solar Energy Conference, Valencia, September 1-5
- Bremen von L., Saleck N., Gräwe U., Tambke J., Heinemann D., 2006. Meteorological Models for Prediction and Simulation of Wind Power, Workshop Energiemeteorologie, ForschungsVerbund Sonnenenergie (FVS), Berlin, November 2, www.fvee.de/fileadmin/publikationen/Workshopbaende/ws2006/ws_2006.pdf
- Breyer Ch., 2007. Concentrating Solar Power – Global Potential and Application in the United Arab Emirates, Diploma thesis, Clausthal University of Technology
- Breyer Ch. and Knies G., 2009. Global Energy Supply Potential of Concentrating Solar Power, Proceedings SolarPACES 2009, Berlin, September 15-18
- Breyer Ch., Gerlach A., Hlusiak M., Peters C., Adelmann P., Winiecki J., Schützeichel H., Tsegaye S., Gashie W., 2009a. Electrifying the Poor: Highly economic off-grid PV Systems in Ethiopia – A Basis for sustainable rural Development, Proceedings 24th European Photovoltaic Solar Energy Conference, Hamburg, September 21-25, DOI: 10.4229/24thEUPVSEC2009-SEP.2.3
- Breyer Ch., Gerlach A., Mueller J., Behacker H., Milner A., 2009b. Grid-Parity Analysis for EU and US regions and market segments – Dynamics of Grid-Parity and Dependence on Solar Irradiance, local Electricity Prices and PV Progress Ratio, Proceedings 24th European Photovoltaic Solar Energy Conference, Hamburg, September 21-25, DOI:10.4229/24thEUPVSEC2009-6DV.2.34
- Breyer Ch., 2010a. How favourable is PV?, Frühjahrssitzung Arbeitskreis Energie der, Deutsche Physikalische Gesellschaft (DPG-AKE), Bad Honnef, May 6, www.uni-saarland.de/fak7/fze/AKE_Archiv/AKE2010F/AKE2010F_Vortraege/AKE2010F_02Breyer_PV-HowFavourable.pdf

- Breyer Ch., 2010b. Value of Solar PV Electricity in MENA Region, Casablanca Forum: Large-Scale Solar Power in MENA: Vision and Reality, Casablanca, June 15-16, http://www.casablanca-forum.org/media/material/Q-Cells_ValueOfSolarPVelectricityInMENAregion_CasablancaForum_cb_final_print_100616.pdf
- Breyer Ch., Birkner Ch., Kersten F., Gerlach A., Stryi-Hipp G., Goldschmidt J.Ch., Montoro D.F., Riede M., 2010c. Research and Development Investments in PV – A limiting Factor for a fast PV Diffusion?, Proceedings 25th European Photovoltaic Solar Energy Conference/ WCPEC-5, Valencia, September 6-10, DOI: 10.4229/25thEUPVSEC2010-6CV.5.22
- Breyer Ch. and Gerlach A., 2010. Global Overview on Grid-Parity Event Dynamics, Proceedings 25th European Photovoltaic Solar Energy Conference/ WCPEC-5, Valencia, September 6-10, DOI: 10.4229/25thEUPVSEC2010-6CV.4.11
- Breyer Ch. and Schmid J., 2010. Population Density and Area weighted Solar Irradiation: global Overview on Solar Resource Conditions for fixed tilted, 1-axis and 2-axes PV Systems, Proceedings 25th European Photovoltaic Solar Energy Conference/ WCPEC-5, Valencia, September 6-10, DOI: 10.4229/25thEUPVSEC2010-4BV.1.91
- Breyer Ch., Gerlach A., Beckel O., Schmid J., 2010d. Value of Solar PV Electricity in MENA Region, IEEE EnergyCon, Manama, December 18-22
- Breyer Ch., Gerlach A., Schäfer D., Schmid J., 2010e. Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, IEEE EnergyCon, Manama, December 18-22
- Breyer Ch., Hlusiak M., Huljic D., 2010f. Kraftwerk, German Patent and Trademark Office, AZ102010017762.8, filed in July 6
- Breyer Ch., Rieke S., Sterner M., Schmid J., 2011a. Hybrid PV-Wind-Renewable Power Methane Power Plants – A Potential Cornerstone of Global Energy Supply, Proceedings 26th European Photovoltaic Solar Energy Conference, Hamburg, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.31
- Breyer Ch., Werner C., Adelmann P., 2011b. Small Photovoltaic Applications in Regions of low Electrification: High Demand, fast financial Amortization and large Market Potential, Proceedings 2nd Symposium Small PV-Applications, Ulm, June 6-7
- Breyer Ch., Werner C., Rolland S., Adelmann P., 2011c. Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, Proceedings 26th European Photovoltaic Solar Energy Conference, Hamburg, September 5-9, DOI: 10.4229/26thEUPVSEC2011-5BV.1.45
- Broe De A., Betancur S., Coninck De R., Rattinhe Van K., Berte J., 2008. The Belgian Antarctic Research Station runs on Wind and Sun, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Bruhn M., 2002. Hybrid geothermal-fossil electricity generation from low enthalpy geothermal resources: geothermal feedwater preheating in conventional power plants, *Energy*, 27, 329-346
- [BSW] – Bundesverband Solarwirtschaft, 2010. Wegweiser Solarwirtschaft: PV-Roadmap 2020, study on behalf of BSW prepared by Roland Berger Strategy Consultants and Prognos, Berlin, www.solarwirtschaft.de/fileadmin/content_files/wegweiser_sw_pvrn-lang.pdf
- Bullard N., 2010. Global STEG market overview 2011 – charging the steam lines, Bloomberg New Energy Finance, research note, December 16
- Bumm P., 2010. Solar Power, Cheuvreux – Crédit Agricole Group, Frankfurt (Main), March 4
- Bundtland G.H. (ed.), 1987. Our Common Future, World Commission on Environment and Development, Oxford University Press, Oxford
- Burch G.D., 2001. Hybrid renewable energy systems, Proceedings U.S. DOE Natural Gas/ Renewable Energy Hybrids Workshops, Golden, August 21, www.netl.doe.gov/publications/proceedings/01/hybrids/GaryBurch8.21.01.pdf
- Burgelman M., 2006. Cadmium Telluride Thin Film Solar Cells: Characterization, Fabrication and Modeling, in: Poortmans J. and Arkhipov V., (eds.), Thin Film Solar Cells: Fabrication, Characterization and Applications, John Wiley & Sons, Chichester

C

- Cabraal A., 2010. Photovoltaics in the World Bank Group Portfolio, in: Palz W. (ed.), Power for the World – The Emergence of Electricity from the Sun. Pan Stanford Publishing, Singapore

- Callendar G.S., 1938. The Artificial Production of Carbon Dioxide and its Influence on Temperature, *Quarterly Journal of Royal Meteorological Society*, 64, 223-237
- Carlson D.E. and Wronski C.R., 1976. Amorphous silicon solar cell, *Applied Physics Letters*, 28, 671-673
- Carter J., 1979. Solar Energy: Message from the President of the United States Transmitting Proposals for a National Solar Energy Strategy, H. Doc. 96-154
- [CEA] – Central Electricity Authority, 2010. Integration of Solar Systems with Thermal/ Hydro Power Stations, Report of Sub-Group II & III, CEA, New Delhi, January, www.cea.nic.in/more_upload/task_force_solar_report.pdf
- [CERC] - Central Electricity Regulatory Commission, 2010. Electricity Price Data, New Delhi, India, www.cercind.gov.in
- Ceuster De D., Cousins P., Rose D., Vicente D., Tipones P., Mulligan W., 2007. Low cost, high volume production of >22% efficiency silicon solar cells, *Proceedings 22nd European Photovoltaic Solar Energy Conference*, September 3-7, 816-819
- Chaurey A. and Kandpal T.C., 2009. Solar lanterns for domestic lighting in India: Viability of central charging station model, *Energy Policy*, 37, 4910-4918
- Chamberlain G.A., 1983. Organic solar cells: A review, *Solar Cells*, 8, 47-83
- Chan S.H., Ho H.K., Tian Y., 2002. Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant, *Journal of Power Sources*, 109, 111-120
- Chapin D.M., Fuller C.S., Pearson G.L., 1954. A new silicon p-n junction photocell for converting solar radiation into electrical power, *Journal of Applied Physics*, 25, 676-677
- Cheddie D.F., 2011. Thermo-economic optimization of an indirectly coupled solid oxide fuel cell/gas turbine hybrid power plant, *International Journal of Hydrogen Energy*, 36, 1702-1709
- Chen H.H., Kang H.-Y., Lee A.H.I., 2010. Strategic selection of suitable projects for hybrid solar-wind power generation systems, *Renewable and Sustainable Energy Reviews*, 14, 413-421
- Cherry W., 1955. Military considerations for a photovoltaic solar energy converter, *Trans. Of the Conference on the Use of Solar Energy*, University of Arizona Tucson, November 1, 5, 127-132
- Christiansson L., 1995. Diffusion and Learning Curves of Renewable Energy Technologies, International Institute for Applied Systems Analysis (IIASA), Laxenburg, WP-95-126, www.iiasa.ac.at/Admin/PUB/Documents/WP-95-126.pdf
- Clark W. (ed.), 1980. Dispersed, decentralized and renewable energy sources: Alternatives to national vulnerability and war, Energy and Defense Project, Federal Emergency Management Agency, Washington, DCPA 01-79-C-0320
- Cochran T.B., Feiveson H.A., Patterson W., Pshakin G., Ramana M.V., Schneider M., Suzuki T., Hippel von F., 2010. Fast Breeder Reactor Programs: History and Status, International Panel on Fissile Materials, Princeton, www.fissilematerials.org/blog/rr08.pdf
- Cohen G., Kearney D., Kolb G., 1999. Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants, Sandia National Laboratories, Albuquerque, SAND99-1290, www.osti.gov/bridge/product.biblio.jsp?osti_id=8378
- Collares-Pereira M. and Rabl A., 1979. The Average Distribution of Solar Radiation – Correlations Between Diffuse and Hemispherical and Between Daily and Hourly Insolation Values, *Solar Energy*, 22, 155-164
- Conibeer G., Green M.A., König D., Perez-Wurfl, I., Huang S., Hao X., Di D., Shi L., Shrestha S., Puthen-Veetil B., So Y., Zhang B., Wan Z., 2010. Silicon Quantum Dot Based Solar Cells: Addressing the Issues of Doping, Voltage and Current Transport, *Proceedings 25th European Photovoltaic Solar Energy Conference*, Valencia, September, 6-10
- Cornett A., 2008. Guidance for Assessing Tidal Current Energy Resources, report prepared by Canadian Hydraulics Centre for International Energy Agency Implementation Agreement on Ocean Energy Systems (IEA-OES), Lisbon, www.iea-oceans.org/_fich/6/Report_T02-1.2.pdf
- Curtright A.E., Morgan M.G., Keith D.W., 2008. Expert Assessments of Future Photovoltaic Technologies, *Environmental Science & Technology*, 42, 9031-9038
- Czisch G., 2005. Szenarien zur zukünftigen Stromversorgung - Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien, PhD Thesis, Faculty of Electrical Engineering and Computer Science, University of Kassel, <https://kobra.bibliothek.uni-kassel.de/bitstream/urn:nbn:de:hebis:34-200604119596/1/DissVersion0502.pdf>

D

- Daly H.E., *Steady-State Economics*, 2nd ed., Island Press, Washington, 1991
- Dany C., 2009. Light for Ethiopia, *Sun & Wind Energy*, 2009(2), 68-73
- DeLeonardo G., Scholz M., Jones C., 2011. FlexEfficiency* 50: Combined Cycle Power Plant, GE Energy, Fairfield, http://media.ge-flexibility.com/downloads/FlexEfficiency_50_CC_Plant_White_Paper.pdf
- Delucchi M.A. and Jacobson M.Z., 2011. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies, *Energy Policy*, 39, 1170-1190
- Denault M., Dupuis D., Couture-Cardinal S., 2009. Complementarity of hydro and wind power: Improving the risk profile of energy inflows, *Energy Policy*, 37, 5376-5384
- Denholm P. and Margolis R.M., 2007. Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies, *Energy Policy*, 35, 4424-4433
- Diaf S., Diaf D., Belhamel M., Haddadi M., Louche A., 2007. A methodology for optimal sizing of autonomous hybrid PV/wind system, *Energy Policy*, 35, 5708-5718
- Diamond J., 1999. *Guns, Germs, and Steel: The Fates of Human Societies*, W. W. Norton & Company, New York
- Diesel & Gas Turbine Worldwide, 2008. 2008 32nd Power Generation Order Survey, Diesel & Gas Turbine Worldwide, 2008(10), www.dieselturbine.com/pdf/power_2008.pdf
- [Dii] – Desertec Industry Initiative, 2010. Energy from deserts – Bringing the Desertec Vision into reality, Dii, Munich, www.dii-eumena.com/fileadmin/Daten/Downloads/Dii-Brochure_EN.pdf
- Dittrich H., Herz K., Eberhardt J., Schumm G., 1997. First Thin Film Solar Cells Based on Sulfosalt Minerals, *Proceedings 14th European Photovoltaic Solar Energy Conference*, Barcelona, June 30 – July 4
- Dittrich H., Bieniok A., Brendel U., Grodzicki M., Topa D., 2007. Sulfosalts – A new class of compound semiconductors for photovoltaic applications, *Thin Solid Films*, 515, 5745-5750
- Doll R., LCOE: an overview, private communication, Thalheim, 2009, July 16
- Dominik H., 1930. Wunschträume beim Jahreswechsel, *Beilage: Technik der Zeit*, Berliner Tageblatt, Berlin, December 31
- [DPG-AKE] - Deutsche Physikalische Gesellschaft – Arbeitskreis Energie, 2010. Elektrizität: Schlüssel zu einem nachhaltigen und klimaverträglichen Energiesystem, DPG-AKE, Bad Honnef, www.dpg-physik.de/veroeffentlichung/broschueren/studien/energie_2010.pdf
- Dürschmidt W., Zimmermann G., Böhme D., (eds.), 2006. *Renewable Energies: Innovations for the Future*, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, www.erneuerbare-energien.de/files/english/renewable_energy/downloads/application/pdf/broschuere_ee_innovation_eng.pdf
- Duffie J.A. and Beckmann W.A., 2006. *Solar Engineering of Thermal Processes*, John Wiley & Sons., Hoboken
- Duguid B. (ed.), 2010. *Ontario's Long-Term Energy Plan*, Ontario Ministry of Energy, Toronto, www.mei.gov.on.ca/en/pdf/MEI_LTEP_en.pdf

E

- Ebert S., Metschies G.P., Schmid D., Wagner A., 2009. *International Fuel Prices 2009 6th Edition*, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), Eschborn, www.gtz.de/de/dokumente/gtz2009-en-ifp-full-version.pdf
- [EC] – European Commission, 2008. *European Energy and Transport: Trends to 2030 – update 2007*, EC DG Energy and Transport, Brussels, April, http://ec.europa.eu/dgs/energy_transport/figures/trends_2030_update_2007/energy_transport_trends_2030_update_2007_en.pdf
- [EC] - European Commission, 2008. *Second Strategic Energy Review: Energy Sources, Production Costs and Performance of Technologies, for Power Generation, Heating and Transport*, EC, Brussels, SEC(2008) 2872,

- [www.ipex.eu/ipex/webdav/site/myjahiasite/groups/CentralSupport/public/2008/SEC_2008_2872/COM_SEC\(2008\)2872_EN.pdf](http://www.ipex.eu/ipex/webdav/site/myjahiasite/groups/CentralSupport/public/2008/SEC_2008_2872/COM_SEC(2008)2872_EN.pdf)
- [EC] - European Commission, 2009. R&D Investment in the Priority Technologies of the European Strategic Energy Technology Plan, EC, Brussels, SEC(2009) 1296, http://ec.europa.eu/energy/technology/set_plan/doc/2009_comm_investing_development_low_carbon_technologies_en.pdf
- [EC] - European Commission, 2009. The 2009 EU Industrial R&D Investment Scoreboard, EC DG Research – Joint Research Centre, Institute for Prospective Technological Studies, Seville, http://iri.jrc.ec.europa.eu/research/scoreboard_2009.htm
- [EC] - European Commission, 2010. Eurostat, Environment and energy, EC, Brussels, <http://epp.eurostat.ec.europa.eu>
- [ECF] - European Climate Foundation, 2010. Roadmap 2050: Practical Guide to a Prosperous low-carbon Europe, ECF, Brussels, www.europeanclimate.org
- [EEPCo] - Ethiopian Electric Power Company, 2007. Electricity Power Industry Master Plan Program, EEPCo, Addis Ababa, www.eepco.gov.et/psdp_progsummary.html
- [EEX] – European Energy Exchange, 2011. EU Emission Allowances – Prices and Trading Volumes, EEX, Leipzig, www.eex.com/en/Market%20Data/Trading%20Data/Emission%20Rights
- [EIA] - Energy Information Administration, 2008. Annual Energy Outlook 2008 – With Projections to 2030, EIA – An agency of US Department of Energy (DoE), Washington, DOE/EIA-0383(2008), June, [www.eia.gov/oiaf/aeo/pdf/0383\(2008\).pdf](http://www.eia.gov/oiaf/aeo/pdf/0383(2008).pdf)
- [EIA] - Energy Information Administration, 2009. Gasoline and Diesel Fuel Update, EIA - An agency of US Department of Energy (DoE), Washington, www.eia.doe.gov/oog/info/gdu/gasdiesel.asp
- [EIA] - Energy Information Administration, 2010. Electricity U.S. Data, EIA - An agency of US Department of Energy (DoE), Washington, www.eia.doe.gov/fuelelectric.html
- [EIA] - Energy Information Administration, 2010. International Electricity Prices and Fuel Costs, EIA - An agency of US Department of Energy (DoE), Washington, www.eia.doe.gov/emeu/international/electricityprice.html
- Einstein A., 1905. Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt, *Annalen der Physik*, 17, 132-148
- Emberger H., Schmid E., Gobrecht E., 2005. Fast Cycling Capabilities for New Plants and Upgrade Opportunities, Siemens Power Generation, Erlangen, Power-Gen, Asia, Singapore, September 13-15, www.energy.siemens.com/co/pool/hq/energy-topics/pdfs/en/combined-cycle-power-plants/4_Fast_Cycling_Capability.pdf
- Enercon, 2009. Wind Turbines – Product Overview, Status 03/09, Enercon, Aurich, www.enercon.de
- Enercon, 2010. Wind Turbines – Product Overview, Status 01/10, Enercon, Aurich, www.enercon.de
- [EPIA] - European Photovoltaic Industry Association, 2008. Photovoltaic industry substantially revises its target to supply 12% of European electricity demand by 2020, EPIA, Brussels, September 4, www.epia.org/fileadmin/EPIA_docs/documents/press/380904_PR_12_Electricity_EN_FINAL.pdf
- [EPIA] - European Photovoltaic Industry Association, 2008. Solar Generation V – 2008: Solar electricity for over one billion people and two million jobs by 2020, EPIA and Greenpeace International, Brussels and Amsterdam, www.epia.org/publications/epia-publications.html
- [EPIA] – European Photovoltaic Industry Association, 2009. SET FOR 2020: Solar Photovoltaic Electricity – A mainstream power source in Europe by 2020, EPIA, Brussels
- [EPIA] - European Photovoltaic Industry Association, 2010. EPIA Annual Report 2009, EPIA, Brussels, 2010, www.epia.org/index.php?eID=tx_nawsecuredl&u=0&file=fileadmin/EPIA_docs/publications/epia/EPIA_Annual_Report_2009.pdf&t=1287413686&hash=f747237f172ef6a3b524134d40bb7af7
- [EPIA] – European Photovoltaic Industry Association, 2010. Global Market Outlook for Photovoltaics until 2014, EPIA, Brussels, www.epia.org/fileadmin/EPIA_docs/public/Global_Market_Outlook_for_Photovoltaics_until_2014.pdf
- [EPIA] – European Photovoltaic Industry Association, 2011. Global Market Outlook for Photovoltaics until 2015, EPIA, Brussels, www.epia.org/publications/photovoltaic-publications-global-market-outlook/global-market-outlook-for-photovoltaics-until-2015.html

- [EPIA] - European Photovoltaic Industry Association, 2011. Solar Generation 6 – Solar Photovoltaic Electricity Empowering the World, EPIA and Greenpeace International, Brussels and Amsterdam,
www.epia.org/index.php?eID=tx_nawsecuredl&u=0&file=fileadmin/EPIA_docs/documents/SG6/Solar_Generation_6_2011_Full_report_Final.pdf
- Epstein P.R., Buonocore J.J., Eckerle K., Hendryx M., Stout B.M., Heinberg R., Clapp R.W., May B., Reinhart N.L., Ahern M.M., Doshi S.K., Glustrom L., 2011. Full cost accounting for the life cycle of coal, *Annals of the New York Academy of Sciences*, 1219, 73-98
- EU PV Technology Platform, 2007. A Strategic Research Agenda for Photovoltaic Solar Energy Technology, Working Group 3: Science, Technology and Applications, Brussels,
http://ec.europa.eu/research/energy/pdf/sra_photovoltaic_en.pdf
- [EWEA] – European Wind Energy Association, 2009. Wind Energy – The Facts: A guide to the technology, economics and future of wind power, Earthscan, London

F

- Fahl U., Frondel M., Löschel A., (eds.), 2010. Die Entwicklung der Energiemärkte bis 2030: Energieprognose 2009, study on behalf of Bundesministerium für Wirtschaft und Technologie (BMWi) prepared by Institut für Energiewirtschaft und Rationelle Energieanwendung (IER), Rheinisch-Westfälisches Institut für Wirtschaftsforschung (RWI), Zentrum für Europäische Wirtschaftsforschung (ZEW), Stuttgart, Essen, Mannheim, March, ftp://ftp.zew.de/pub/zew-docs/gutachten/Energieprognose_2009_Hauptbericht.pdf
- Fath, P., Herbst, W., Jooß, W., Feilmeier, F.-J., 2009. Webcast: centrotherm's grid parity factory. centrotherm photovoltaics, Blaubeuren, February 4,
www.centrotherm.de/fileadmin/ct_group/Downloads/IR_Sonstige/Konferenzen/090204_WebCast_IntegrierteFabrik_EN.pdf
- Fath P., 2011. Fully-integrated c-Si module production towards 0.60 €/Wp, Photon's 6th PV Production Equipment Conference (c-Si), Berlin, April 14
- Fell H.-J., Kotting-Uhl S., Koczy U., Behm C., Hettlich P., Scheel C., Friedl P., Eichelbrönnner T., 2006. Die Klimakatastrophe lässt sich nur mit einer Nullemissionsstrategie abwenden, Bündnis 90 Die Grünen, Berlin, www.cornelia-behm.de/cms/default/dokbin/156/156479.klimastrategiepapier.pdf
- Fell H.-J., 2010. Will This Work? Is It Realistic? – Thoughts and Acts of a Political Practitioner with a Solar Vision, in: Palz W. (ed.), *Power for the World – The Emergence of Electricity from the Sun*. Pan Stanford Publishing, Singapore
- Fiedler F., Pazmino V., Berruezo I., Maison V., 2008. PV-Wind hybrid Systems for Swedish Locations, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- First Solar, 2010. 2009 Annual Report, First Solar, Tempe, February 24,
http://files.shareholder.com/downloads/FSLR/1312112662x0x457364/41B0F663-25E3-4633-834C-F59C23F7EF7A/Request-2009_annual_report.pdf
- First Solar, 2010. Q2 2010 Earnings Call, First Solar, Tempe, July 29, www.firstsolar.com,
<http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9NTU1MjV8Q2hpbGRJRDR0tMXxUeXBIPTM=&t=1>
- First Solar, 2011. First Solar Acquires RayTracker Inc., First Solar, Tempe, press release, January 7,
<http://investor.firstsolar.com/phoenix.zhtml?c=201491&p=irol-newsArticle&ID=1514073&highlight=>
- First Solar, 2011. Q1 2011 Earnings Call, First Solar, Tempe, May 3, www.firstsolar.com,
http://files.shareholder.com/downloads/FSLR/1312112662x0x477645/75afb26c-09bd-4237-8718-6dc7d098bf41/Q12011_Earnings_Call_FINAL.pdf
- First Solar, 2011. First Solar Sets World Record for CdTe Solar PV Efficiency: 17.3 Percent Efficiency Confirmed by NREL, First Solar, Tempe, press release, July 26,
<http://investor.firstsolar.com/releasedetail.cfm?ReleaseID=593994>
- Fischer H., and Pschunder W., 1977. Low-Cost Solar Cells Based on Large-Area Unconventional Silicon, *IEEE Transactions on Electron Devices*, 24, 438-442
- Fischer W.J., 2010. SGT5-8000H / Irsching 4, on the way to 60% world record efficiency and path to 60 Hz SGT6-8000H, Siemens Energy Sector, Erlangen, Conference of the Electric Power Supply Industry (CEPSI), Taipei, October 24-28, www.aesieap0910.org/upload/File/PDF/4-

- Technical%20Sessions/TS34/TS3401/TS3401_FP.pdf
- Fisher J., Wilson R., Hughes N., Wittenstein M., Biewald B., 2011. Benefits of Beyond BAU: Human Social and Environmental Damages Avoided through the Retirement of the US Coal Fleet, prepared by Synapse Energy Economics for Civil Society Institute, Cambridge, January 25, www.civilsocietyinstitute.org/012511_Beyond_BAU_report.pdf
- Focken U., 2011. Feed in of PV-power: Benefits of a good prognosis, Photon's 6th Solar Electric Utility Conference, Berlin, April 14
- Focken U., 2011. private communication, April 14
- Førsund F.R., Singh B., Jensen T., Larsen C., 2008. Phasing in wind-power in Norway: Network congestion and crowding-out of hydropower, *Energy Policy*, 36, 3514-3520
- Fraidenraich N. and Vilela O.C., 2007. Dynamic Behaviour of Water Wells Coupled to PV Pumping Systems, *Progress in Photovoltaics: Research and Applications*, 15, 317-330
- Frankl P., Masini A., Gamberale M., Toccaceli D., 1998. Simplified Life-cycle Analysis of PV Systems in Buildings: Present Situation and Future Trends, *Progress in Photovoltaics: Research and Applications*, 6, 137-146
- Fritsche U., Rausch L., Schmidt K., 2007. Treibhausgasemissionen und Vermeidungskosten der nuklearen, fossilen und erneuerbaren Strombereitstellung, Öko-Institute, Darmstadt, www.oeko.de/oekodoc/318/2007-008-de.pdf
- Fronzel M., Ritter N., Schmidt C.M., Vance C., 2010. Economic impacts from the promotion of renewable energy technologies: The German experience, *Energy Policy*, 38, 4048-4056.
- Fthenakis V. and Alsema E., 2006. Photovoltaic Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004-early 2005 Status, *Progress in Photovoltaics: Research and Applications*, 14, 275-280
- Fthenakis V.M., Kim H.C., Alsema E., 2008. Emissions from Photovoltaic Life Cycles, *Environmental Science & Technology*, 42, 2168-2174; plus supporting information
- Fthenakis V.M. and Kim H.C., 2011. Photovoltaics: Life-cycle analyses, *Solar Energy*, in press, doi:10.1016/j.solener.2009.10.002

G

- Gabler H., 2008. Photovoltaik zur netzfernen Energieversorgung, 23. Symposium Photovoltaische Energieversorgung, Bad Staffelstein, March, 5-7
- Gagnon L., Bélanger C., Uchiyama Y., 2002. Life-cycle assessment of electricity generation options: The status of research in year 2001, *Energy Policy*, 30, 1267-1278
- Garcia-Valverde R., Cherni J.A., Urbina A., 2010. Life cycle analysis of organic photovoltaic technologies, *Progress in Photovoltaics: Research and Applications*, 18, 535-558
- Gasch R. and Twele J., (eds.), 2010. Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb, 6th ed., Vieweg + Teubner, Weisbaden
- Geidl M. and Andersson G., 2006. Operational and structural optimization of multi-carrier energy systems, *European Transactions on Electrical Power*, 16, 463-477
- Geidl M., 2007. Integrated Modeling and Optimization of Multi-Carrier Energy Systems, PhD Thesis, ETH Zurich, www.eeh.ee.ethz.ch/uploads/tx_ethpublications/eth-diss-17141.pdf
- Geidl M. and Andersson G., 2007. Optimal Power Flow of Multiple Energy Carriers, *IEEE Transactions on Power Systems*, 22, 145-155
- Gerlach A., 2009. Wirtschaftlichkeit von Photovoltaik in nicht subventionierten Märkten, Diploma thesis [supervised by the author of this PhD thesis], Clausthal University of Technology
- Gerlach A.-K., 2011. Interaction of Solar and Wind Resources for Photovoltaic and Wind Power Plants, Diploma thesis [supervised by the author of this PhD thesis], Faculty of Electrical Engineering and Computer Science, University of Kassel
- Gerlach A.-K., Stetter D., Schmid J., Breyer Ch., 2011. PV and Wind Power – Complementary Technologies, *Proceedings 26th European Photovoltaic Solar Energy Conference*, Hamburg, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.32
- Gharghi M., Bai H., Stevens G., Sivothythaman S., 2005. Modeling and Simulation of Spherical Solar Cells, *Proceedings 31st IEEE Photovoltaic Specialists Conference*, Lake Buena Vista, January 3-7
- Ghermandi A. and Messalem R., 2009. Solar-driven desalination with reverse osmosis: the state of the art, *Desalination and Water Treatment*, 7, 285-296
- Gipe P., 1999. *Wind Energy Basics – A Guide to Small and Micro Wind Systems*, Chelsea Green

- Publishing, White River Junction
- Glasnovic Z. and Margeta J., 2009. Optimal Sizing of Photovoltaic-hydro Power Plant, *Progress in Photovoltaics: Research and Applications*, 17, 542-553
- Görig M., 2011. Solare Brüter – unter besonderer Berücksichtigung der Erntefaktoren von PV und Windkraft, Bachelor thesis [supervised by the author of this PhD thesis], Anhalt University of Applied Sciences
- Goetzberger A. and Greubel W., 1977. Solar Energy Conversion with Fluorescent Collectors, *Applied Physics*, 14, 123-139
- Götzberger A. and Stahl W., 1985. Global Estimation of Available Solar Radiation and Cost of Energy for Tracking and Non-tracking PV-Systems, *Proceedings 18th IEEE Photovoltaic Specialists Conference*, Las Vegas, October 21-25
- Goetzberger A., Knobloch J., Voss Bernhard, 1998. *Crystalline Silicon Solar Cells*, John Wiley & Sons, Chichester
- Goldberg M. (ed.), 2000. Federal Energy Subsidies: Not all Technologies are created equal, Renewable Energy Policy Project, Washington, www.repp.org/repp_pubs/pdf/subsidies.pdf
- Goldschmidt J.C., 2009. Novel Solar Cell Concepts, PhD thesis, faculty of physics, University of Konstanz
- Goldschmidt J.C., Peters M., Bösch A., Helmers H., Dimroth F., Glunz S.W. and Willeke G., 2009. Increasing the efficiency of fluorescent concentrator systems, *Solar Energy Materials and Solar Cells*, 93, 176-182
- Gombert A., Gerstmaier T., Heile I., Riesen van S., Röttger M., Wüllner J., 2010. Analysis of Long Term Operation Data of Flatcon CPV Systems, *Proceedings 25th European Photovoltaic Solar Energy Conference*, Valencia, September 6-10
- Gommes R., Petrassi F., Thomas G., 1999. Global Climate Maps: Map of biomass potential, Food and Agriculture Organization (FAO) of the United Nations, Rome, www.fao.org/WAICENT/FAOINFO/sustdev/Eldirect/climate/EIsp0002.htm
- Gorn M., 2008. Most Economic Design for Profitable Investment and Experiences during Implementation of Solar PV-Diesel Hybrid Systems: The case of Remote Villages in Central China Gansu, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- Grätzel M., 2006. Nanocrystalline Injection Solar Cells, in: Poortmans J. and Arkhipov V., (eds.), *Thin Film Solar Cells: Fabrication, Characterization and Applications*, John Wiley & Sons, Chichester
- Grama S., Wayman E., Bradford T., 2008. *Concentrating Solar Power - Technology, Cost, and Markets*, Prometheus Institute for Sustainable Development, Chicago, www.prometheus.org
- Graw K.-U., 2007. Wellenkraftwerke – Energiereservoir Ozean, in: Bührke T. and Wengenmayr R., (eds.), *Erneuerbare Energie: Alternative Energiekonzepte für die Zukunft*, WILEY-VCH, Weinheim
- Gredler C., 2008. Das Wachstumspotenzial der Photovoltaik und der Windkraft – divergierende Wahrnehmungen zentraler Akteure, Diploma thesis, University Salzburg
- Gredler C., 2009. Update of PV and wind power market development compared to forecasts, private communication, November 13
- Green M.A., 1998. *Solar Cells: Operating Principles, Technology and System Applications*, The University of New South Wales, Sydney
- Green M.A., 2003. *Third Generation Photovoltaics: Advanced Solar Energy Conversion*, Springer-Verlag, Berlin
- Green M.A., 2006. Improved Estimates for Te and Se Availability from Cu Anode Slimes and Recent Price Trends, *Progress in Photovoltaics: Research and Applications*, 14, 743-751
- Green M.A., Conibeer G., König D., Shrestha S., Huang S., Aliberti P., Treiber L., Patterson R., Puthen-Veetil B., Hsieh A., Luque A., Marti A., Linares P.G., Cánovas E., Antolín E., Fuertes-Marrón D., Tablero C., Hernández E., Guillemoles J.F., Huang L., Schmidt T., Clady R., Tayebjee M., 2010. Recent Progress with Hot Carrier Solar Cells, *Proceedings 25th European Photovoltaic Solar Energy Conference*, Valencia, September, 6-10
- Green M.A., Emery K., Hishikawa Y., Warta W., 2010. Solar cell efficiency tables (version 36), *Progress in Photovoltaics: Research and Applications*, 18, 346-352

- Green M.A., Emery K., Hishikawa Y., Warta W., 2011. Solar cell efficiency tables (version 37), Progress in Photovoltaics: Research and Applications, 19, 84-92
- Grimmer D.P., 1981. Solar energy breeders, Solar Energy, 26, 49-53
- Grober U., 2010. Die Entdeckung der Nachhaltigkeit, Verlag Antje Kunstmann, München
- Grubler A., 2010. The cost of the French nuclear scale-up: A case of negative learning by doing, Energy Policy, 38, 5174–5188
- Grubler A., Nakicenovic N., Victor D.G., 1999. Dynamics of energy technologies and global change, Energy Policy, 27, 247-280
- Grunow P. and Lehmann S., 2009. General assessment of the reliability of crystalline silicon photovoltaic modules, Photovoltaik Institut Berlin, Berlin
- [GTZ] - Deutsche Gesellschaft für Technische Zusammenarbeit, 2007. Energy-policy Framework Conditions for Electricity Markets and Renewable Energies, Division Environment and Infrastructure, GTZ, Eschborn, www.gtz.de/de/dokumente/en-windenergy-countrystudy-2007.pdf
- Günes S. and Sariciftci N.S., 2008. Hybrid solar cells, Inorganica Chimica Acta, 361, 581-588
- Günter B., Karau T., Kastner E.-M., Warmuth W., 2011. Berechnung einer risikoadäquaten Versicherungsprämie zur Deckung der Haftpflichtrisiken, die aus dem Betrieb von Kernkraftwerken resultieren, study on behalf of Bundesverband Erneuerbare Energien (BEE) prepared by Versicherungsforen Leipzig, April 1, www.bee-ev.de/_downloads/publikationen/studien/2011/110511_BEE-Studie_Versicherungsforen_KKW.pdf
- Gueymard C.A., Myers D., Emery K., 2002. Proposed Reference Irradiance Spectra for Solar Energy Systems Testing, Solar Energy, 73, 443-467
- Gupta, S., Lu, S., Humphrey A., Srethapramote S., Paradise J., 2010. Global Solar: Sovereign Debt Concerns ... Not a Solar Eclipse, Morgan Stanley Asia, Singapore, May 10
- Gusdorf J., 1992. Energy paybacks and renewable breeders, Energy, 17, 1137-1151
- [GWEC] - Global Wind Energy Council, Global Wind 2008 Report, GWEC, Brussels, 2009, www.gwec.net/fileadmin/documents/Global%20Wind%202008%20Report.pdf
- [GWEC] - Global Wind Energy Council, Global Wind 2009 Report, GWEC, Brussels, 2010, www.gwec.net/fileadmin/documents/Publications/Global_Wind_2007_report/GWEC_Global_Wind_2009_Report_LOWRES_15th.%20Apr..pdf

H

- Hagedorn G., 1989. Kumulierter Energieverbrauch und Erntefaktoren von Photovoltaik-Systemen, Energiewirtschaftliche Tagesfragen, 1989(11), 712-718
- Hammond A.L. and Metz W.D., 1977. Solar Energy Research: Making Solar After the Nuclear Model?, Science, 197, 241-244
- Hao X., Dong G., Yang Y., Xu Y., Li Y., 2007. Coal to Liquid (CTL): Commercialization Prospects in China, Chemical Engineering Technology, 30, 1157-1165
- Hartmann A. and Huhn W., (eds.), 2009. Wettbewerbsfaktor Energie: Neue Chancen für die deutsche Wirtschaft, McKinsey & Company, Frankfurt
- Harvey L.D.D., 1995. Solar-Hydrogen Electricity Generation in the Context of Global CO₂ Emission Reduction, Climatic Change, 29, 53-89
- Hau E., 2008. Windkraftanlagen – Grundlagen, Technik, Einsatz, Wirtschaftlichkeit, 4th edition, Springer-Verlag, Berlin
- Hay J.E. and McKay D.C., 1985. Estimating Solar Irradiance on Inclined Surfaces: A Review and Assessment of Methodologies, International Journal of Solar Energy, 3, 203-240
- Heier S., 2009. Windkraftanlagen – Systemauslegung, Netzintegration und Regelung, 5th edition, Vieweg + Teubner, Wiesbaden
- Heinberg R., 2009. Searching for a miracle: Net energy limits & the fate of industrial society, The International Forum on Globalization and The Post Carbon Institute, San Francisco and Sebastopol, www.postcarbon.org/new-site-files/Reports/Searching_for_a_Miracle_web10nov09.pdf
- Heinemann D., 2006. Energiemeteorologie: Ein Überblick, Workshop Energiemeteorologie, ForschungsVerbund Sonnenenergie (FVS), Berlin, November 2, www.fvee.de/fileadmin/publikationen/Workshopbaende/ws2006/ws_2006.pdf

- Henkel N., Schmid E., Gobrecht E., 2008. Operational Flexibility Enhancements of Combined Cycle Power Plants, Siemens Power Generation, Power-Gen Asia, Kuala Lumpur, October 21-23, www.energy.siemens.com/hq/pool/hq/energy-topics/pdfs/en/combined-cycle-power-plants/OperationalFlexibilityEnhancementsOfCombinedCyclePowerPlants.pdf
- Hering G., 2010. Applied Materials Restructuring – Sans SunFab, Photon International, 2010(8), 60-71
- Hering G., 2011. Survey on cell production 2010: Year of the tiger, Photon International, 2011(3), 186-218
- Himri Y., Boudghene Stambouli A., Draoui B., Himri S., 2008. Techno-economical study of hybrid power system for a remote village in Algeria, *Energy*, 33, 1128-1136
- Hirschberg S. and Bauer C., 2006. Clean Energy for China, *Energie-Spiegel* a publication of the Paul Scherrer Institut, Villingen, No. 17, November, 1-6
- Hirshman W.P. and Schug A., 2010. Von wegen Krise: Solarzellenproduktion im Jahr 2009, *Photon – Das Solarstrom-Magazin*, 2010(4), 38-65
- Hoffmann C., Greiner M., Bremen v. L., Knorr K., Bofinger S., Speckmann M., Rohrig K., 2008. Design of transport and storage capacities for a future European power supply system with a high share of renewable energies, 3rd International Renewable Energy Storage Conference IRES, Berlin, November 24-25
- Hoffmann W., Wieder S., Pellkofer T., 2009. Differentiated Price Experience Curves as Evaluation Tool for Judging the further Development of Crystalline Silicon and Thin Film PV Solar Electricity Products, *Proceedings 24th European Photovoltaic Solar Energy Conference*, Hamburg, September 21–25
- Hoffmann W., 2009. Europe's Ambitious Goals for Making PV Solar a Mainstream Electricity Provider, presentation held at EWE Workshop on PV Trends 2030, Oldenburg, November 10
- Hofmann D. and Emberger H.-M., 2006. Taking Advantage of Market Opportunities through Siemens Reference Power Plants, Siemens Power Generation, Erlangen, www.energy.siemens.com/us/pool/hq/energy-topics/pdfs/en/gas-turbines-power-plants/3_Taking_Advantage_of_Market.pdf
- Horlock J.H., 2002. Combined Power Plants – Including Combined Cycle Gas Turbine (CCGT) Plants, Krieger Publishing, Malabar
- Howarth R.W., Santoro R., Ingraffea A., 2011. Methane and the green house-gas footprint of natural gas from shale formations, *Climate Change*, DOI 10.1007/s10584-011-0061-5
- Hubbert M.K., 1949. Energy from Fossil Fuels, *Science*, 109, 103–109
- Hubbert M.K., 1956. Nuclear Energy and the Fossil Fuels, Spring Meeting of the Southern District, American Petroleum Institute, San Antonio, March 7-9
- Hubbert M.K., 1971. The energy resources on the Earth, in: *Energy and Power*, a Scientific American Book, W. H. Freeman & Co., San Francisco
- Huld T., Šúri M., Dunlop E.D., 2008. Geographical Variation of the Conversion Efficiency of Crystalline Silicon Photovoltaic Modules in Europe. *Progress in Photovoltaics: Research and Applications*, 16, 595-607
- Hunt L.P., 1976. Total energy use in the production of silicon solar cells from raw materials to finished product, *Proceedings 12th IEEE PV Specialists Conference*, Baton Rouge, November 15-18
- Hyundai Heavy Industries, 2009. Engine & Machinery Division, Hyundai Heavy Industries, Ulsan, www.hyundai-engine.com

I

- [IEA] - International Energy Agency, 2006. World Energy Outlook 2006, IEA, Paris, www.iea.org/textbase/nppdf/free/2006/weo2006.pdf
- [IEA] - International Energy Agency, 2008. Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050, IEA, Paris
- [IEA] - International Energy Agency, 2008. World Energy Outlook 2008, IEA, Paris, www.iea.org/textbase/nppdf/free/2008/weo2008.pdf
- [IEA] - International Energy Agency, 2008. World Energy Outlook, Electricity Access Database, IEA, Paris, www.worldenergyoutlook.org/database_electricity/electricity_access_database.htm

- [IEA] - International Energy Agency, 2009. Energy Technology RD&D Budgets in OECD, IEA, Paris, <http://iea.org/stats/rd.asp>
- [IEA] - International Energy Agency, 2009. Global Gaps in Clean Energy Research, Development and Demonstration, IEA, Paris, www.iea.org/papers/2009/global_gaps.pdf
- [IEA] - International Energy Agency, 2009. Key World Energy Statistics 2009, IEA, Paris, www.iea.org/textbase/nppdf/free/2009/key_stats_2009.pdf
- [IEA] - International Energy Agency, 2009. Technology Roadmap: Wind energy, IEA, Paris, www.iea.org/Papers/2009/Wind_Roadmap.pdf
- [IEA] - International Energy Agency, 2009. World Energy Outlook 2009, IEA, Paris
- [IEA] - International Energy Agency, 2009. The Impact of the Financial and Economic Crisis on Global Energy Investment, IEA Background paper for the G8 Energy Ministers' Meeting May 24-25, IEA, Paris, www.iea.org/ebc/files/impact.pdf
- [IEA] - International Energy Agency, 2010. Energy Technology Perspectives 2010 – Scenarios and Strategies to 2050, IEA, Paris
- [IEA] - International Energy Agency, 2010. Projected Costs of Generating Electricity 2010 Edition, IEA, Paris
- [IEA] - International Energy Agency, 2010. Technology Roadmap: Concentrating Solar Power, IEA, Paris, www.iea.org/papers/2010/csp_roadmap.pdf
- [IEA] - International Energy Agency, 2010. Technology Roadmap: Solar photovoltaic energy, IEA, Paris, www.iea.org/papers/2009/PV_roadmap_targets_printing.pdf
- [IEA] - International Energy Agency, 2010. World Energy Outlook 2010, IEA, Paris
- [IEA-OES] - International Energy Agency Implementation Agreement on Ocean Energy Systems, 2006. Ocean Energy: Opportunity, present status and challenges, IEA-OES, Lisbon, www.iea-oceans.org/_fich/6/Poster_Ocean_Energy.pdf
- [IEA-PVPS] - International Energy Agency Photovoltaic Power Systems Programme, 2007. Trends in Photovoltaic Applications: Survey report of selected IEA countries between 1992 and 2006, IEA-PVPS, St. Ursen, www.iea-pvps.org/products/download/rep1_16.pdf
- [IEA-PVPS] - International Energy Agency Photovoltaic Power Systems Programme, 2009. Trends in Photovoltaic Applications: Survey report of selected IEA countries between 1992 and 2008, IEA-PVPS, St. Ursen, www.iea-pvps.org/products/download/rep1_18.pdf
- [IEA-PVPS] - International Energy Agency Photovoltaic Power Systems Programme, 2010. Trends in Photovoltaic Applications: Survey report of selected IEA countries between 1992 and 2009, IEA-PVPS, St. Ursen, www.iea-pvps.org/products/download/Trends-in-Photovoltaic_2010.pdf
- [IEA-PVPS] - International Energy Agency Photovoltaic Power Systems Programme, 2011. Trends in Photovoltaic Applications: Survey report of selected IEA countries between 1992 and 2010, IEA-PVPS, St. Ursen, www.iea-pvps.org/products/download/Trends-in-Photovoltaic_2011.pdf
- [IEC] – International Electrotechnical Commission, 2006. International Standard 60904-1 2nd edition 2006-09 - Part 1: Measurement of photovoltaic current-voltage characteristics, IEC, Geneva, www.iec.ch
- Ikki O. and Kaizuka I., 2010. PV in Japan – Yesterday, Today and Tomorrow, in: Palz W. (ed.), Power for the World – The Emergence of Electricity from the Sun. Pan Stanford Publishing, Singapore
- [IPCC] - Intergovernmental Panel on Climate Change, 2007. IPCC 4th Assessment Report: Climate Change 2007, IPCC, Geneva, www.ipcc.ch
- [IPCC] - Intergovernmental Panel on Climate Change, 2007. IPCC 4th Assessment Report: Climate Change 2007 – Working Group III (Mitigation), IPCC, Geneva, www.ipcc.ch/pdf/assessment-report/ar4/
- [IPCC] - Intergovernmental Panel on Climate Change, 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), IPCC WG III – Mitigation of Climate Change, Geneva, <http://srren.ipcc-wg3.de/report>
- [ITC] - International Trade Centre, 2011. International Trade Centre Market Analysis Tool, Product Map, ITC, Market Analysis and Research Section, Geneva, <http://www.intracen.org/marketanalysis/TermsConditions.aspx>
- Ito M., Komoto K., Kurokawa K., 2010. Life-cycle analyses of very-large scale PV systems using six types of PV modules, Current Applied Physics, 10, S271-S273

Ito M., Kudo M., Nagura M., Kurokawa K., 2010. A comparative study on life-cycle analysis of 20 different PV modules installed at a Hokuto mega-solar plant, Proceedings 5th World Conference on Photovoltaic Energy Conversion, Valencia, September, 6-10

J

- Jackson P., Hariskos D., Lotter E., Paetel S., Wuerz R., Menner R., Wischmann W., Powalla M., 2011. New world record efficiency for Cu(In,Ga)Se₂ thin-film solar cells beyond 20%, Progress in Photovoltaics: Research and Applications, DOI:10.1002/pip.1078
- Jacobson M.Z. and Delucchi M.A., 2009. A Path to Sustainable Energy by 2030, Scientific American, 2009(11), 58-65
- Jacobson M.Z. and Delucchi M.A., 2011. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials, Energy Policy, 39, 1154-1169
- Jäger-Waldau A., 2004. PV Status Report 2004, European Commission Joint Research Centre Institute for Energy, Ispra, www.solarseek.com/analysis/eujrc2004.pdf
- Jäger-Waldau A., 2008. PV Status Report 2008, European Commission Joint Research Centre Institute for Energy, Ispra, <http://sunbird.jrc.it/refsys/pdf/PV%20Report%202008.pdf>
- James L.W. and Moon R.L., 1975. GaAs concentrator solar cell, Applied Physics Letters, 26, 467-470
- Jaramillo O.A., Borja M.A., Huacuz J.M., 2004. Using hydropower to complement wind energy: a hybrid system to provide firm power, Renewable Power, 29, 1887-1909
- Jeltsch K.F., Schädel M., Bonekamp J.-B., Niyamakom P., Rauscher F., Lademann H.W.A., Dumsch I., Allard S., Scherf U., Meerholz K., 2011. Efficiency Enhanced Hybrid Solar Cells Using a Blend of Quantum Dots and Nanorods, Advanced Functional Materials, XX, 1-8
- Johnston F. and Sun S., 2011. Compressed air energy storage: an expanding opportunity?, Bloomberg New Energy Finance, research note, March 2
- Jourde P., 2000. Battery energy pay-back time, Proceedings 16th European Photovoltaic Solar Energy Conference, Glasgow, May 1-5
- Judkins Z.S., Johnston K.W., Almy C., Linderman R.J., Wares, B., Barton N.A., Dawson M., Peurach J., 2010. Performance Results of a Low-concentration Photovoltaic System Based on High Efficiency Back Contact Cells, Proceedings 25th European Photovoltaic Solar Energy Conference, Valencia, September 6-10

K

- Kalogirou S.A., 2009. Solar Energy Engineering – Processes and Systems, Academic Press, Burlington
- Kaltschmitt M., 2006. Nutzung der Energien des Meeres, in: Kaltschmitt M., Streicher W., Wiese A., (eds.), Erneuerbare Energien: Systemtechnik, Wirtschaftlichkeit, Umweltaspekte, 4th ed., Springer-Verlag, Berlin
- Kaltschmitt M., Streicher W., Wiese A. (eds.), 2006. Erneuerbare Energien: Systemtechnik, Wirtschaftlichkeit, Umweltaspekte, 4th ed., Springer-Verlag, Berlin
- Kamat P.V., 2008. Quantum Dot Solar Cells. Semiconductor Nanocrystals as Light Harvesters, Journal of Physical Chemistry C, 112, 18737-18753
- Kar M., 2010. Grid Parity of PV Power in India, Indo-German Energy Symposium, New Delhi, April 28
- Kato K., Murata A., Sakuta K., 1998. Energy Pay-back Time and Life-cycle CO₂ Emissions of Residential PV Power System with Silicon PV Module, Progress in Photovoltaics: Research and Applications, 6, 105-115
- Kazmerski L., 2011. NREL compilation of best research solar cell efficiencies, National Renewable Energy Laboratory (NREL), Golden, [http://en.wikipedia.org/wiki/File:PVeff\(rev111103\).jpg](http://en.wikipedia.org/wiki/File:PVeff(rev111103).jpg)
- Keevers M.J., Young T.L., Schubert U., Green M.A., 2007. 10% Efficient CSG minimodules, Proceedings 22nd European Photovoltaic Solar Energy Conference, Milan, September, 3-7
- Kehlhofer R., Hannemann F., Stirnimann F., Rukes B., 2009. Combined-Cycle Gas & Steam Turbine Power Plants, 3rd ed., PennWall, Tulsa
- Keoleian G.A. and Lewis G.McD., 1997. Application of Life-cycle Energy Analysis to Photovoltaic Module Design, Progress in Photovoltaics: Research and Applications, 5, 287-300

- Kershman S.A., Rheinländer J., Neumann T., Goebel O., 2005. Hybrid wind/PV and conventional power for desalination in Libya – GECOL's facility for medium and small scale research at Ras Ejder, Desalination, 183, 1-12
- Kersten F., Doll R., Kux A., Huljić D.M., Görig M.A., Breyer Ch., Müller J., Wawer P., 2011. PV-Learning Curves: Past and Future Drivers of Cost Reduction, Proceedings 26th European Photovoltaic Solar Energy Conference, Hamburg, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.63
- Kersten F., 2011. Photovoltaik-Lernkurve auf Systemebene und Analyse zukünftiger Kostensenkungspotentiale, Bachelor thesis, Anhalt University of Applied Sciences
- Photovoltaik-Lernkurve auf Systemebene und Analyse zukünftiger Kostensenkungspotentiale
- Ketjoy N., Sirisumpunwong C., Thanarak P., Rakwichian W., Chew L.H., 2004. First Year Investigation of PV Mini Grid System in Chiangria Province of Thailand, Proceedings 19th European Photovoltaic Solar Energy Conference, Paris, June 7-11
- [KfW] - Kreditanstalt für Wiederaufbau, 2001. PV-Hydro Initiative: Stages 1 & 2 – Assessment of the Potential for the Commercialization of Conjunctive Photovoltaic – Hydro Power Generation, study on behalf of KfW and United Nations Environmental Programme (UNEP) prepared by Lahmeyer International and Solar-Institut Jülich
- Khan J. and Bhuyan G., 2009. Ocean Energy: Global Technology Development Status, report prepared by Powertech Labs for International Energy Agency Implementation Agreement on Ocean Energy Systems (IEA-OES), Lisbon, www.iea-oceans.org/_fich/6/ANNEX_1_Doc_T0104.pdf
- Khan J., Bhuyan G. and Moshref A., 2009. Potential Opportunities and Differences Associated with Integration of Ocean Wave and Marine Current Energy Plants in Comparison to Wind Energy, report on behalf of International Energy Agency Implementation Agreement on Ocean Energy Systems (IEA-OES) prepared by Powertech Labs, Lisbon, www.iea-oceans.org/_fich/6/T0311_document.pdf
- Kiefer K., Dimberger D., Müller B., Heydenreich W., Kröger-Vodde A., 2010. A degradation analysis of PV power plants, Proceedings 5th World Conference on Photovoltaic Energy Conversion, Valencia, September, 6-10
- Kim D.S., Gabor A.M., Yelundur V., Upadhyaya A., Meemongkolkiat V., Rohatgi A., 2003. String Ribbon Silicon Solar Cells With 17.8% Efficiency, Proceedings 3rd World Conference on Photovoltaic Energy Conversion, Osaka, May 11-18
- King R.R., Boca A., Edmondson K.M., Romero M.J., Yoon H., Law D.C., Fetzer C.M., Haddad M., Zakaria A., Hong W., Mesropian S., Krut D.D., Kinsey G.S., Pien P., Sherif R.A., Karam N.H., 2008. Raising the Efficiency Ceiling with Multijunction III-V Concentrator Photovoltaics, Proceedings 23rd European Photovoltaic Solar Energy Conference, Valencia, September 1-5
- Kippelen B., Yoo S., Haddock J.A., Domercq B., Barlow S., Minch B., Xia W., Marder S.R., Armstrong N.R., 2005. Liquid-Crystal Approaches to Organic Photovoltaics, in: Sun S.-S. and Sariciftci N.S., (eds.), Organic Photovoltaics: Mechanisms, Materials and Devices, CRC Press, Boca Raton
- Kistner R., 2003. Simulation of solar thermal power plants and their evaluation emphasising on energy economic issues and financing issues, PhD thesis, Faculty of Electrical Engineering and Computer Science, Technical University of Berlin
- Klärner H. and Schulz M., 2009. SET for 2020, PV Japan, Chiba, June 24
- Klaus W., 2009. private communication, Lahmeyer International, July 7
- Kleemann M., 2002. Windenergie, Wasserkraft, Gezeitenenergie und Erdwärme, in: Rebhan E. (ed.), Energiehandbuch: Gewinnung, Wandlung und Nutzung von Energie, Springer-Verlag, Berlin
- Kleemann M. and Meliß M., 1993. Regenerative Energiequellen, Springer-Verlag, Berlin
- Klenk R. and Lux-Steiner M.Ch., 2006. Chalcopyrite Based Solar Cells, in: Poortmans J. and Arkhipov V., (eds.), Thin Film Solar Cells: Fabrication, Characterization and Applications, John Wiley & Sons, Chichester
- Klucher T.M., 1979. Evaluation of Models to predict Insolation on tilted Surfaces, Solar Energy, 23, 111-114
- Knies G. (ed.), 2009. Clean Power from Deserts – The Desertec Concept for Energy, Water and Climate Security, Whitebook 4th Ed., DESERTEC Foundation, Hamburg, www.desertec.org

- [Kohlenwirtschaft] – Statistik der Kohlenwirtschaft, 2010. Internationale Klassifikation der Kohle, Kohlenwirtschaft, Cologne, www.kohlenstatistik.de/ftp/Kohlearten.pdf
- Kohn W., 2010. A world powered predominantly by solar and wind energy, in: Schellnhuber, H.J., Molina, M., Stern, N., Huber, V., Kadner, S., (eds.), *Global Sustainability – A Nobel Cause*, Cambridge University Press, Cambridge
- Koinuma H. and Kurokawa K., 2010. Silicon Solar Breeder Plan in Sahara, IEA-PVPS Task 8 Symposium, Yokohama, June 27
- Komoto K., Ito M., Vleuten van der P., Faiman D., Kurokawa K., (eds.), 2009. *Energy from the Desert – Very Large Scale Photovoltaic Systems: Socio-economic, Financial, Technical and Environmental Aspects*, Earthscan, London
- Konings P., Syngellakis K., Yangmog F., Bouet V., Wortel O., 2008. PV Mini-Grids for Yap State: Sustainable design for remote Pacific islands, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- Konstantin P., 2009. *Praxisbuch Energiewirtschaft – Energiewandlung, -transport und -beschaffung im liberalisierten Markt*, 2nd ed., Springer-Verlag, Berlin
- Kost C. and Schlegl T., 2010. Stromgestehungskosten Erneuerbare Energien, Fraunhofer-Institut für Solar Energiesysteme (FhG-ISE), Freiburg, Dezember, www.ise.fraunhofer.de/veroeffentlichungen/studie-stromgestehungskosten-erneuerbare-energien
- Koutroulis E., Kolokotsa D., Potirakis A., Kalaitzakis K., 2006. Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms, *Solar Energy*, 80, 1072-1088
- Kreutzman A. and Siemer J., 2010. Market survey on solar modules 2010: Smooth sailing, *Photon International*, 2010(2), 136-169
- Krewitt W., Heck T., Trukenmüller A., Friedrich R., 1999. Environmental damage costs from fossil electricity generation in Germany and Europe, *Energy Policy*, 27, 173-183
- Krewitt W., Simon S., Graus W., Teske S., Zervos A., Schäfer O., 2007. The 2°C scenario – A sustainable world energy perspective, *Energy Policy*, 35, 4969-4980
- Krewitt W., Nitsch J., Nienhaus K., 2008. Globale Energieszenarien - Bedeutung der Erneuerbaren Energien und der Energieeffizienz, FVEE Jahrestagung, Berlin, November 24-25, www.fvee.de/fileadmin/publikationen/Themenhefte/th2009/th2009_03_02
- Krewitt W., Teske S., Simon S., Pregger T., Graus W., Blomen E., Schmid S., Schäfer O., 2009. Energy [R]evolution 2008 – a sustainable world energy perspective, *Energy Policy*, 37, 5764-5775
- Kumar S. and Scholes G.D., 2008. Colloidal nanocrystal solar cells, *Microchim Acta*, 160, 315-325
- Kurokawa K. (ed.), 2003. *Energy from the Desert: Feasibility of Very Large Scale Photovoltaic Power Generation (VLS-PV) Systems*, James & James (Science Publishers), London
- Kymakis E., Kalykakis S., Papazoglou T.M., 2009. Performance analysis of a grid connected photovoltaic park on the island of Crete, *Energy Conversion and Management*, 50, 433-438

L

- Landsberg P.T. and Tonge G., 1980. Thermodynamic energy conversion efficiencies, *Journal of Applied Physics*, 51, R1-R20
- Langreder W. and Bade P., 2010. Der Wind, in: Gasch R. and Tewe J., (eds.), *Windkraftanlagen – Grundlagen, Entwurf, Planung und Betrieb*, 6th ed., Vieweg + Teubner, Weisbaden
- Larsen J., 2011. Plan B Updates: Cancer Now Leading Cause of Death in China, *Earth Policy Institute*, Washington, May 25, www.earth-policy.org/plan_b_updates/2011/update96
- Lee B., Iliev I., Preston F., 2009. Who owns our low carbon future?, Chatham House, London, www.chathamhouse.org.uk/files/14699_r0909_lowcarbonfuture.pdf
- Lehovec K., 1948. The Photo-Voltaic Effect, *Physical Review*, 74, 463-471
- Lenton T.M., Held H., Kriegler E., Hall J.W., Lucht W., Rahmstorf S., Schellnhuber H.J., 2008. Tipping elements in the Earth's climate system, *Proceedings of the National Academy of Science*, 105, 1786-1793
- Lerchenmüller H., 2011. DNI Values in good CPV Sites, private communication, April 19
- Levine J.D., Hotchkiss G.B., Hammerbacher M.D., 1991. Basic Properties of the Spherical Solar Cell, *Proceedings 22nd IEEE Photovoltaic Specialists Conference*, Las Vegas, October 7-11

- Lia de F., Catello S., Abenante L., 2003. Efficiency degradation of c-silicon photovoltaic modules after 22-year continuous field exposure, Proceedings 3rd World Conference on Photovoltaic Energy Conversion, Osaka, May 11-18
- Lilienthal P., 2004, The HOMER® Micropower Optimization Model, DOE Solar Energy Technologies, Denver
- Lin B. and Liu J., 2010. Estimating coal production peak and trends of coal imports in China, *Energy Policy*, 38, 512-519
- Linares A., López-Manzanares L., Cendagorta-Galarza M., Friend M., Khazen El A., Janssen R., Rutz D., 2010. Hybrid RE System: Minigrid Set-up First Result and Lessons Learned, Proceedings 25th European Photovoltaic Solar Energy Conference/ WCPEC-5, Valencia, September, 6-10
- Liu B.Y.H. and Jordan R.C., 1960. The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation, *Solar Energy*, 4, 1-19
- Liu Z., Masuda A., Nagai T., Miyazaki T., Takano M., Takano M., Yoshigahara H., Sakai K., Asai K., Kondo M., 2007. A concentrator module of spherical Si solar cell, *Solar Energy Materials & Solar Cells*, 91, 1805–1810
- Loferski J.J., 1993. The First Forty Years: a Brief History of the Modern Photovoltaic Age, *Progress in Photovoltaics: Research and Applications*, 1, 67-78
- López N., Reichertz L.A., Yu K.M., Campman K., Walukiewicz W., 2011. Multiband Solar Cell, Proceedings 26th European Photovoltaic Solar Energy Conference, Hamburg, September 5-9
- Lorenz E., 2006. Solarstrahlungsvorhersage und ihre Anwendung in der Solarenergie, Workshop Energiemeteorologie, ForschungsVerbund Sonnenenergie (FVS), Berlin, November 2, www.fvee.de/fileadmin/publikationen/Workshopbaende/ws2006/ws_2006.pdf
- Lorenz E., Scheidsteger T., Hurka J., Heinemann D., Kurz C., 2010. Regional PV power prediction for improved grid integration, *Progress in Photovoltaics: Research and Applications*, DOI: 10.1002/pip.1033
- Lübbert, D., 2005. Das Meer als Energiequelle – Wellenkraftwerke, Osmose-Kraftwerke und weitere Perspektiven der Energiegewinnung aus dem Meer, Info-Brief WF VIII – 116/2005, Wissenschaftliche Dienste des Deutschen Bundestages, Berlin, www.bundestag.de/dokumente/analysen/2005/2005_11_101.pdf
- Lu X., McElroy M.B., Kiviluoma J., 2009. Global potential for wind-generated electricity, Proceedings of the National Academy of Science, PNAS early edition, www.pnas.org/cgi/doi/10.1073/pnas.0904101106
- Luque A. and Martí A., 1997. Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions at Intermediate Levels, *Physical Review Letters*, 78, 5014-5017
- Luque A., Martí A., Bett A., Andreev V.M., Jaussaud C., Roosmalen J.A.M. van, Alonso J., Räuber A., Strobl G., Stolz W., Algora C., Bitnar B., Gombert A., Stanley C., Wahnnon P., Conesa J.C., Sark W.G.J.H.M. van, Meijerink A., Klink G.P.M. van, Barnham K., Danz R., Meyer T., Luque-Heredia I., Kenny R., Christofides C., Sala G., Benítez P., 2005. FULLSPECTRUM: a new PV wave making more efficient use of the solar spectrum, *Solar Energy Materials & Solar Cells*, 87, 467–479
- Luque A.L. and Andreev V.M., (eds.), 2007. *Concentrator Photovoltaics*, Springer-Verlag, Berlin

M

- Mackensen R., Rohrig K., Adzic L., Saint-Drenan Y.-M., 2008. No limits for a full electricity supply by renewables, Institut für Solare Energieversorgungstechnik (ISET), ewec 2008, Brussels, www.ewec2008proceedings.info/ewec2008/allfiles2/117_EWEC2008fullpaper.pdf
- Mackensen R., Rohrig K., Emanuel H., 2008. Das regenerative Kombikraftwerk, Final Report, Institut für Solare Energieversorgungstechnik (ISET), Kassel, April, www.kombikraftwerk.de/fileadmin/downloads/2008_03_31_Ma_KombiKW_Abschlussbericht.pdf
- Marcel J.-C. and Sauvage E., 2008. Various rural electrification design for 7 villages in Northern Mauritania, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Markandya A. and Wilkinson P., 2007. Electricity generation and health, *The Lancet*, 370, 979-990
- Markandya A., Armstrong B.G., Hales S., Chiabai A., Criqui P., Mima S., Tonne C., Wilkinson P., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation, *The Lancet*, 374, 2006-2015

- Markowitz H., 1952. Portfolio Selection, *The Journal of Finance*, 7, 77-91
- Marti A. and Araujo G.L., 1996. Limiting efficiencies for photovoltaic energy conversion in multigap systems, *Solar Energy Materials and Solar Cells*, 43, 203-222
- Martin G. and Kroposki B., 2010. Assessment of Photovoltaic Hybrid Power Systems in the United States, *Proceedings 5th European PV-Hybrid and Mini-Grid Conference*, Tarragona, April 29-30
- Mason J.E., Fthenakis V.M., Hansen T., Kim H.C., 2006. Energy Payback and Life-cycle CO₂ Emissions of the BOS in an Optimized 3.5 MW PV Installation, *Progress in Photovoltaics: Research and Applications*, 14, 179-190
- Mason J., Fthenakis V., Zweibel K., Hanson T., Nikolakakis T., 2008. Coupling PV and CAES Power Plants to Transform Intermittent PV Electricity into a Dispatchable Electricity Source, *Progress in Photovoltaics*, 16, 649-668
- Matthes F.C., 2010. Energiepreise für aktuelle Modellierungsarbeiten. Regressionsanalytisch basierte Projektionen - Teil 1: Preise für Importenergien und Kraftwerksbrennstoffe, Öko-Institut, Berlin, March, www.oeko.de/oekodoc/984/2010-004-de.pdf
- Matsushashi R. and Ishitani H., 1995. Model analyses for sustainable energy supply under CO₂ restrictions, *IEEE Transactions on Energy Conversion*, 10, 730-735
- May H., 2009. Windindustrie in China – Faktor 10, *neue energie*, 2009(7), 79-87
- Mayer O., Buechl D., Forstmeier M., Feichter W., 2008. Photovoltaic Powered Water Purification – Bringing Water to Remote Areas, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- McDonald A. and Schrattenholzer L., 2001. Learning rates for energy technologies, *Energy Policy*, 29, 255-261
- McGowan J.G. and Manwell J.F., 1999. Hybrid Wind/PV/Diesel System Experiences, *Renewable Energy*, 16, 928-933
- McNelis B., 2010. Promoting PV in Developing Countries, in: Palz W. (ed.), *Power for the World – The Emergence of Electricity from the Sun*. Pan Stanford Publishing, Singapore
- Meadows D.H., Meadows D.L., Randers J., Behrens W.W., 1972. *The limits to growth*, Potomac Associates, New York
- Meadows D.H., Randers J., Meadows D.L., 2004. *Limits to growth: the 30-year update*, Chelsea Green Publishing, White River Junction, 2004
- [MED-ENEC] - Energy Efficiency in the Construction Sector in the Mediterranean, 2010. Electricity Price Data, MED-ENEC, Cairo, www.med-enec.com
- Meinhardt M., Burger B., Engler A., 2007. PV-Systemtechnik – Motor der Kostenreduktion für die Photovoltaische Stromerzeugung, *ForschungsVerbund Sonnenenergie (FVS), Produktionstechnologie für die Solarenergie*, Annual Meeting, Hannover, September 26–27, www.fvee.de/fileadmin/publikationen/Themenhefte/th2007/th2007.pdf
- Merten J., Vallvé X., Malbranche P., 2007. Seven key points for successful rural electrification programmes with solar energy, *Proceedings 22nd European Photovoltaic Solar Energy Conference*, Milan, June 3-7
- Meyer B., Schmidt S., Eidems V., 2009. Staatliche Förderung der Atomenergie, Greenpeace, Hamburg, www.greenpeace.de/fileadmin/gpd/user_upload/themen/atomkraft/Studie_Subventionen_Atomennergie.pdf
- Meyer C., 2010. Der gelbe Fluch, *Der Spiegel*, 2010(13), <http://wissen.spiegel.de/wissen/image/show.html?did=69744040&aref=image042/2010/03/27/CO-SP-2010-013-0108-0113.PDF&thumb=false>
- MiaSolé, 2010. MiaSolé Sets World Record for Highest Efficiency of Commercial Scale Thin-film Solar Modules, MiaSolé, Santa Clara, press release, June 10, www.miasole.com/sites/default/files/MiaSole_release_June_10_2010.pdf
- Miller D., 2009. *Selling Solar – The Diffusion of Renewable Energy in Emerging Markets*, Earthscan, London
- Milner A., 2008. The Solar Industry within the SET-Plan, 5th EU PV Industry Forum, Valencia, September 3, www.epia.org/index.php?eID=tx_nawsecured1&u=0&file=filemin/EPIA_docs/documents/23EUPVSEC/Presentations/IF_3_4_Milner.pdf
- Mints P., 2009. *First Markets and Applications for OPV*, Navigant Consulting, Organics Photovoltaic

- Summit, Boston, October 15-16
- Mitra I., 2008. Optimum Utilization of Renewable Energy for Electrification of Small Islands in Developing Countries, PhD Thesis, Faculty of Electrical Engineering and Computer Science, University of Kassel, www.uni-kassel.de/upress/online/frei/978-3-89958-694-7.volltext.frei.pdf
- Mohns W. and Stein D., 2008. Community Powerhouse: A Rural Electrification Model for Vanuatu, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Moody's, 2008. Nuclear plant construction poses risks to credit metrics, ratings, Moody's, New York, June 2
- Müller H. and Siepker B., 1998. Awareness – Training – Financing: The way to a sustainable dissemination of stand-alone PV systems for rural electrification, Proceedings 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, July, 6-10
- Müller M., 2008. Sustainable operation experience in PV-Hybrid Systems – some success factors and data analysis, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Müller J., 2011. Crystalline Silicon PV Technology: Status and Outlook, Forum on Solar-Electric Energy Systems, Abu Dhabi, March 27-28
- Müller-Kraenner S., 2008. Energy Security: Re-Measuring the World, earthscan, London
- Müller-Steinhagen H. and Trieb F., 2004. Concentrating solar power: A review of the technology, Quarterly of the Royal Academy of Engineering, *Ingenia* 18, 2004(2), 43-50
- Muñoz J., Narvarte L., Lorenzo E., 2004. First Operating Year of Two Village PV-Diesel Plants in the South of Morocco, Proceedings 19th European Photovoltaic Solar Energy Conference, Paris, June 7-11
- Munoz J., Narvarte L., Lorenzo E., 2007. Experience With PV-diesel Hybrid Village Power Systems in Southern Morocco, Progress in Photovoltaics: Research and Applications, 15, 529-539
- Murphy D.J. and Hall C.A.S., 2010. Year in review – EROI or energy return on (energy) invested, New York Academy of Science, 1185, 102-118

N

- Nag P., Little D., Teehan D., Wetzl K., Elwood D., 2008. Low Load Operational Flexibility for Siemens G Class Gas Turbines, Siemens Power Generation, Power-Gen International, Orlando, December 2-4, www.energy.siemens.com/co/pool/hq/energy-topics/pdfs/en/gas-turbines-power-plants/PowerGen08_LLOPFlexibilityforSiemenGClassGT.pdf
- Nandi S.K. and Ghosh H.R., 2009. A wind-PV-battery hybrid power system at Sitakunda in Bangladesh, Energy Policy 37, 3659-3664
- [NAO] - National Audit Office, 2008. The Nuclear Decommissioning Authority: Taking forward decommissioning, NOA, London, www.nao.org.uk/publications/0708/the_nuclear_decommissioning_au.aspx
- Narvarte L. and Lorenzo E., 2008. Tracking and Ground Cover Ratio, Progress in Photovoltaics: Research and Application, 16, 703-714
- Narvarte L. and Lorenzo E., 2010. Sustainability of PV water pumping programmes: 12-years of successful experience, Progress in Photovoltaics: Research and Applications, 18, 291-298
- Nashawi I.S., Malallah A., Al-Bisharahn M., 2010. Forecasting World Crude Oil Production using Multicyclic Hubbert Model, Energy Fuels, 10, 1788-1800
- Nauclér T., Enkvist P.-A., (eds.), 2009. Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve, McKinsey & Company, <https://solutions.mckinsey.com/ClimateDesk/default.aspx>
- Navigate, 2010. Bunker Prices, <http://navigatemag.ru/bunker/0>
- Neij L., 1997. Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology, Energy Policy, 23, 1099-1107
- Nelson R.E., 2003. A brief history of thermophotovoltaic development, Semiconductor Science and Technology, 18, S141-S143
- Nemet G.F., 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics, Energy Policy, 34, 3218-3232
- Nemet G.F. and Kammen D.M., 2007. US energy research and development: Declining investment, increasing need, and the feasibility of expansion, Energy Policy, 35, 746-755

- Nemet G.F., 2009. Interim monitoring of cost dynamics for publicly supported energy technologies, *Energy Policy*, 37, 825-835
- Nielsen K. and Pontes T., 2010. Report T02-1.1 OES IA Annex II Task 1.1 Generic and site related wave energy data, report prepared for International Energy Agency Implementation Agreement on Ocean Energy Systems (IEA-OES), Lisbon, www.iea-oceans.org/_fich/6/Annex_II_Report_02_1.1_revision_3.pdf
- Niemann N., 2010. Meereskraftwerke – Die Energie und Vielfalt der Ozeane, in: Aufenanger V., Friedrichsen N., Koch S., (eds.), *Gerechtigkeit und Verantwortung in der Klima- und Energiepolitik*, Verlagshaus Monsenstein und Vannerdat OHG, Münster
- Nissen H., 2009. private communications on BOS cost components, April 14
- [NOAA] – National Oceanic & Atmospheric Administration, 2011. Trends in Atmospheric Carbon Dioxide – Recent Global CO₂, NOAA, Earth System Research Laboratory, Global Monitoring Division, Washington, www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global_growth
- Nokia Corp., Annual Reports 1994 - 2008, www.nokia.com
- Nordmann T., Vontobel T., Clavadetscher L., Boström T., Remlo H.T., 2009. Large Scale Hybrid PV Hydro Electricity Production in Floating Devices on Water, Proceedings 24th European Photovoltaic Solar Energy Conference, Hamburg, September 21-25
- Nordmann T., Ossenbrink H., Vontobel T., 2010. Large Scale PV Implementation and Grid Integration with Hybrid PV Hydro Power Plants Using Floating PV Devices Potential Study and Future Markets, Proceedings 25th European Photovoltaic Solar Energy Conference/ WCPEC-5, Valencia, September 6-10
- [NREL] - National Renewable Energy Laboratory, 2005. PV Module Production Experience (or “Learning”) Curve, NREL, Golden, <http://www.nrel.gov>
- [NREL] - National Renewable Energy Laboratory, 2010. PVWatts, NREL, Golden, www.nrel.gov/rredc/pvwatts/changing_parameters.html#tilt_angle
- [NYS] – New York State, 2009. Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining, Regulatory Program, NYS Department of Environmental Conservation, Albany, September, <ftp://ftp.dec.state.ny.us/dmn/download/OGdSGEISFull.pdf>

O

- [OECD] - Organisation for Economic Co-operation and Development, 2010. Price indices (MEI), OECD, Paris, <http://stats.oecd.org>
- Ohl R.S., 1941. Light-sensitive electric device, US Patent 2,402,662, filed in May 27
- Oreskes N., 2004. The Scientific Consensus on Climate Change, *Science*, 306, 1686
- O’Regan B. and Grätzel M., 1991. A low-cost high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films, *Nature*, 353, 737-740
- O’Rourke S., Kim P., Polavarapu H., 2007. Solar Photovoltaics - Technology and economics: thin films and crystalline silicon, Deutsche Bank Securities, New York, July 9
- O’Rourke S., 2009. Solar Photovoltaic Industry, Deutsche Bank Securities, New York, IEEE Photovoltaic Specialists Conference, June 8
- O’Rourke S., Kim P., Polavarapu H., (eds.), 2010. Solar Photovoltaic Industry 2010 global outlook Déjà vu?, Deutsche Bank Securities, New York, February 8
- Ortiz B., Vetter M., Bourg C., Crehay R., 2010. Sustainable Renewable Energy Projects for Intelligent Rural Electrification in Laos, Cambodia and Vietnam, Proceedings 5th European PV-Hybrid and Mini-Grid Conference, Tarragona, April 29-30
- Osterwald C.R., Adelstein J., Cueto del J.A., Kroposki B., Trudell D., Morairty T., 2006. Comparison of degradation rates of individual modules held at maximum power, Proceedings 4th World Conference on Photovoltaic Energy Conversion, Hawaii, May 8-12

P

- Palz W. and Zibetta H., 1991. Energy pay-back time of photovoltaic modules, *International Journal of Solar Energy*, 10, 211-216
- Papadakis G., Mohamed E.Sh., Kyriakarakos G., Kassem A.-W.S., 2010. Hybrid Renewable Energy Systems for the Supply of Services in Rural Settlements of Mediterranean Partner Countries. The

- HYRESS Project – The Case Study of the Hybrid System – Microgrid in Egypt, Proceedings 5th European PV-Hybrid and Mini-Grid Conference, Tarragona, April 29-30
- Paska J., Biczek P., Klos M., 2009. Hybrid power systems – An effective way of utilising primary energy sources, *Renewable Energy*, 34, 2414-2421
- Pegram W.M., 1991. The Photovoltaics Commercialization Program, in: Cohen, L.R., Noll, R.G., (eds.), *The Technology Pork Barrel*, The Brookings Institution, Washington
- Peharz G. and Dimroth F., 2005. Energy Payback Time of the High-concentration PV System FLATCON, *Progress in Photovoltaics: Research and Applications*, 13, 627-634
- Pehnt M., Franke B., Hertle H., Kauertz B., Otter P., Goscurth H.-M., Boßmann T., Kasten P., Mey J., 2007. Das Steinkohle-Kraftwerk Hamburg Moorburg und seine Alternativen, study on behalf of Bund für Umwelt- und Naturschutz (BUND) prepared by Institut für Energie- und Umweltforschung (ifeu) and arrhenius Institute for Energy and Climate Policy, Heidelberg, Hamburg, November, www.ifeu.de/energie/pdf/IFEU%20Arrhenius%20_2007_%20-%20BUND%20Alternativkraftwerk%20final%20V3.pdf
- Pérez-Navarro A., Alfonso D., Álvarez C., Ibáñez, Sánchez C., Segura I., 2010. Hybrid biomass-wind power plant for reliable energy generation, *Renewable Energy*, 35, 1436-1443
- Perlin J., 1999. *From Space to Earth – The Story of Solar Electricity*, aatec publications, Ann Arbor
- Perlot G. and Mostafa M., 2009. Younicos Company Overview, Conference on German Solar Technology for the Sultanate Oman, Muscat, November 3, http://vae.ahk.de/fileadmin/ahk_vae/Events/Conference_Solar_Technolog/Younicos.pdf
- Perpinan O., Lorenzo E., Castro M.A., Eyras R., 2009. Energy Payback Time of Grid Connected PV Systems: Comparison Between Tracking and Fixed Systems, *Progress in Photovoltaics: Research and Applications*, 17, 137-147
- Perrakis K., Tzen E., Baltas P., Taoumi M., Haouari El E., 1998. Design of stand alone PV-Desalination system for rural areas, Proceedings 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, July 6-10
- Peter S. and Lehmann H., 2008. Renewable Energy Outlook 2030: Energy Watch Group Global Renewable Energy Scenarios, Energy Watch Group, Berlin, www.energywatchgroup.org/fileadmin/global/pdf/2008-11-07_EWG_REO_2030_E.pdf
- Peterschmidt N., Schmidt-Reindahl J., Beck H.-P., Baur J., 2008. Taking the step from Solar-Home-Systems to Micro-Grids: The business model of micro power economy for rural electrification in Senegal, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Petersen E.L., 2006. State of the Art and Challenges in Wind Power Meteorology, Workshop Energiemeteorologie, ForschungsVerbund Sonnenenergie (FVS), Berlin, November 2, www.fvee.de/fileadmin/publikationen/Workshopbaende/ws2006/ws_2006.pdf
- Petter K., Ludwig Y., Bakowskie R., Hlusiak M., Diez S., Ritz L.L., Lantzsche R., Rupp S., Freudenberg A., Scholz S., Hoffmann V., 2010. Latest Results on Production of Solar Cells Using umg-Si Feedstock, Proceedings 25th European Photovoltaic Solar Energy Conference, Valencia, September, 6-10
- Photon, 2010. Entwicklung der Anlagenpreise, *Photon – Das Solarstrom-Magazin*, 2010(4), 143
- Pietzcker R., Manger S., Bauer N., Luderer G., Bruckner T., 2009. The Role of Concentrating Solar Power and Photovoltaics for Climate Protection, Proceedings 10th IAAE European Energy Conference, Vienna, September 7-10
- Pinho J.T. and Araújo R.G., 2004. Wind-PV-Diesel Hybrid System for the Electrification of the Village of São Tomé – Municipality of Maracanã – Brazil, Proceedings 19th European Photovoltaic Solar Energy Conference, Paris, June 7-11
- Pitz-Paal R., Dersch J., Milow B., (eds.), 2004. *Ecostar – European Concentrated Solar Thermal Road-Mapping*, German Aerospace Center (DLR), Cologne, www.trec-uk.org.uk/reports/ecostar_report_2004.pdf
- Pitz-Paal R., 2007. Solarthermische Kraftwerke: Wie die Sonne ins Kraftwerk kommt, in: Bührke T. and Wengenmayr R., (eds.), *Erneuerbare Energie: Alternative Energiekonzepte für die Zukunft*, WILEY-VCH, Weinheim
- Platts, 2009. UDI World Electric Power Plants data base, Platts – A Division of The McGraw-Hill, Washington, version of March 31
- Pontes T. and Candelária A., 2009. Wave Data Catalogue for Resource Assessment of IEA-OES Member Countries, report on behalf of International Energy Agency Implementation Agreement

- on Ocean Energy Systems (IEA-OES) prepared by INETI, Lisbon, [www.iea-oceans.org/_fich/6/Wave_Data_Catalogue-_9_April_2009_\(1\).pdf](http://www.iea-oceans.org/_fich/6/Wave_Data_Catalogue-_9_April_2009_(1).pdf)
- Price H., Lüpfer E., Kearney D., Zarza E., Cohen G., Gee R., Mahoney R., 2002. Advances in Parabolic Trough Solar Power Technology, *Journal of Solar Energy Engineering*, 124, 109-125
- [PwC] – PricewaterhouseCoopers, 2010. 100% renewable electricity: A roadmap to 2050 for Europe and North Africa, study prepared by PwC, Potsdam Institute for Climate Impact Research (PIK), International Institute for Applied Systems Analysis (IIASA) and European Climate Foundation (ECF), London, Potsdam, Laxenburg, Brussels, www.pwc.co.uk/eng/publications/100_percent_renewable_electricity.html

Q

- Q-Cells Research, 2010. Electricity Price Data, Q-Cells, Bitterfeld-Wolfen, China Office, Tokyo Office, India Office
- Q-Cells, 2011. Q-Cells achieves with 13.4% new efficiency world record for CIGS thin film solar module out of mass production, Q-Cells, Bitterfeld-Wolfen, press release, March 29, www.q-cells.com/medien/presse/pressemitteilungen/downloads_eng/2011/2011_0329_PR_QCE_CIGSrecord_ENG.pdf
- Quaschnig V., Kistner R., Ortmanns W., 2002. Influence of Direct Normal Irradiance Variation on the Optimal Parabolic Trough Field Size: A Problem Solved with Technical and Economical Simulations, *Journal of Solar Energy Engineering*, 124, 160-164
- Quaschnig V., 2007. Regenerative Energiesysteme: Technologie – Berechnung – Simulation, 5th ed., Carl Hanser Verlag, Munich
- Quaschnig V., 2011. Bewertung von Methoden zur Bestimmung des PV-Anteils sowie von Ausbauszenarien und Einflüssen auf die Elektrizitätswirtschaft, presentation held at 26. Symposium Photovoltaische Solarenergie, March 2, www.volker-quaschnig.de/publis/vortraege/Vortrag_Staffelstein-2011.pdf

R

- Rahmstorf S. and Schellnhuber H.J., 2006. *Der Klimawandel*, Verlag C.H. Beck, München
- Rana S., Chandra R., Singh S.P., Sodha M.S., 1998. Optimal Mix of Renewable Energy Resources to Meet the Electrical Energy Demand in Villages of Madhya Pradesh, *Energy Conversion Management*, 39, 203-216
- Rapping L., 1965. Learning and World War II Production Functions, *The Review of Economics and Statistics*, 47, 81-86
- Rau U., Einsele F. and Glaeser G.C., 2005. Efficiency limits of photovoltaic fluorescent collectors, *Applied Physics Letters*, 87, 171101-171103
- Raugei M., Bargigli S., Ulgiati S., 2007. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si, *Energy*, 32, 1310-1318
- Reagan R., 1981. Program for Economic Recovery, Message from the President of the United States, H. Doc. 97-21
- Real del A.J., Arce A., Bordons C., 2009. Optimization strategy for element sizing in hybrid power systems, *Journal of Power Sources*, 193, 315-321
- Reichling J.P. and Kulacki F.A., 2008. Utility scale hybrid wind-solar thermal electrical generation: A case study for Minnesota, *Energy*, 33, 626-638
- Reindl D.T., Beckmann W.A., Duffie J.A., 1990. Evaluation of Hourly Tilted Surface Radiation Models, *Solar Energy*, 45, 9
- Reuter M., Gruse A.K., 2010. European PV Module Price Monitor: First Quarter Results 2010, EuPD Research, Bonn, February
- Richter C., Teske S., Short R., 2009. Concentrating Solar Power: Global Outlook 09, Greenpeace International, IEA Solar PACES and European Solar Thermal Electricity Association (ESTELA), Amsterdam, Tabernas, Brussels, www.estelasolar.eu/fileadmin/ESTELAdocs/documents/Greenpeace_Concentrating_Solar_Power_2009.pdf
- Rifkin J., 2002. *The Hydrogen Economy*, Penguin Putnam, New York

- Rogol M., Doi S., Wilkinson A., 2004. Sun screen: Investment opportunities in solar power, CLSA Asia-Pacific Markets, Hong Kong, July
- Rogol M., Flynn H., Porter C., Rogol J., Song J., 2007. Solar Annual 2007: Big Things in a Small Package, Photon Consulting, Boston, Autumn
- Rogol M., Farber M., Flynn H., Meyers M., Paap S., Porter C., Rogol J., Song J., 2008. Solar Annual 2008: Four Peaks, Photon Consulting, Boston, Autumn
- Rohatgi A., Kim D.S., Yelundur V., Nakayashiki K., Upadhyaya A., Hilali M., Meemongkolkiat V., 2004. Record-High-Efficiency Solar Cells on Multicrystalline Materials Through Understanding and Implementation of RTP-enhanced SiNx-induced Defect Hydrogenation, Proceedings 14th PVSEC, Bangkok
- Roth-Deblon A. and Mitra I., 2008. PV-Wind Hybrid Power on the Roof of the World, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Rout U.K., Blesl M., Fahl U., Remme U., Voß A., 2009. Uncertainty in the learning rates of energy technologies: An experiment in a global multi-regional energy system model, Energy Policy, 37, 4927-4942
- Roy M., Greenwald S., Baliff J., Kroner A., Gilbertson H.J., Sauvage J., Barnes S.K., Fink C., Spitzley R., 2007. Loan Guarantees for Advanced Nuclear Energy Facilities - Bankers' Comments on DoE Notice of Proposed Rulemaking, Citigroup, Credit Suisse, Goldman Sachs, Lehman Brothers, Merrill Lynch, Morgan Stanley, July 2

S

- Saleh Ibrahim I.M.S., Abouhdima I., Gantrari M.B., 2009. Performance of Thirty Years Stand Alone Photovoltaic System, Proceedings 24th European Photovoltaic Solar Energy Conference, Hamburg, September 21-25
- Sandén B.A., 2005. The economic and institutional rationale of PV subsidies, Solar Energy, 78, 137-146
- Sariciftci N.S., Smilowitz L., Heeger A.J., Wudl F., 1992. Photoinduced Electron Transfer from a Conducting Polymer to Buckminsterfullerene, Science, 258, 1474-1476
- Sark v. W.G.J.H.M., Alsema E.A., Junginger H.M., Moor de H.H.C., Schaeffer G.J., 2008. Accuracy of Progress Ratios Determined From Experience Curves: The Case of Crystalline Silicon Photovoltaic Module Technology Development, Progress in Photovoltaics: Research and Applications, 16, 441-453
- Sawin J.L. and Moomaw W.R., 2008. An enduring energy future, in: Sarke L. (ed.): State of the World: Into a Warming World, The Worldwatch Institute, Washington, www.worldwatch.org/files/2008/02/SOW39_cha4.pdf
- Sayyaadi H. and Sabzaligol T., 2010. Comprehensive exergetic and economic comparison of PWR and hybrid fossil fuel-PWR power plants, Energy, 35, 2953-2964
- Schaefer H. and Hagedorn G., 1992. Hidden energy and correlated environmental characteristics of PV power generation, Renewable Energy, 2, 159-166
- Schaeffer G.J., Alsema E., Seebregts A., Beurskens L., Moor de H., Sark v. W., Durstewitz M., Perrin M., Boulanger P., Laukamp H., Zuccaro C., 2004. Learning from the Sun – Analysis of the use of experience curves for energy policy purposes: The case of photovoltaic power, Final report of the Photex project, ECN-C-04-035, Energy research Center of the Netherlands (ECN), Petten, www.ecn.nl/docs/library/report/2004/c04035.pdf
- Schindler J. and Zittel W., (eds.), 2008. Crude Oil - The supply outlook, Energy Watch Group, Berlin, www.energywatchgroup.org/fileadmin/global/pdf/2008-02_EWG_Oil_Report_updated.pdf
- Schindler R., 2010. Towards Green Energy: Challenges and Options, Solar Expert Luncheon, Phoenix, http://usa.sanfrancisco.ahk.de/fileadmin/user_upload/Dokumente/Solar_Expert_Luncheon_-_Prof_Schindler_-_Phoenix_AZ.pdf
- Schlegl T., 2005. GaSb-Photovoltaikzellen für die Thermophotovoltaik, PhD thesis, Naturwissenschaftliche Fakultät II – Physik, Universität Regensburg
- Schmelter J. and Focken U., 2011. Operationelle Erfahrungen mit kombinierten Solarleistungsvorhersagen für deutsche ÜNBs und VNBs, 26. Symposium Photovoltaische Solarenergie, Bad Staffelstein, March 2-4

- Schmetz E., 2005. Coal to Liquid Fuels, U.S. Department of Energy Office of Sequestration, Hydrogen & Clean Coal Fuels, November 18,
http://fossil.energy.gov/international/Publications/cwg_nov05_schmetz.pdf
- Schmid A.L. and Hoffmann C.A.A., 2004. Replacing diesel by solar in the Amazon: short-term economic feasibility of PV-diesel hybrid systems, *Energy Policy*, 32, 881-898
- Schmid J., Hauer A., Schmidt D., Schmidt M., Staiß F., Stadermann G., Sterner M., Stryi-Hipp G., 2010. Energiekonzept 2050: Eine Vision für ein nachhaltiges Energiekonzept auf Basis von Energieeffizienz und 100% erneuerbaren Energien, ForschungsVerbund Erneuerbare Energien (FVEE), Berlin,
www.fvee.de/fileadmin/politik/10.06.vision_fuer_nachhaltiges_energiekonzept.pdf
- Schmidt-Reindahl J., Krause W., Dahouenon M.A., 2008. Market development for economically viable off-grid power supply in Senegal, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- Schneider M., Froggatt, Thomas S., 2011. The World Nuclear Industry Status Report 2010-2011: Nuclear Power in a Post-Fukushima World – 25 Years After the Chernobyl Accident, Worldwatch Institute, Washington, Paris, Berlin, April,
www.worldwatch.org/system/files/NuclearStatusReport2011_prel.pdf
- Schock R.N., Fulkerson W., Brown M.L., San Martin R.L., Greene D.L., Edmonds J., 1999. How Much is Energy Research & Development Worth as Insurance?, *Annual Review Energy Environment*, 24, 487-512
- Schölkopf W., 2002. Solarthermie, in: Rebhan E. (ed.), *Energiehandbuch: Gewinnung, Wandlung und Nutzung von Energie*, Springer-Verlag, Berlin
- Schoenung S.M. and Hassenzahl W.V., 2003. Long- vs short-term energy storage: Technologies analysis - A life-cycle cost study, Sandia National Laboratories, Albuquerque, SAND2003-2783,
<http://prod.sandia.gov/techlib/accesscontrol.cgi/2003/032783.pdf>
- Scholz Y., Hoyer-Click C., Schillings C., Gehrung J., Krewitt W., 2009. High Resolution Inventory of Renewable Electricity Generation Potentials in Europe, German Aerospace Center (DLR), Stuttgart,
www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/publications/REMIX_renewables_inventory.pdf
- Schott Solar, 2010. Power ohne Ende: Nach 26 Jahren noch über 90% Leistung, Schott Solar, Mainz, press release, December 14,
www.schottsolar.com/de/news/solarzeit/artikel/?tx_bbschottnews_pi1%5Bnews%5D=1948&tx_bbschottnews_pi1%5Baction%5D=single&tx_bbschottnews_pi1%5Bcontroller%5D=SchottNews&cHash=3ab67abd732eba5c08a28d22f5807800
- Schottky W., 1929. Photoelectric Generator, US Patent 2,040,632, filed in May 1
- Schroeter A. and Martin S., 2008. Profitable and affordable energy services for remote areas in Lao PDR: Private – Public Partnership as mutual leverage for Hybrid Village Grids in areas off the national grid, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- Schubert B., 2008. Q-Cells presentation, PHTON's 1st TECAF Conference, San Francisco, December 4
- Schubert B.-A., Marsen B., Cinque S., Unold T., Klenk R., Schorr S., Schock H.-W., 2011. Cu₂ZnSnS₄ thin film solar cells by fast coevaporation, *Progress in Photovoltaics: Research and Applications*, DOI: 10.1002/pip.976
- Schultz O., Glunz S.W., Willeke G.P., 2004. Multicrystalline Silicon Solar Cells Exceeding 20% Efficiency, *Progress in Photovoltaics: Research and Applications*, 12, 553-558
- Schwaegerl P. and Albrecht W., 2011. Solar impact on distribution grids – from the point of view of a southern German Distribution System Operator, 6th Photon Solar Electric Utility Conference, April 14
- Schwartz S.I. (ed.), 1998. *Atomic Audit: The Costs and Consequences of US Nuclear Weapons since 1940*, Brookings Institution Press, Washington
- Schwunk S., Ortiz B., Bopp G., Vetter M., 2008. Simulation of Hybrid PV Systems – Concepts for technology development system design and performance improvement, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30

- Seltmann T. and Zittel W., 2009. Natural gas reserves: a false hope, *Sun & Wind Energy*, 2009(12), 16-18
- Senjyu T., Hayashi D., Yona A., Urasaki N., Funabashi T., 2007. Optimal configuration of power generating systems in isolated island with renewable energy, *Renewable Energy*, 32, 1917-1933
- Severance C.A., 2009. Business Risks and Costs of New Nuclear Power, Grand Junction, <http://climateprogress.org/wp-content/uploads/2009/01/nuclear-costs-2009.pdf>
- Shah V., Greenblatt J., Madlani R., Basu A., 2010. Solar - Investor Guide 2010, Barclays Capital, New York, May 14
- Shah V. and Greenblatt J., 2010. Solar Energy Handbook: The Third Growth Phase of the Solar Era, Barclays Capital, New York, September 23
- Shanko M., Lakew H., Kyezi A., 2006. Rural solar PV market potential: A case for Jima region in Ethiopia, Megen Power, Addis Ababa
- Shealy M. and Dorian J.P., 2010. Growing Chinese coal use: Dramatic resource and environmental implications, *Energy Policy*, 38, 2116-2122
- Shirakawa H., Louis E.J., MacDiarmid A.G., Chiang C.K., Heeger A.J., 1977. Synthesis of Electrically Conducting Organic Polymers: Halogen Derivatives of polyacetylene (CH)_x, *Journal of the Chemical Society Chemical Communications*, 578-580
- Shockley W. and Queisser H.J., 1961. Detailed Balance Limit of Efficiency of p-n Junction Solar Cells, *Journal of Applied Physics*, 32, 510-519
- Short W., Packey D.J., Holt T., 1995. A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies, National Renewable Energy Laboratory (NREL), Golden, NREL/TP-462-5173, www.nrel.gov/csp/troughnet/pdfs/5173.pdf
- Shrestha G., Menke C., Klinghammer W., 2008. Case Studies of PV-Diesel Hybrid Systems in Operation in Rural Asia: Experiences and Conclusions from China, Thailand and Vietnam, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- Siemer J., 2009. Trackers Survey: An industry in transition, *Photon International*, 2009(11), 138-189
- Siemer J., 2009. Leveled out, *Photon International*, 2009(11), 86-88
- Slesser M. and Hounam I., 1976. Solar energy breeders, *nature*, 262, 244-245
- SMA Solar Technology, 2010. Geschäftsbericht 2009, Niestetal, March 16, www.sma.de/de/no_cache/investor-relations/publikationen/finanzberichte.html
- Smith W., 1873. Effect of light on selenium during the passage of an electric current, *nature*, 7, 303
- Smith J., 1983. The Solar Breeder: A Bold Step by Solarex, *Alternative Sources of Energy*, 60, 19
- Snelling W.O., 1920. Photo-electric apparatus, US Patent 1,375,474, filed in July 20
- Sörgel H., 1932. *Atlantropa*, Fretz & Wasmuth, Zürich
- Soitec Solar, 2011. Soitec Announces Major U.S. CPV Solar Power Project, Soitec Solar, Bernin, San Diego, press release, March 10, www.soitec.com/pdf/tenaska_release_final_eng.pdf
- Solar Energy Foundation, 2009. Country Data for Ethiopia, Solar Energy Foundation, Addis Ababa, www.solar-energy-foundation.org
- Solar Frontier, 2011. Solar Frontier Sets New Efficiency Record in Thin-Film CIS Technology, Solar Frontier, Tokyo, press release, March 29, www.solar-frontier.com/news/109
- Solar Junction, 2011. Solar Junction Breaks World Record with 43.5% Efficient CPV Production Cell, Solar Junction, San Jose, press release, April 14, www.sj-solar.com/downloads/Solar_Junction_World_Record_%20Efficiency_14April11.pdf
- Sollmann D., 2009. Eine Insel mit drei Akkus, *Photon – Das Solarstrom-Magazin*, 2009(8), 80-83
- Sovacool B.K., 2008. Valuing the greenhouse gas emissions from nuclear power: A critical survey, *Energy Policy*, 36, 2940-2953.
- Sovacool B.K. and Watts C., 2009. Going Completely Renewable: Is It Possible (Let Alone Desirable)?, *The Electricity Journal*, 22, 95-111
- Specht M., Sterner M., Stürmer B., Frick V., Hahn B., 2009. Renewable Power Methane - Stromspeicherung durch Kopplung von Strom- und Gasnetz - Wind/PV-to-SNG, Patent No: 10 2009 018 126.1, patent filed in March 9
- Specht M., Baumgart F., Feigl B., Frick V., Stürmer B., Zuberbühler U., Sterner M., Waldstein G., 2009. Speicherung von Bioenergie und Erneuerbarem Strom im Erdgasnetz, ForschungsVerbundes Erneuerbare Energien (FVEE), Annual Meeting, Berlin, November 25, www.fvee.de/fileadmin/publikationen/Themenhefte/th2009/th2009.pdf

- Specht M., Brellochs J., Frick V., Stürmer B., Zuberbühler U., Sterner M., Waldstein G., 2010. Speicherung von Bioenergie und erneuerbarem Strom im Erdgasnetz, Erdöl Erdgas Kohle, 2010(10), 342-346
- Spire, 2010. Spire Semiconductor produces a world-record 42.3% efficient CPV cell, Spire Semiconductor, Bedford, press release, October 6, <http://phx.corporate-ir.net/phoenix.zhtml?c=76421&p=irol-newsArticle&ID=1479650&highlight=>
- Sprengel U. and Hoyer W., 1989. Solarer Wassersoff – Energieträger der Zukunft, Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR), Stuttgart
- Stackhouse P.W., Whitlock C.H., (eds.), 2008. Surface meteorology and Solar Energy (SSE) release 6.0, NASA SSE 6.0, Earth Science Enterprise Program, National Aeronautic and Space Administration (NASA), Langley, <http://eosweb.larc.nasa.gov/sse/>
- Stackhouse P.W., Whitlock C.H., (eds.), 2009. Surface meteorology and Solar Energy (SSE) release 6.0 Methodology, NASA SSE 6.0, Earth Science Enterprise Program, National Aeronautic and Space Administration (NASA), Langley, <http://eosweb.larc.nasa.gov/sse/documents/SSE6Methodology.pdf>
- Staffhorst M., 2006. The Way to Competitiveness of PV – An Experience Curve and Break-even Analysis, PhD Thesis, Faculty of Electrical Engineering and Computer Science, University of Kassel, www.upress.uni-kassel.de/online/frei/978-3-89958-241-3.volltext.frei.pdf
- Stern N. (ed.), 2006. Stern Review on the economics of climate change, HM Treasury, London, www.sternreview.org.uk
- Stern R.J., 2010. United States cost of military force projection in the Persian Gulf 1976 – 2007, Energy Policy, 38, 2816-2825
- Sterner M., 2009. Bioenergy and renewable power methane in integrated 100% renewable energy systems, PhD thesis, Faculty of Electrical Engineering and Computer Science, University of Kassel
- Sterner M., Saint-Drenan Y.-M., Gerhardt N., Specht M., Stürmer B., Zuberbühler U., 2010. Erneuerbares Methan – Eine Lösung zur Integration und Speicherung Erneuerbarer Energien und ein Weg zur regenerativen Vollversorgung, Solarzeitalter, 2010(1), 51-58
- Stevens P., 2010. The ‘Shale Gas Revolution’: Hype and Reality, The Royal Institute of International Affairs, London, September, www.chathamhouse.org.uk/files/17317_r_0910stevens.pdf
- Sun S.-S. and Sariciftci N.S., (eds.), 2005. Organic Photovoltaics: Mechanisms, Materials and Devices, CRC Press, Boca Raton
- SunPower, 2011. Ground-Mounted Solar Trackers, SunPower, San Jose, <http://us.sunpowercorp.com/commercial/products-services/solar-trackers/>
- Suntech Power, 2011. Introducing Reliathon: Lowering the LCOE of Multi-Megawatt Projects, Suntech Power Holdings, San Francisco, http://am.suntech-power.com/images/stories/pdf/other/reliathon%20brochure_9-29-10_fnl.pdf
- Swanson R.M., 2006. A vision for crystalline silicon photovoltaics, Progress in Photovoltaics, 14, 443-453
- Swanson R.M., 2005. Approaching the 29% Limit Efficiency of Silicon Solar Cells, Proceedings 31st IEEE Photovoltaic Specialists Conference, Orlando, January 3-7, 889-894

T

- Taggart S., 2009. A Pan-Asian Energy Infrastructure, DESERTEC Asia, Sydney, www.desertec-asia.com/content/ts-introduction.html [access 18.03.2011]
- Taira K., Kogo N., Kikuchi H., Kumagai N., Kuratani N., Inagawa I., Omoto S., Nakata J., Biancardo M., 2005. New Type of Standard Measurements of Transparent Sphelar Modules, Proceedings 15th Photovoltaic Science & Engineering Conference, Shanghai, October 10-15
- Takeda Y. and Motohiro T., 2010. Realistic Limiting Conversion Efficiency Utilizing Multiple Exciton Generation, Proceedings 25th European Photovoltaic Solar Energy Conference/ WCPEC-5, Valencia, September, 6-10
- Tang C.W., Marchetti A.P., Young R.H., 1978. Organic photovoltaic element, US Patent 4,125,414, filed in November 14
- Tang C.W., 1986. Two-layer organic photovoltaic cell, Applied Physics Letters, 48, 183-185
- Teske S., Schäfer O., Zervos A., Béraneek J., Tunmore S., Krewitt W., Simon S., Pregger T., Schmid S., Graus W., Blomen W., 2008. energy [r]evolution: A Sustainable World Energy Outlook,

- Greenpeace International and EREC, Amsterdam and Brussels, October,
www.greenpeace.org/denmark/PageFiles/205220/new-global-energy-r-evolution.pdf
- Teske S. (ed.), 2010. energy [r]evolution: A Sustainable World Energy Outlook, Greenpeace International and EREC, Amsterdam and Brussels,
www.greenpeace.org/international/Global/international/publications/climate/2010/fullreport.pdf
- Teske S., 2011. private communications, June 13
- Thim F., Tapanlis S., Wade S., 2010. Conception and Operation of a Unique Large-scale PV Hybrid System on a Hebridean Island, Proceedings 25th European Photovoltaic Solar Energy Conference/WCPEC-5, Valencia, September 6-10
- [TI] – Transparency International, 2009. Global Corruption Report 2009: Corruption and the Private Sector, TI, Berlin, Cambridge University Press, Cambridge,
www.transparency.org/content/download/46187/739801/Global_Corruption_Report_2009_170909_2_web_2011.pdf
- Todorov T.K., Reuter K.B., Mitzi D.B., 2010. High-Efficiency Solar Cell with Earth-Abundant Liquid-Processed Absorber, *Advanced Energy Materials*, 22, E156-E159
- Trieb F., Quaschnig V., Viebahn P., Schillings C., Meyer R., Assmann D., Kronshage S., Lerchenmüller H., Morin G., Mannstein H., Geuder N., Dersch J., Häberle A., 2004. SOKRATES – Solarthermische Kraftwerkstechnologie für den Schutz des Erdklimas, study on behalf of Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit prepared by German Aerospace Center (DLR), Wuppertal Institut für Klima, Umwelt, Energie and Fraunhofer-Institute for Solar Energy Systems (FhG-ISE), Stuttgart, Wuppertal, Freiburg,
www.dlr.de/sokrates
- Trieb F., Kronshage S., Quaschnig V., Dersch J., Lerchenmüller H., Morin G., Häberle A., 2004. Sokrates-Projekt – Solarthermische Kraftwerkstechnologie für den Schutz des Erdklimas – AP 2.1 Modellbildung und -implementierung, German Aerospace Center (DLR), Stuttgart,
www.dlr.de/tt/institut/abteilungen/system/projects/all_projects/Projektbeschreibung_Sokrates/
- Trieb F., Schillings C., Kronshage S., Klann U., Viebahn P., May N., Wilde R., Paul C., Kabariti M., Bennouna A., Nokraschy El H., Hassan S., Yusef L.G., Hasni T., Bassam El N., 2005. Concentrating Solar Power for the Mediterranean Region, German Aerospace Center (DLR) by order of Federal Ministry for the Environment (BMU), Berlin, www.dlr.de/tt/med-csp
- Trieb F., Schillings C., Kronshage S., Viebahn P., May N., Paul C., (eds.), 2006. Trans-Mediterranean Interconnection for Concentrating Solar Power, Research of German Aerospace Center (DLR) by order of Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, www.dlr.de/tt/trans-csp
- Trieb F., Schillings C., O’Sullivan M., Pregger T., Hoyer-Klick C., 2009. Global Potential of Concentrating Solar Power, Proceedings SolarPACES 2009, Berlin, September 15–18
- Trieb F., Müller-Steinhagen H., Kern J., 2011. Financing concentrating solar power in the Middle East and North Africa – Subsidy or investment?, *Energy Policy*, 39, 307-317
- Trina Solar, 2010. Annual Report 2009, Changzhou, July 17, http://phx.corporate-ir.net/phoenix.zhtml?c=206405&p=irol-sec&secCat01.1_rs=11&secCat01.1_rc=10
- Tringas T. and Ballardin G., 2009. Q3 Levelised Cost of Energy Outlook, New Energy Finance, London, October 28
- Trupke T., Green M.A., Würfel P., 2002. Improving solar cell efficiencies by up-conversion of sub-band-gap light, *Journal of Applied Physics*, 92, 4117-4122
- Trupke T., Green M.A., Würfel P., 2002. Improving solar cell efficiencies by down-conversion of high-energy photons, *Journal of Applied Physics*, 92, 1668-1674

U

- [UN] - United Nations, 2007. World Population Prospects: The 2006 Revision Highlights, UN Department of Economic and Social Affairs, Population Division, New York, Working Paper No. ESA/P/WP.202,
www.un.org/esa/population/publications/wpp2006/WPP2006_Highlights_rev.pdf
- [UN] - United Nations, 2008. Statistical Yearbook 52nd issue, UN Department of Economic and Social Affairs Statistics Division, New York, <http://unstats.un.org/unsd/syb/syb52.pdf>
- [UN] - United Nations, 2009. Carbon Dioxide Emissions (CO₂), UN Department of Economic and Social Affairs Statistics Division, New York,

- <http://mdgs.un.org/unsd/mdg/SeriesDetail.aspx?srid=749&crd=>
- [UN] - United Nations, 2009. World Population Prospects: The 2008 Revision Highlights, UN Department of Economic and Social Affairs, Population Division, New York, Working Paper No. ESA/P/WP.210, http://esa.un.org/unpd/wpp2008/pdf/WPP2008_Highlights.pdf
- [UN] - United Nations, 2010. The Millennium Development Goals Report, UN Department of Economic and Social Affairs, New York, www.un.org/millenniumgoals/pdf/MDG%20Report%202010%20En%20r15%20-low%20res%2020100615%20-.pdf
- [UNDP] - United Nations, 2007. Human Development Report 2007/2008, UNDP, New York, <http://hdr.undp.org/en/reports/global/hdr2007-2008/>
- [UNEP] - United Nations Environment Programme, 2009. Global Trends in Sustainable Energy Investment 2009, UNEP and New Energy Finance (NEF), Paris and London, www.unep.org/pdf/Global_trends_report_2009.pdf
- [UNEP] - United Nations Environment Programme, 2010. Global Trends in Sustainable Energy Investment 2010, UNEP and Bloomberg New Energy Finance (BNEF), Paris and London, www.rona.unep.org/documents/news/GlobalTrendsInSustainableEnergyInvestment2010_en_full.pdf
- [UNFCCC] - United Nations Framework Convention on Climate Change, 2007. Investment and financial flows to address climate change, UNFCCC, Bonn, http://unfccc.int/cooperation_and_support/financial_mechanism/items/4053.php
- Ungeheuer U., 2006. Schott White Paper on Solar Thermal Power Plant Technology, Schott North America, New York, www.us.schott.com/solarthermal/english/download/schott_white_paper.pdf
- United Solar, 2011. United Solar Reaches 16.3% Efficiency with Nano-Crystalline Technology, United Solar a company of Energy Conversion Devices, Auburn Hills, press release, July 12, www.uni-solar.com/2011/07/united-solar-reaches-16-3-efficiency-with-nano-crystalline%E2%84%A2-technology/
- [UPDEA] - Union of Producers, Transporters and Distributors of Electric Power in Africa, 2009. Comparative study of electricity tariffs used in Africa, UPDEA, Abidjan, www.updea-africa.org/updea/DocWord/TarifAng2010.pdf

V

- Vallat-Sauvain E., Shah A., Bailat J., 2006. Advances in Microcrystalline Silicon Solar Cell Technologies, in: Poortmans J. and Arkhipov V., (eds.), Thin Film Solar Cells: Fabrication, Characterization and Applications, John Wiley & Sons, Chichester
- Vallvé X., Vossler I., Cisneros de E.J., Gafas G., Serrassolses J., Vázquez M., Schweizer-Ries P., Mosler H.J., 2001. First Experiences from the Electrification of Rural Villages in Spain with Multi-user Solar Hybrid Grids (MSG), Proceedings 17th European Photovoltaic Solar Energy Conference, Munich, October 22-26
- Vallvé X., Graillot A., Cadilla D., Vázquez I., Izquierdo P., Pose M., Vázquez M., 2008. PV Hybrid Micro-Grid Experience in Morocco, Proceedings 4th European PV-Hybrid and Mini-Grid Conference, Athens, May 29-30
- Vázquez M., Fernandes F., Santos J., 2004. A 14 kWp Stand-alone Photovoltaic Plant in the Natural Park of O'Invernandero in Galicia, Spain, Proceedings 19th European Photovoltaic Solar Energy Conference, Paris, June 7-11
- Vetter M., Dennenmoser M., Schwunk S., Smolinka T., Dötsch C., Berthold S., Tübke J., Noack J., 2010. Redox flow batteries – Already an alternative storage solution for hybrid PV mini-grids?, Proceedings 5th European PV-Hybrid and Mini-Grid Conference, Tarragona, April 29-30
- Viebahn P., Kronshage S., Trieb F., Lechon Y., 2008. NEEDS: Final report on technical data, costs and life cycle inventories of solar thermal power plants, German Aerospace Centre (DLR), Stuttgart, www.needs-project.org/RS1a/RS1a%20D12.2%20Final%20report%20concentrating%20solar%20thermal%20power%20plants.pdf
- Viebahn P., Lechon Y., Trieb F., 2011. The potential role of concentrated solar power (CSP) in Africa and Europe – A dynamic assessment of technology development cost development and life cycle inventories until 2050, Energy Policy, 39, 4420-4430
- Villiers De T., 2007. Terminal Evaluation of the project 'Building Sustainable Commercial

- Dissemination Networks for Household PV Systems in Eastern Africa', Project No: GF/4040-04-22, United Nations Environment Programme (UNEP), Nairobi,
www.unep.org/eou/Pdfs/Household_PV.pdf
- Voigt W., 2007. *Atlantropa. Weltbauen am Mittelmeer. Ein Architektentraum der Moderne*, Grosser + Stein, Pforzheim
- Vos de A. and Pauwels H., 1981. On the Thermodynamic Limit of Photovoltaic Energy Conversion, *Applied Physics*, 25, 119-125
- Vosseler I., Ramírez E., Vallvé X., Carreras J.M., 2004. PV Hybrid Village Electrification in Spain: 6 Years Experience with MSG (Multi-user Solar Hybrid Grids), *Proceedings 19th European Photovoltaic Solar Energy Conference*, Paris, June 7-11

W

- Wacker Chemie, 2010. *Geschäftsbericht 2009*, Munich, March 17,
www.wacker.com/cms/media/de/documents/wacker_group/annual_report_09.pdf
- Wackernagel M., Onisto L., Bello P., Linares A.C., Falfán I.S.L., García J.M., Guerrero A.I.S., Guerrero G.S., 1999. National natural capital accounting with the ecological footprint concept, *Ecological Economics*, 29, 375-390
- Wackernagel M., Schulz N.B., Deumling D., Linares A.C., Jenkins M., Kapos V., Monfreda C., Loh J., Myers N., Norgaard R., Randers J., 2002. Tracking the ecological overshoot of the human economy, *Proceedings of the National Academy of Science*, 99, 9266-9271
- Wackernagel M. and Beyers B., 2010. *Der Ecological Footprint: Die Welt neu vermessen*, Europäische Verlagsanstalt, Hamburg
- Wadia C., Alivisatos A.P., Kammen D.M., 2009. Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment, *Environmental Science & Technology*, 43, 2072-2077
- Wärtsilä, 2009. *Oil Power Plants*, Wärtsilä, Helsinki, www.wartsila.com
- Wagemann H.-G. and Eschrich H., 1994. *Grundlagen der photovoltaischen Energiewandlung: Solarstrahlung, Halbleitereigenschaften und Solarzellenkonzepte*, B.G. Teubner, Stuttgart
- Wagner S., Shay J.L., Migliorato P., Kasper H.M., 1974. CuInSe₂/CdS heterojunction photovoltaic detectors, *Applied Physics Letters*, 25, 434-435
- Walter J., Wade H., Jensen T., Clay B., Langham E., 2008. A Trail PV Mini-Grid Installation for Small Islands, *Proceedings 4th European PV-Hybrid and Mini-Grid Conference*, Athens, May 29-30
- Wang L. and Singh C., 2007. PSO-based Hybrid Generating System Design Incorporating Reliability Evaluation and Generation/Load Forecasting, *Proceedings of the Power Technology*, Lausanne, July 1-5
- Watanabe C., Wakabayashi K., Miyazawa T., 2000. Industrial dynamism and the creation of a "virtuous cycle" between R&D market growth and price reduction: The case of photovoltaic power generation (PV) development in Japan, *Technovation*, 20, 299-312
- [WBGU] – German Advisory Council on Global Change, 2003. *World in Transition: Towards Sustainable Energy Systems*, WBGU, Berlin, Earthscan, London,
www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2003/wbgu_jg2003_engl.pdf
- [WBGU] – German Advisory Council on Global Change, 2007. *Climate Change as a Security Risk*, WBGU, Berlin, Earthscan, London,
www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2007/wbgu_jg2007_engl.pdf
- [WBGU] – German Advisory Council on Global Change, 2011. *Welt im Wandel: Gesellschaftsvertrag für eine Große Transformation*, WBGU, Berlin,
www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/hauptgutachten/jg2011/wbgu_jg2011.pdf
- Weingart J.M., 1978. The Helios Strategy: An Heretical View of the Potential Role of Solar Energy in the Future of a Small Planet, *Technological Forecasting and Social Change*, 12, 273-315
- Weingart J.M., 1979. Global aspects of sunlight as a major energy source, *Energy*, 4, 775-798
- Welzer H., 2008. *Klimakriege – Wofür im 21. Jahrhundert getötet wird*, S. Fischer Verlag, Frankfurt a.M.

- Wengenmayr R., 2007. Wasserkraftwerke: Fließende Energie, in: Bührke T. and Wengenmayr R., (eds.), Erneuerbare Energie: Alternative Energiekonzepte für die Zukunft, WILEY-VCH, Weinheim
- Wenzel B. and Nitsch J., 2010. Langfristszenarien und Strategien für den Ausbau der Erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global: Entwicklung der EEG-Vergütungen, EEG-Differenzkosten und der EEG-Umlage bis zum Jahr 2030 auf Basis des Leitszenario 2010, study on behalf of BMU prepared by DLR, FhG-IWES and IfnE, June, www.erneuerbare-energien.de/files/pdfs/allgemein/application/pdf/langfristszenarien_ee_bf.pdf
- Werner C., Gerlach A., Adelmann P., Breyer Ch., 2011. Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, Proceedings 26th European Photovoltaic Solar Energy Conference, Hamburg, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.8
- Werner C., Gerlach A., Adelmann P., Breyer Ch., 2011. Global Overview on cumulative installed Photovoltaic Power, Proceedings 2nd Symposium Small PV-Applications, Ulm, June 6-7
- Werner C., 2011. Grid-Parity für Photovoltaik mit Energiespeicher, Bachelor thesis [supervised by the author of this PhD thesis], Anhalt University of Applied Sciences
- [WHO] – World Health Organization, 2010. Progress on Sanitation and Drinking-water: 2010 Update, WHO and UNICEF, Geneva, http://whqlibdoc.who.int/publications/2010/9789241563956_eng_full_text.pdf
- Wild-Scholten de M.J., Glockner R., Odden J.O., Halvorsen G., Tronstad R., 2008. LCA comparison of the Elkem solar metallurgical route and conventional gas routes to solar silicon, Proceedings 23rd European Photovoltaic Solar Energy Conference, Valencia, September 1-5
- Wild-Scholten de M. and Schottler M., 2009. Solar as an environmental product: Thin-film modules – production processes and their environmental assessment, Thin Film Industry Forum, Berlin, April 24
- Wild-Scholten de M., 2011. Solar as an environmental product, SRC/ Masdar Institute Forum on Solar-Electric Energy Systems (SEES), Abu Dhabi, March 27-28
- Winter C.J., 1981. Wasserstoff als Sekundärenergieträger, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR), Stuttgart
- [WIPO] - World Intellectual Property Organization, 2009. World Intellectual Property Indicators 2009, WIPO, Geneva, www.wipo.int/ipstats/en/statistics/patents/
- [WIPO] - World Intellectual Property Organization, 1883. Paris Convention for the Protection of Industrial Property, WIPO, Paris, March 20, www.wipo.int/treaties/en/ip/paris/trtdocs_wo020.html
- Wiser R., Barbose G., Peterman C., Darghouth N., 2009. Tracking the Sun II – The Installed Cost of Photovoltaics in the U.S. form 1998-2008, Lawrence Berkeley National Laboratory, Berkeley, LBNL-2674E, <http://eetd.lbl.gov/ea/emp/reports/lbnl-2674e.pdf>
- [WNA] - World Nuclear Association, 2010. Supply of Uranium, WNA, London, December, <http://www.world-nuclear.org/info/inf75.html>
- Wojtczuk S., Chiu P., Zhang X., Derkacs D., Harris C., Pulver D., Timmons M., 2010. InGaP/GaAs/InGaAs concentrators using Bi-facial epigrowth, Proceedings 35th IEEE Photovoltaic Specialists Conference, Honolulu, June 20-25
- Wood R., Gilbert P., Sharmina M., Anderson K., Footitt A., Glynn S., Nicholls F., 2011. Shale gas: a provisional assessment of climate change and environmental impacts, Tyndall Centre for Climate Change Research, Manchester, January, www.tyndall.ac.uk/sites/default/files/tyndall-coop_shale_gas_report_final.pdf
- World Bank, 2009. Gross domestic product 2008, World Development Indicators database, World Bank, Washington, <http://siteresources.worldbank.org/DATASTATISTICS/Resources/GDP.pdf>
- World Bank, 2010. Gross Domestic Production 2009, World Development Indicators database, World Bank, Washington, <http://siteresources.worldbank.org/datastatistics/Resources/GDP.pdf>
- Wright T.P., 1936. Factors Affecting the Cost of Airplanes, Journal of the Aeronautical Sciences, 3, 122-126
- Wu X., Keane J.C., Dhere R.G., DeHart C., Albin D.S., Duda A., Gessert T.A., Asher S., Levi D.H., Sheldon P., 2001. 16.5%-Efficient CdS/CdTe polycrystalline thin-film solar cell, Proceedings 17th European Photovoltaic Solar Energy Conference, Munich, October 22-26
- Würfel P., 2000. Physik der Solarzellen, 2nd ed., Spektrum Akademischer Verlag, Heidelberg

- [WWF] – World Wild Fund for Nature International, 2010. Living Planet Report 2010: Biodiversity, biocapacity and development, WWF, Zoological Society of London and Global Footprint Network, Gland, <http://assets.panda.org/downloads/lpr2010.pdf>
- [WWF] – World Wild Fund for Nature International, 2011. The Energy Report: 100% Renewable Energy by 2050, WWF, Ecofys and Office for Metropolitan Architecture, Gland, http://assets.panda.org/downloads/101223_energy_report_final_print_2.pdf

Y

- Yelle L.E., 1979. The learning curve: historical review and comprehensive survey, *Decision Science*, 10, 302-328
- Yingli Green Energy Holding, 2010. Annual Report 2009, Baoding, June 25, <http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9Mzg3NjE5fENoaWxkSUQ9MzkwMTk3fFR5cGU9MQ==&t=1>
- Yoshimi M., Sasaki T., Sawada T., Suezaki T., Meguro T., Matsuda T., Santo K., Wadano K., Ichikawa M., Nakajima A., Yamamoto K., 2003. High Efficiency Thin Film Silicon Hybrid Solar Cell Module on 1m²-Class Large Area Substrate, *Proceedings 3rd World Conference on Photovoltaic Energy Conversion*, Osaka, May 11-18, 1566–1569

Z

- Zehner M., Weigl T., Hartmann M., Mayer B., Betts T., Gottschalg R., Löblein H., Giesler B., Becker G., Mayer O., 2011. Europaweite Untersuchung des Irradiance Enhancement Effects und erste Analysen der Bedeutung im PV-System, 26. Symposium Photovoltaische Solarenergie, Bad Staffelstein, March 2-4
- Zeman M., 2006. Advanced Amorphous Silicon Solar Cell Technology, in: Poortmans J. and Arkhipov V., (eds.), *Thin Film Solar Cells: Fabrication, Characterization and Applications*, John Wiley & Sons, Chichester
- Zhang B., Yang Y., Gan L., 2008. Dynamic Control of Wind/Photovoltaic Hybrid Power Systems Based on an Advanced Particle Swarm Optimization, *Proceedings of IEEE International Conference on Industrial Technology*, Chengdu
- Zhao J., Wang A., Green M.A., 1999. 24.5% Efficiency Silicon PERT Cells on MCZ Substrates and 24.7% Efficiency PERL Cells on FZ Substrates, *Progress in Photovoltaics: Research and Applications*, 7, 471-474
- Zhou Y., Riehle F.S., Yuan Y., Schleiermacher H.-F., Niggemann M., Urban G.A., Krüger M., 2010. Improved efficiency of hybrid solar cells based on non-ligand-exchanged CdSe quantum dots and poly(3-hexylthiophene), *Applied Physics Letters*, 96, 013304
- Zhou W., Yang H., Fang Z., 2008. Battery behaviour prediction and battery working states analysis of a hybrid solar-wind power generation system, *Renewable Energy*, 33, 1413-1423
- Zittel W. and Schindler J., (eds.), 2006. Uranium Resources and Nuclear Energy, Energy Watch Group, EWG-Series No 1/2006, Ottobrunn, www.energywatchgroup.org/files/uraniumreport.pdf
- Zittel W. and Schindler J., (eds.), 2007. Coal: Resources and future production, Energy Watch Group, EWG-Series No 1/2007, Ottobrunn, www.energywatchgroup.org/files/coalreport.pdf
- Zittel W., 2008. Ist Erdgas eine Alternative zum Erdöl?, ASPO Deutschland, Ottobrunn, February 5, <http://energiekrise.de/index.html>
- Zittel W., 2010. Unkonventionelles Erdgas, study on behalf of ASPO Deutschland and EWG, Ottobrunn, May, www.energiekrise.de/news/gazette/2010/shale_gas_15_Mai2010final.pdf
- Zwaan v.d. B. and Rabl A., 2003. Prospects for PV: a learning curve analysis, *Solar Energy*, 74, 19-31
- Zwaan v.d. B. and Rabl A., 2004. The learning potential of photovoltaics: implications for energy policy, *Energy Policy*, 32, 1545-1554
- Zweibel K., James E.M., Fthenakis V., 2008. A solar grand plan, *Scientific American*, 298(1), 64-73
- Zweibel K., 2010. The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics, *Science*, 328, 699-671
- Zweibel K., 2010. Should solar photovoltaics be deployed sooner because of long operating life at low, predictable cost?, *Energy Policy*, 38, 7519-7530

List of Acronyms and Abbreviations

III-V TJ triple junction solar cells based on semiconductors of the III. and V. main group elements

A

AC alternating current
ARE Alliance for Rural Electrification, Brussels
ASPO Association for the Study of Peak Oil and Gas

B

BCG Boston Consulting Group
BMU Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, Germany
BMWi Bundesministerium für Wirtschaft und Technologie, Berlin, Germany
bnCU billion currency unit, mainly € and USD
BOS balance of systems

C

Capex capital expenditures, often investment cost
CCGT combined cycle gas turbine
CCS carbon capture and sequestration
ccTLD country code top-level domain
CdTe Cadmium and Tellurium, used in relation to CdTe PV
CEA Central Electricity Authority, New Delhi
CERC Central Electricity Regulatory Commission, New Delhi
CIESIN Center for International Earth Science Information Network, New York
CIGS Copper Indium Gallium Selenide, used in relation to CIGS PV
CO₂ carbon dioxide
CSG crystalline silicon on glass
c-Si crystalline silicon, used in relation to c-Si PV
CSP concentrating solar power; similar to STEG
CZTS Copper Zinc Tin Sulfur, used in relation to CZTS PV

D

d day(s)
DC direct current
DHI direct horizontal irradiation
DIF diffuse horizontal irradiation
Dii Desertec Industrial Initiative, Munich
DLR German Aerospace Center
DNI direct normal irradiation
DoE US Department of Energy, Washington
DPG-AKE Deutsche Physikalische Gesellschaft – Arbeitskreis Energie
DR annual system degradation rate
DSO distribution service operator
DSSC dye-sensitized solar cell

E

EBIT earnings before interest and tax
EC European Commission, Brussels
ECF European Climate Foundation
EDI energy development index

EEPCo	Ethiopian Electricity Power Company
EIA	Energy Information Administration, an agency of US Department of Energy
eg-Si	electronic-grade silicon
EPIA	European Photovoltaic Industry Association, Brussels
EPBT	energy payback time
EROI	energy return on energy investment
ESTELA	European Solar Thermal Electricity Association
ETB	Ethiopian Birr
EU	European Union
EU-MENA	European Union and Middle East North Africa
EWEA	European Wind Energy Association, Brussels

F

FiT	feed-in tariff
FLh	full load hours

G

GaAs	Gallium Arsenide, used in relation to GaAs PV
GCR	ground cover ratio
GDP	gross domestic product
GEOS-4	Goddard Earth Observing System model version 4
GEWEX	NASA's Global Energy and Water Cycle Experiment
GHG	greenhouse gas
GHI	global horizontal irradiation
GMAO	Global Model and Assimilation Office
GNI	global normal irradiation
GT	gas turbine
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit, Eschborn, now GIZ
GWEC	Global Wind Energy Council
GWh _{el}	electric gigawatt hours
GWh _{th}	thermal gigawatt hours
GW	gigawatt (10^9 W)
GWp	gigawatt peak (10^9 Wp), i.e. peak power at STC
GWpV3	Gridded Population of the World Version 3

H

h	hour(s)
HC	headcount, often staff or associates
HCPV	high concentrating PV
HDI	human development index
HDKR	Hay-Davis-Klucher-Reindl (HDKR) model
HVAC	high voltage alternating current
HVDC	high voltage direct current

I

IBSC	intermediate bandgap solar cell
IEA	International Energy Agency, Paris
IEA-OES	International Energy Agency Implementation Agreement on Ocean Energy Systems
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme
IEEE	Institute of Electrical and Electronics Engineers
IGCC	integrated gasification combined cycle
IP	intellectual property
IPCC	Intergovernmental Panel on Climate Change, Geneva
IRR	internal rate of return
ITC	International Trade Centre, Geneva

J**K**

kCU	thousand currency unit, mainly € and USD
KfW	Kreditanstalt für Wiederaufbau
kWh _{el}	electric kilowatt hours
kWh _{th}	thermal kilowatt hours
kW	kilowatt (10^3 W)
kWp	kilowatt peak (10^3 Wp), i.e. peak power at STC

L

LCA	life cycle assessment
LCOE	levelized cost of electricity
LCPV	low concentrating PV
LNG	liquefied natural gas
LR	learning rate, equal to unity minus progress ratio

M

mc-Si	multi-crystalline Si
mCU	million currency unit, mainly € and USD
MED-ENEC	Energy Efficiency in the Construction Sector in the Mediterranean
MENA	Middle East and North Africa
MERRA	Modern Era Retrospective-analysis for Research and Applications
Mtoe	megaton oil equivalent
MWh _{el}	electric megawatt hours
MWh _{th}	thermal megawatt hours
MW	megawatt (10^6 W)
MWp	megawatt peak (10^6 Wp), i.e. peak power at STC

N

NAFTA	North American Free Trade Agreement
NAO	National Audit Office, UK
NASA	National Aeronautics and Space Administration
NG	natural gas
NREL	National Renewable Energy Laboratory, an agency of US Department of Energy
NYS	New York State

O

OECD	Organisation for Economic Co-operation and Development
Opex	operational expenditures, often operation and maintenance cost
OPV	organic PV
ORC	organic Rankine cycles

P

PCT	Patent Cooperation Treaty
PR	progress ratio, equal to unity minus learning rate
PS	pico system, similar to SHS
PV	Photovoltaic
PVSEC	Photovoltaic Solar Energy Conference and Exhibition

Q

QD	quantum dot
QW	quantum well

R

RES	renewable energy sources
R&D	research and development
RO	reverse osmosis
RoE	return on equity
RoW	rest of world
RPM	renewable power methane

S

SC	solar cell
sc-Si	mono-crystalline silicon, often single-crystalline silicon
SHS	solar home system
Si	silicon
SM	solar multiple
sog-Si	solar-grade silicon, often upgraded metallurgical silicon (umg-Si)
SRB	Surface Radiation Budget
SSE	Surface meteorology and Solar Energy
SSERC	Sahara Solar Energy Research Center
ST	steam turbine
STC	standard test conditions of PV systems
STEG	solar thermal electricity generation, often concentrating solar power (CSP)

T

TF	thin-film
TI	Transparency International
TPV	thermo photovoltaic
TLCC	total life cycle cost
TSO	transmission service operator
TWh _{el}	electric terawatt hours
TWh _{th}	thermal terawatt hours
TW	terawatt (10^{12} W)
TWp	terawatt peak (10^{12} Wp), i.e. peak power at STC

U

UDI	Platts' Utility Data Institute, a division of The McGraw-Hill Companies
umg-Si	upgraded metallurgical silicon, often solar-grade silicon (sog-Si)
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UPDEA	Union of Producers, Transporters and Distributors of Electric Power in Africa
US	United States of America
USD	US Dollar

V**W**

WACC	weighted average cost of capital
WHO	World Health Organization
WIPO	World Intellectual Property Organization
W	watt
Wp	watt peak, i.e. peak power at STC
WWF	World Wild Fund for Nature International

X**Y**

y year(s)

Z

List of Figures

- Fig. 1.1-1:** Global electricity generation in the years 1945 to 2009.
- Fig. 1.2-1:** Global distribution of energy related CO₂ emissions per area for the year 2006.
- Fig. 1.2-2:** Global distribution of energy related CO₂ emissions per capita for the year 2006.
- Fig. 1.2-3:** Security risks associated with climate change at selected hotspots.
- Fig. 1.3-1:** Annual discoveries and production of crude oil for the years 1920 – 2006.
- Fig. 1.3-2:** Oil producing nations being already beyond the peak in annual production.
- Fig. 1.3-3:** Historic global oil production in the past and prognosis on the future.
- Fig. 1.3-4:** Natural gas discoveries and exploitation curve for the 1920s – 2000s and projected expectations.
- Fig. 1.3-5:** Global hard and lignite coal production for the years 1950 – 2005 and a projection up to the year 2100.
- Fig. 1.3-6:** Global uranium mining in the past and the commercial potential in future compared to the demand of nuclear power plants.
- Fig. 1.3-7:** Net energy of the nuclear fuel chain as a function of uranium ore grade.
- Fig. 1.3-8:** Specific greenhouse gas emissions of the nuclear power normalized to natural gas fired power plants as a function of uranium ore grade.
- Fig. 1.4-1:** Global distribution of population without access to electricity in the year 2009 and expected for the year 2030.
- Fig. 1.4-2:** Incremental electricity generation and capital investment for reaching the universal modern energy access target in the year 2010 – 2030.
- Fig. 1.4-3:** The human development index as a function of the energy development index for developing countries for the year 2009.
- Fig. 1.4-4:** GDP per capita in dependence on the final electricity consumption per capita for all countries in the world.
- Fig. 1.4-5:** Major individual aspects indicating social progress in dependence on final electricity consumption per capita for nearly all countries in the world.
- Fig. 1.5-1:** Development of global ecological footprint by major contributors for the years 1961 – 2007.
- Fig. 2.1-1:** Annual global horizontal irradiation.
- Fig. 2.1-2:** Diffuse horizontal irradiation.
- Fig. 2.1-3:** Ratio of diffuse to global annual horizontal irradiation.
- Fig. 2.2-1:** Overview on different solar power technologies and their respective solar resources.
- Fig. 2.2-2:** Components of irradiation on tilted surfaces and geometric composition of coordinate systems of earth, sun and PV module.
- Fig. 2.2-3:** Annual irradiation on module surface of fixed optimally tilted PV systems at tilt angle for optimised irradiation.
- Fig. 2.2-4:** Annual increased irradiation on module surface of fixed optimally tilted PV systems at tilt angle for optimised irradiation versus global horizontal irradiation in absolute and relative numbers.
- Fig. 2.2-5:** Optimal tilt angles for fixed tilted PV systems for optimised irradiation on module surface.
- Fig. 2.2-6:** Deviation of irradiation optimised to latitude tilt angle of fixed tilted PV systems.
- Fig. 2.2-7:** Hourly irradiation on module profile of fixed optimally tilted PV systems.
- Fig. 2.2-8:** Optimal tilt angles for fixed tilted PV systems for minimising LCOE.
- Fig. 2.2-9:** Deviation of levelized cost of electricity optimised to latitude tilt angle of fixed tilted PV systems.
- Fig. 2.2-10:** Tilt angle dependence of annual irradiation on module surface for a site in Southern Germany.
- Fig. 2.2-11:** Annual irradiation on module surface of 1-axis horizontal east-west continuous tracking PV systems.
- Fig. 2.2-12:** Annual increased irradiation on module surface of 1-axis horizontal east-west continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute and relative numbers.
- Fig. 2.2-13:** Hourly irradiation on module profile of 1-axis horizontal east-west continuous tracking PV systems and irradiation increase in reference to fixed optimally tilted PV systems.
- Fig. 2.2-14:** Annual irradiation on module surface of 1-axis horizontal north-south continuous tracking PV systems.
- Fig. 2.2-15:** Annual increased irradiation on module surface of 1-axis horizontal north-south continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute and relative numbers and versus 1-axis horizontal east-west continuous tracking PV systems in absolute and relative numbers.

- Fig. 2.2-16:** Hourly irradiation on module profile of 1-axis horizontal north-south continuous tracking PV systems, irradiation increase in reference to fixed optimally tilted PV systems and irradiation increase in reference to 1-axis horizontal east-west continuous tracking PV systems.
- Fig. 2.2-17:** Annual irradiation on module surface of 1-axis vertical optimally tilted continuous tracking PV systems.
- Fig. 2.2-18:** Annual increased irradiation on module surface of 1-axis vertical optimally tilted continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute and relative numbers and versus 1-axis horizontal north-south continuous tracking PV systems in absolute and relative numbers.
- Fig. 2.2-19:** Hourly irradiation on module profile of 1-axis vertical optimally tilted continuous tracking PV systems, irradiation increase in reference to fixed optimally tilted PV systems and irradiation increase in reference to 1-axis horizontal north-south continuous tracking PV systems.
- Fig. 2.2-20:** Annual irradiation on module surface of 1-axis optimally tilted north-south continuous tracking PV systems.
- Fig. 2.2-21:** Annual increased irradiation on module surface of 1-axis optimally tilted north-south continuous tracking PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute and relative numbers, versus 1-axis horizontal north-south continuous tracking PV systems in absolute and relative numbers and versus 1-axis vertical optimally tilted continuous tracking PV systems in absolute and relative numbers.
- Fig. 2.2-22:** Hourly irradiation on module profile of 1-axis optimally tilted north-south continuous tracking PV systems and irradiation increase in reference to fixed optimally tilted PV systems.
- Fig. 2.2-23:** Annual irradiation on module surface of 2-axes non-concentrating continuous tracking PV systems.
- Fig. 2.2-24:** Annual increased irradiation on module surface of 2-axes non-concentrating continuous tracking (GNI) PV systems versus fixed optimally tilted PV systems at tilt angle for optimised irradiation in absolute and relative numbers and versus 1-axis horizontal north-south continuous tracking PV systems in absolute and relative numbers.
- Fig. 2.2-25:** Annual increased irradiation on module surface of 2-axes non-concentrating continuous tracking (GNI) PV systems versus 1-axis vertical optimally tilted continuous tracking PV systems in absolute and relative numbers and versus 1-axis optimally tilted north-south continuous tracking PV systems in absolute and relative numbers.
- Fig. 2.2-26:** Hourly irradiation on module profile of 2-axes non-concentrating continuous tracking (GNI) PV systems, irradiation increase in reference to fixed optimally tilted PV systems and irradiation increase in reference to 1-axis horizontal north-south continuous tracking PV systems.
- Fig. 2.2-27:** Annual irradiation on module surface of 2-axes concentrating continuous tracking PV systems.
- Fig. 2.2-28:** Annual irradiation loss on module surface of 2-axes concentrating continuous tracking (DNI) PV systems versus 2-axes non-concentrating continuous tracking (GNI) PV systems in absolute and relative numbers and versus 1-axis horizontal north-south continuous tracking PV systems in absolute and relative numbers.
- Fig. 2.3-1:** Global population density for the year 2010.
- Fig. 2.3-2:** Distribution of world population and land masses on earth in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 2.3-3:** Global electricity generation in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 2.4-1:** Absolute solar resource quality and respective relative performance in reference to fixed optimally tilted PV systems of representative coordinates in Southern (Brazil) and Northern (Saudi Arabia) hemisphere.
- Fig. 3.1-1:** Historic PV production in dependence of major inventions and market segments.
- Fig. 3.1-2:** Growth rates of PV and comparable industries.
- Fig. 3.1-3:** Learning curve for PV modules for the mid 1970s - 2010.
- Fig. 3.1-4:** Public energy R&D investments in OECD for the years 1974 – 2008 in absolute and relative numbers.
- Fig. 3.1-5:** Public R&D investments of OECD in RES for the years 1974 – 2008 in absolute and relative numbers.
- Fig. 3.1-6:** Annual and historic cumulated public R&D investments of OECD in PV for the years 1974 – 2008.
- Fig. 3.1-7:** Correlation of PV industry sales growth rates and R&D investment growth rate for public listed PV companies for the years 2004 - 2009.
- Fig. 3.1-8:** PV and inverter patent families filed in at least one country for the years 1950 – 2008.
- Fig. 3.1-9:** Correlation of PV industry sales growth rates and PV patent application growth rate for the years 1994 - 2009.

- Fig. 3.1-10:** International PV patent families in absolute numbers and relative numbers for the years 1950 – 2008.
- Fig. 3.1-11:** Ratio of PV and inverter to all international patent families filed in the world for the years 2000 – 2008.
- Fig. 3.1-12:** International PV patent families by countries of origin in absolute and relative numbers for the years 1950 – 2008.
- Fig. 3.1-13:** International PV patent families by technology for the years 1960 – 2008.
- Fig. 3.1-14:** Public and business assignees of international patent families in absolute and relative numbers for the years 1950 – 2008.
- Fig. 3.1-15:** Total PV R&D investments estimated by international patent families per year and historic cumulated for the years 1950 – 2008.
- Fig. 3.1-16:** Ratio of public to total PV R&D investments for the years 1975 – 2008.
- Fig. 3.1-17:** PV R&D headcount in global absolute numbers and in ratio to total global R&D headcount for the years 2000 – 2009.
- Fig. 3.1-18:** PV industry sales for the years 1979 – 2010.
- Fig. 3.1-19:** PV markets in absolute and relative numbers per country for the years 1993 – 2010.
- Fig. 3.1-20:** Global installed PV capacity per country by end of 2010.
- Fig. 3.1-21:** Growth rate of cumulative installed PV capacity in the year 2010.
- Fig. 3.1-22:** Global installed PV capacity per gross domestic product by end of 2010.
- Fig. 3.1-23:** Ratio of global installed PV capacity to total power plant capacity per country by end of 2010.
- Fig. 3.1-24:** Overview on PV technologies already introduced to the market and still in the laboratory.
- Fig. 3.1-25:** Progress of best solar cell research efficiencies of all major PV technologies for the years 1976 – 2011.
- Fig. 3.1-26:** Large area module efficiency range of commercially sold products for all major PV technologies in the year 2010.
- Fig. 3.1-27:** Market share of all major commercial PV technologies for the years 1999 – 2010.
- Fig. 3.1-28:** Overview on device structure of major PV technologies.
- Fig. 3.1-29:** Abundance of elements in earth's upper continental crust normalised to silicon.
- Fig. 3.1-30:** Energy payback time of currently used PV technologies at sunny sites.
- Fig. 3.1-31:** Specific CO_{2eq} greenhouse gas emissions of currently used PV technologies at sunny sites.
- Fig. 3.2-1:** Schematic overview on the LCOE and its impact factors and interdependencies.
- Fig. 3.2-2:** Fundamental geometric characteristics for shading in PV power plants.
- Fig. 3.2-3:** Irradiation on module surface in dependence on ground cover ratio.
- Fig. 3.2-4:** Shading loss characteristic of a PV system.
- Fig. 3.2-5:** Capital expenditures of PV systems in 2010s for the scenarios realistic, aggressive and bloody.
- Fig. 3.2-6:** LCOE, Capex and final yield in dependence on module efficiency and GCR of a fixed optimally tilted PV system in realistic scenario assumptions.
- Fig. 3.2-7:** LCOE, Capex and final yield in dependence on module efficiency and GCR of a 1-axis horizontal north-south continuous tracking PV system in realistic scenario assumptions.
- Fig. 3.2-8:** Highest irradiation on module surface and lowest LCOE of PV systems.
- Fig. 3.2-9:** LCOE of PV systems in the 2010s for the scenarios realistic, aggressive and bloody.
- Fig. 3.2-10:** Global fully-loaded PV industry cost curve for utility-scale and roof-top systems in the year 2010.
- Fig. 3.2-11:** Global fully-loaded PV industry cost curve for c-Si and thin-film module manufacturers in the year 2010.
- Fig. 3.2-12:** Global fully-loaded PV industry cost curve for non-module costs in the relevant PV markets in the year 2010.
- Fig. 3.2-13:** Global LCOE of relevant PV systems in the year 2010 for the realistic scenario.
- Fig. 3.2-14:** Least LCOE of all PV systems and name of respective system in the realistic scenario in year 2010.
- Fig. 3.2-15:** Relative difference of each PV systems to least LCOE of all PV systems in the realistic scenario in year 2010.
- Fig. 3.2-16:** Least cost of fixed optimally tilted PV system in the 2010s for the realistic scenario.
- Fig. 3.2-17:** Least cost of all PV systems in the 2010s for the realistic scenario.
- Fig. 3.2-18:** Least cost of all PV systems in the 2010s for the aggressive scenario.
- Fig. 3.2-19:** Least cost PV system technology in the year 2010 for the realistic scenario in dependence on module efficiency.
- Fig. 3.2-20:** Least cost PV system technology in the year 2010 for the aggressive scenario in dependence on module efficiency.
- Fig. 3.2-21:** Least cost PV system technology for 15% efficient modules for the realistic scenario in the 2010s.
- Fig. 3.2-22:** Least cost PV system technology for 15% efficient modules for the aggressive scenario in the 2010s.

- Fig. 3.2-23:** Least cost PV system technology in the year 2020 for the realistic scenario in dependence on module efficiency.
- Fig. 3.2-24:** Least cost PV system technology in the year 2020 for the aggressive scenario in dependence on module efficiency.
- Fig. 3.3-1:** Global overview on residential and industrial electricity prices for the year 2010.
- Fig. 3.3-2:** Grid-parity analysis for Europe in 2010, 2013, 2016 and 2020.
- Fig. 3.3-3:** Grid-parity analysis for the Americas in 2010, 2013, 2016 and 2020.
- Fig. 3.3-4:** Grid-parity analysis for Africa in 2010, 2013, 2016 and 2020.
- Fig. 3.3-5:** Grid-parity analysis for Asia-Pacific in 2010, 2013, 2016 and 2020.
- Fig. 3.3-6:** Global overview on residential grid-parity for the years 2010 to 2020.
- Fig. 3.3-7:** Overview on residential grid-parity event dynamics in dependence on local electricity prices and solar irradiation.
- Fig. 3.3-8:** Grid-Parity market volume for residential segments in absolute and relative numbers for all regions in the world in the years 2010 to 2020.
- Fig. 3.3-9:** Grid-Parity market volume for industrial segments in absolute and relative numbers for all regions in the world in the years 2010 to 2020.
- Fig. 3.3-10:** PV system prices in the 2010s assumed for grid-parity analysis.
- Fig. 3.3-11:** Grid-parity dynamics in Spain – residential segment.
- Fig. 3.4-1:** Global access to electricity in percent of local population.
- Fig. 3.4-2:** Population without access to electricity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 3.4-3:** Payback period of small off-grid PV systems in Ethiopia.
- Fig. 3.4-4:** Electrification rate in dependence on GDP per capita for developing countries.
- Fig. 3.4-5:** Global diesel price distribution.
- Fig. 3.4-6:** Amortization period for 2 Wp PS, 10 Wp SHS and 50 Wp SHS.
- Fig. 3.4-7:** Capitalized value of 2 Wp PS, 10 Wp SHS and 50 Wp SHS at the point in time of full amortization till the end of lifetime.
- Fig. 3.4-8:** Electric design of a hybrid PV-Wind-Hydro-Battery-Diesel system coupled at a direct current bus bar and an alternating current bus bar.
- Fig. 3.4-9:** Typical layout of a hybrid PV-Diesel mini-grid.
- Fig. 3.4-10:** Optimal system type at different natural conditions with fixed diesel price of about 0.55 €/l and about 1.00 €/l.
- Fig. 3.4-11:** General design scheme of a PV–reverse osmosis desalination plant.
- Fig. 3.4-12:** Solar-driven reverse osmosis desalination systems: geographical distribution and type in Mediterranean and MENA countries but also worldwide.
- Fig. 3.4-13:** Efficiency dependence of diesel and heavy fuel oil generators and power plants on unit size.
- Fig. 3.4-14:** Global market distribution of diesel and natural gas power generation in unit size and operation modus.
- Fig. 3.4-15:** Cost structure of oil fuels. Prices for oil fuels are mainly driven by crude oil price, assumed to be approximately 80 USD/barrel, plus taxation minus subsidization.
- Fig. 3.4-16:** Levelized cost of electricity for diesel generators and PV systems dependent on irradiation.
- Fig. 3.4-17:** Competitiveness of PV systems for fuel saving of diesel generators excluding storage in the year 2010.
- Fig. 3.4-18:** Competitiveness of PV-Storage systems for fuel saving of diesel generators for complete replacement of diesel generators including storage in the year 2010.
- Fig. 4.1-1:** Annual utilisable irradiation on aperture area of solar thermal electricity generation plants for regions of at least 1,700 kWh/m²/y.
- Fig. 4.1-2:** Definition of STEG plant configuration with different solar multiples (SM).
- Fig. 4.1-3:** STEG full load hours for solar multiples of one to four for the efficiency standards of the year 2010.
- Fig. 4.1-4:** STEG full load hours for solar multiples of one to four for the efficiency standards of the year 2020.
- Fig. 4.1-5:** STEG plant Capex estimates in 2010s for the scenarios aggressive, realistic and breakthrough in dependence on solar multiples.
- Fig. 4.1-6:** Global LCOE of STEG plants and a solar multiple of 2 in the 2010s for the aggressive scenario.
- Fig. 4.1-7:** Global LCOE of STEG plants and a solar multiple of 3 in the 2010s for the aggressive scenario.
- Fig. 4.1-8:** Global LCOE of STEG plants and a solar multiple of 2 in the 2010s for the breakthrough scenario.
- Fig. 4.1-9:** Global LCOE of STEG plants and a solar multiple of 3 in the 2010s for the breakthrough scenario.
- Fig. 4.1-10:** STEG LCOE for a site in Egypt for solar multiples one to four in aggressive, realistic and breakthrough scenario.
- Fig. 4.1-11:** Impact of DNI resource and solar multiples on STEG LCOE is shown for the years 2010 and 2020 for the scenarios realistic, aggressive and breakthrough, respectively.

- Fig. 4.1-12:** STEG LCOE in dependence on DNI resource and the year in the 2010s for the solar multiple one to four in the aggressive scenario.
- Fig. 4.2-1:** Average annual wind speed 50 m above ground.
- Fig. 4.2-2:** Average annual roughness lengths.
- Fig. 4.2-3:** Average annual wind speed 100 m and 150 m above ground.
- Fig. 4.2-4:** Histogram for wind speed classes of average annual conditions and the corresponding Weibull function.
- Fig. 4.2-5:** Global wind power plant capacity in georeferenced coordinates by early 2009.
- Fig. 4.2-6:** Global wind power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 4.2-7:** Global wind power plant capacity in dependence on respective power plant size.
- Fig. 4.2-8:** Global electricity generation by wind per capita for the year 2007.
- Fig. 4.2-9:** Global wind power plant capacity per country by end of 2009.
- Fig. 4.2-10:** Wind power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 4.2-11:** Average annual air density distribution.
- Fig. 4.2-12:** Wind turbine E-82 from Enercon and its power curve and power coefficient.
- Fig. 4.2-13:** Average annual full load hours of wind power plants.
- Fig. 4.2-14:** Offshore wind power potential of depths down to 100 m, 50 m and 25 m.
- Fig. 4.2-15:** Wind power Capex estimates for onshore and offshore plants.
- Fig. 4.2-16:** Global LCOE of onshore wind power plants in the 2010s for the realistic scenario.
- Fig. 4.2-17:** Global LCOE of onshore wind power plants in the 2010s for the aggressive scenario.
- Fig. 4.2-18:** Global LCOE of offshore wind power plants in the 2010s for the realistic scenario.
- Fig. 4.2-19:** Global LCOE of offshore wind power plants in the 2010s for the aggressive scenario.
- Fig. 4.3-1:** Status and development of Capex for PV, STEG and wind power plants.
- Fig. 4.3-2:** Status and development of LCOE of PV, STEG and wind power plants.
- Fig. 4.3-3:** Least cost PV, STEG and wind power technology in the 2010s for the aggressive scenario.
- Fig. 4.3-4:** Least power generation cost of covered PV, STEG and wind power technologies in the 2010s for the aggressive scenario.
- Fig. 4.3-5:** Difference of least PV LCOE to all solar and wind LCOE in the 2010s for the aggressive scenario.
- Fig. 5.1-1:** Global electricity generation per capita for the year 2007.
- Fig. 5.1-2:** Global electricity consumption per country and per GDP for the year 2007.
- Fig. 5.1-3:** GDP per capita in dependence on electricity consumption per capita for the year 2007.
- Fig. 5.1-4:** Global electricity consumption per area for the year 2007.
- Fig. 5.1-5:** Global power plant capacity per country by early 2009.
- Fig. 5.1-6:** Global power plant capacity in georeferenced coordinates by early 2009.
- Fig. 5.1-7:** Global power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 5.1-8:** Global power plant capacity in dependence on respective power plant size.
- Fig. 5.1-9:** Global annual power plant capacity investments by power technology for the years 1970 to 2008.
- Fig. 5.1-10:** Regional annual power plant capacity investments in Europe, North America, Asia, China, India and other regions by power technology for the years 1970 to 2008.
- Fig. 5.1-11:** Power plant capacity in dependence on annual full load hours per country and per major power technology.
- Fig. 5.1-12:** Power plant capacity in dependence on domestic electricity generation relevance per country and per major power technology for all countries and for large absolute and relative dependence.
- Fig. 5.1-13:** Global distribution of power plant technologies of largest relative electricity supply by name and contribution.
- Fig. 5.2-1:** Global potential of biomass production.
- Fig. 5.2-2:** Global biomass and waste power plant capacity in georeferenced coordinates by early 2009.
- Fig. 5.2-3:** Global biomass and waste power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 5.2-4:** Global biomass and waste power plant capacity in dependence on respective power plant size.
- Fig. 5.2-5:** Global electricity generation by biomass and waste per capita for the year 2007.
- Fig. 5.2-6:** Global biomass and waste power plant capacity per country by early 2009.
- Fig. 5.2-7:** Biomass and waste power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 5.3-1:** Global geothermal heat flux.
- Fig. 5.3-2:** Global geothermal power plant capacity in georeferenced coordinates by early 2009.
- Fig. 5.3-3:** Global geothermal power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 5.3-4:** Global geothermal power plant capacity in dependence on respective power plant size.

- Fig. 5.3-5:** Global electricity generation by geothermal power per capita for the year 2007.
- Fig. 5.3-6:** Global geothermal power plant capacity per country by early 2009.
- Fig. 5.3-7:** Geothermal power plant capacity in dependence on full load hours per country.
- Fig. 5.3-8:** Geothermal power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 5.4-1:** Global wave power resource potential.
- Fig. 5.5-1:** Distribution of global uranium reserves.
- Fig. 5.5-2:** Global nuclear power plant capacity in georeferenced coordinates by early 2009.
- Fig. 5.5-3:** Global nuclear power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 5.5-4:** Global nuclear power plant capacity in dependence on respective power plant size.
- Fig. 5.5-5:** Global electricity generation by nuclear power per capita for the year 2007.
- Fig. 5.5-6:** Global nuclear power plant capacity per country by early 2009.
- Fig. 5.5-7:** Nuclear power plant capacity in dependence on full load hours per country.
- Fig. 5.5-8:** Nuclear power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 6.1-1:** General hybrid energy hub diagram.
- Fig. 6.1-2:** Hybrid technologies matrix of systems being commercial, pre-commercial in research and development or even plausible.
- Fig. 6.1-3:** The heat balance and energy flows of a modern approximately 58% efficient single-pressure CCGT.
- Fig. 6.1-4:** Start-up capability of modern CCGT power plants in contrast to conventional older ones.
- Fig. 6.1-5:** Part load efficiency of CCGT power plants with four single-shaft blocks.
- Fig. 6.1-6:** Fossil fuel prices in absolute financial units and normalized to crude oil on thermal energy units for major trade centres in the years 1984 to 2009.
- Fig. 6.1-7:** Crude oil price expectation of various sources for the years 2010 to 2050.
- Fig. 6.1-8:** Price coupling factor expectations for natural gas and hard coal to crude oil of various sources for the years 2010 to 2050.
- Fig. 6.1-9:** Crude oil price projection of the International Energy Agency and real price development for the 1990s to the 2020s.
- Fig. 6.2-1:** Distribution of global crude oil reserves.
- Fig. 6.2-2:** Global oil power plant capacity in georeferenced coordinates by early 2009.
- Fig. 6.2-3:** Global oil fired power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 6.2-4:** Global oil power plant capacity in dependence on respective power plant size.
- Fig. 6.2-5:** Global electricity generation by oil per capita for the year 2007.
- Fig. 6.2-6:** Global oil power plant capacity per country by early 2009.
- Fig. 6.2-7:** Oil power plant capacity in dependence on full load hours per country.
- Fig. 6.2-8:** Oil power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 6.2-9:** Global distribution of oil power plant full load hours and the ratio to total domestic electricity generation.
- Fig. 6.2-10:** LCOE structure of oil fired and PV power plants based on major driving forces.
- Fig. 6.2-11:** Global average oil power plant full load hours of at least 2,000 FLh, 3,000 FLh and 4,000 FLh.
- Fig. 6.2-12:** Oil LCOE for local FLh based on a crude oil level of 45 USD/barrel and variations on oil power plant efficiency and carbon emission cost.
- Fig. 6.2-13:** Oil LCOE for local FLh based on a crude oil level of 80 USD/barrel and variations on oil power plant efficiency and carbon emission cost.
- Fig. 6.2-14:** Oil LCOE for local FLh based on a crude oil level of 120 USD/barrel and variations on oil power plant efficiency and carbon emission cost.
- Fig. 6.2-15:** Oil LCOE for local FLh based on a crude oil level of 160 USD/barrel and variations on oil power plant efficiency and carbon emission cost.
- Fig. 6.2-16:** Oil LCOE for local FLh in the 2010s for the base case scenario.
- Fig. 6.2-17:** Parity of fixed optimally tilted PV and oil power plants for total plant LCOE and fuel-only LCOE for PV realistic and oil base case scenario assumptions.
- Fig. 6.2-18:** Parity of fixed optimally tilted PV and oil power plants for total plant LCOE and fuel-only LCOE for PV aggressive and oil base case scenario assumptions.
- Fig. 6.2-19:** PV LCOE benefit in comparison to fuel-only oil LCOE for fixed optimally tilted PV realistic and oil base case scenario assumptions in the 2010s.
- Fig. 6.2-20:** PV LCOE benefit in comparison to fuel-only oil LCOE for fixed optimally tilted PV aggressive and oil base case scenario assumptions in the 2010s.
- Fig. 6.2-21:** Global hybrid PV-Oil power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV realistic and oil base case scenario assumptions in the 2010s.

- Fig. 6.2-22:** Global hybrid PV-Oil power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV aggressive and oil base case scenario assumptions in the 2010s.
- Fig. 6.3-1:** Distribution of global natural gas reserves.
- Fig. 6.3-2:** Global gas power plant capacity in georeferenced coordinates by early 2009.
- Fig. 6.3-3:** Global gas fired power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 6.3-4:** Global gas power plant capacity in dependence on respective power plant size.
- Fig. 6.3-5:** Global electricity generation by gas per capita for the year 2007.
- Fig. 6.3-6:** Global gas power plant capacity per country by early 2009.
- Fig. 6.3-7:** Gas power plant capacity in dependence on full load hours per country.
- Fig. 6.3-8:** Gas power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 6.3-9:** Global distribution of gas power plant full load hours and the ratio to total domestic electricity generation.
- Fig. 6.3-10:** LCOE structure of gas fired and PV power plants based on major driving forces.
- Fig. 6.3-11:** Global average gas power plant full load hours of at least 2,000 FLh, 3,000 FLh and 4,000 FLh.
- Fig. 6.3-12:** Gas LCOE for local FLh based on a crude oil level of 45 USD/barrel, natural gas to crude oil coupling of 0.8, variations on gas power plant efficiency and carbon emission cost.
- Fig. 6.3-13:** Gas LCOE for local FLh based on a crude oil level of 80 USD/barrel, natural gas to crude oil coupling of 0.8, variations on gas power plant efficiency and carbon emission cost.
- Fig. 6.3-14:** Gas LCOE for local FLh based on a crude oil level of 120 USD/barrel, natural gas to crude oil coupling of 0.8, variations on gas power plant efficiency and carbon emission cost.
- Fig. 6.3-15:** Gas LCOE for local FLh based on a crude oil level of 160 USD/barrel, natural gas to crude oil coupling of 0.8, variations on gas power plant efficiency and carbon emission cost.
- Fig. 6.3-16:** Gas LCOE for local FLh in the 2010s for the base case scenario.
- Fig. 6.3-17:** Parity of fixed optimally tilted PV and gas power plants for total plant LCOE and fuel-only LCOE for PV realistic and gas base case and low cost scenario assumptions.
- Fig. 6.3-18:** Parity of fixed optimally tilted PV and gas power plants for total plant LCOE and fuel-only LCOE for PV aggressive and gas base case and low cost scenario assumptions.
- Fig. 6.3-19:** PV LCOE benefit in comparison to fuel-only gas LCOE for fixed optimally tilted PV realistic and gas base case scenario assumptions in the 2010s.
- Fig. 6.3-20:** PV LCOE benefit in comparison to fuel-only gas LCOE for fixed optimally tilted PV aggressive and gas base case scenario assumptions in the 2010s.
- Fig. 6.3-21:** Global hybrid PV-Gas power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV realistic and gas base case scenario assumptions in the 2010s.
- Fig. 6.3-22:** Global hybrid PV-Gas power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV aggressive and gas base case scenario assumptions in the 2010s.
- Fig. 6.3-23:** Global hybrid PV-Gas power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV in the realistic and aggressive and gas low cost case scenario assumptions in the 2010s.
- Fig. 6.4-1:** Distribution of coal reserves.
- Fig. 6.4-2:** Global coal power plant capacity in georeferenced coordinates by early 2009.
- Fig. 6.4-3:** Global coal fired power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 6.4-4:** Global coal power plant capacity in dependence on respective power plant size.
- Fig. 6.4-5:** Global electricity generation by coal per capita for the year 2007.
- Fig. 6.4-6:** Global coal power plant capacity per country by early 2009.
- Fig. 6.4-7:** Coal power plant capacity in dependence on full load hours per country.
- Fig. 6.4-8:** Coal power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 6.4-9:** Global distribution of coal power plant full load hours and the ratio to total domestic electricity generation.
- Fig. 6.4-10:** LCOE structure of coal fired and PV power plants based on major driving forces.
- Fig. 6.4-11:** Global average coal power plant full load hours of at least 2,000 FLh, 3,000 FLh and 4,000 FLh.
- Fig. 6.4-12:** Coal LCOE for local FLh based on a crude oil level of 45 USD/barrel, coal to crude oil coupling of 0.3, variations on coal power plant efficiency and carbon emission cost.
- Fig. 6.4-13:** Coal LCOE for local FLh based on a crude oil level of 80 USD/barrel, coal to crude oil coupling of 0.3, variations on coal power plant efficiency and carbon emission cost.
- Fig. 6.4-14:** Coal LCOE for local FLh based on a crude oil level of 120 USD/barrel, coal to crude oil coupling of 0.3, variations on coal power plant efficiency and carbon emission cost.
- Fig. 6.4-15:** Coal LCOE for local FLh based on a crude oil level of 160 USD/barrel, coal to crude oil coupling of 0.3, variations on coal power plant efficiency and carbon emission cost.
- Fig. 6.4-16:** Coal LCOE for local FLh in the 2010s for the base case scenario.

- Fig. 6.4-17:** Parity of fixed optimally tilted PV and coal power plants for total plant LCOE and fuel-only LCOE for PV realistic and coal base case and low cost scenario assumptions.
- Fig. 6.4-18:** Parity of fixed optimally tilted PV and coal power plants for total plant LCOE and fuel-only LCOE for PV aggressive and coal base case and low cost scenario assumptions.
- Fig. 6.4-19:** PV LCOE benefit in comparison to fuel-only coal LCOE for fixed optimally tilted PV realistic and coal base case scenario assumptions in the 2010s.
- Fig. 6.4-20:** PV LCOE benefit in comparison to fuel-only coal LCOE for fixed optimally tilted PV aggressive and coal base case scenario assumptions in the 2010s.
- Fig. 6.4-21:** Global hybrid PV-Coal power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV realistic and coal base case scenario assumptions in the 2010s.
- Fig. 6.4-22:** Global hybrid PV-Coal power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV aggressive and coal base case scenario assumptions in the 2010s.
- Fig. 6.4-23:** Global hybrid PV-Coal power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV in the realistic and aggressive and coal low cost case scenario assumptions in the 2010s.
- Fig. 6.5-1:** Global hybrid PV-Fossil power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV in the realistic and fossil base case scenario assumptions in the 2010s.
- Fig. 6.5-2:** Global hybrid PV-Fossil power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV in the aggressive and fossil base case scenario assumptions in the 2010s.
- Fig. 6.5-3:** Global hybrid PV-Fossil power plant demand curve in the 2010s on total and fuel-only LCOE parity for fixed optimally tilted PV in the realistic and aggressive and fossil low cost case scenario assumptions in the 2010s.
- Fig. 6.6-1:** Forecasts of PV development and real cumulated installed PV capacity for the status of the year 2008.
- Fig. 6.6-2:** Projections of cumulated and annual installed PV capacity of various institutions.
- Fig. 6.6-3:** Total economic on-grid market potential for PV systems in the 2010s in the upper and lower limit.
- Fig. 7.1-1:** Global potential of hydro power and locations of hydro power plants.
- Fig. 7.1-2:** Global hydro power plant capacity in georeferenced coordinates by early 2009.
- Fig. 7.1-3:** Global hydro power plant capacity in dependence on respective local solar irradiation on module surfaces of fixed optimally tilted PV systems.
- Fig. 7.1-4:** Global hydro power plant capacity in dependence on respective power plant size.
- Fig. 7.1-5:** Global electricity generation by hydro per capita for the year 2007.
- Fig. 7.1-6:** Global hydro power plant capacity per country by early 2009.
- Fig. 7.1-7:** Hydro power plant capacity in dependence on full load hours per country.
- Fig. 7.1-8:** Hydro power plant capacity in dependence on domestic electricity generation relevance per country.
- Fig. 7.1-9:** Global distribution of hydro power plant full load hours and the ratio to total domestic electricity generation.
- Fig. 7.2-1:** Principle structure of a hybrid PV-STEG power plant configuration with different solar multiples.
- Fig. 7.2-2:** STEG LCOE differences in dependence on DNI resource and the year in the 2010s for the solar multiple reduction two to one, three to two and four to three in the aggressive scenario.
- Fig. 7.2-3:** PV LCOE potential for the PV sub-plant of hybrid PV-STEG plants in dependence on DNI resource and the year in the 2010s for the solar multiple reduction two to one, three to two and four to three in the aggressive scenario.
- Fig. 7.2-4:** Attractiveness for a PV sub-plant within a hybrid PV-STEG plant indicated by PV LCOE benefit in absolute and relative numbers for an original STEG SM2 sub-plant for aggressive scenario assumptions of PV and STEG sub-plants and for the years 2010, 2015 and 2020.
- Fig. 7.2-5:** Attractiveness for a PV sub-plant within a hybrid PV-STEG plant indicated by PV LCOE benefit in absolute and relative numbers for an original STEG SM3 sub-plant for aggressive scenario assumptions of PV and STEG sub-plants and for the years 2010, 2015 and 2020.
- Fig. 7.3-1:** Hourly solar and wind resource data for June 21st 2005 at 12:30 UTC time.
- Fig. 7.3-2:** Feed-in power potential of 1 GW installed PV and wind power capacity according to historic data.
- Fig. 7.3-3:** Global full load hours of fixed optimally tilted PV power plants, wind power plants at 150 m hub height and combined PV plus wind power plants for the year 2005.
- Fig. 7.3-4:** Global overlap full load hours of PV and wind power plants and the respective ratio to total FLh of hybrid PV-Wind power plants for the year 2005.
- Fig. 7.3-5:** Global critical overlap full load hours of PV and wind power plants and the respective ratio to total FLh of hybrid PV-Wind power plants for the year 2005.
- Fig. 7.4-1:** Hybrid PV-Wind-RPM power plant embedded in the power grid and the natural gas grid.

- Fig. 7.4-2:** Overview on major electricity storage technologies in dependence on energetic storage capacity and charge cycling.
- Fig. 7.4-3:** Hybrid PV-Wind-RPM plant as the integral centrepiece of a future sustainable energy supply system.
- Fig. 7.4-4:** Fixed optimally tilted PV power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh and LCOE expected for the year 2020.
- Fig. 7.4-5:** 1-axis horizontal north-south continuous tracking PV power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh and LCOE expected for the year 2020.
- Fig. 7.4-6:** Wind 150 meter hub height power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh and LCOE expected for the year 2020.
- Fig. 7.4-7:** Hybrid fixed tilted PV Wind 150 meter hub height power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh and LCOE expected for the year 2020.
- Fig. 7.4-8:** Hybrid 1-axis PV Wind 150 meter hub height power plant component for hybrid PV-Wind-RPM-CCGT power plant characterized by FLh and LCOE expected for the year 2020.
- Fig. 7.4-9:** Renewable power methane production cost in dependence on input electricity LCOE and FLh of electrolysis and dialysis and electrolysis unit.
- Fig. 7.4-10:** Hybrid PV-Wind-RPM-CCGT LCOE in dependence on input electricity LCOE and FLh of electrolysis and dialysis and electrolysis unit for 5,000 FLh of the hybrid power plant.
- Fig. 7.4-11:** Renewable power methane production cost in dependence on input hybrid PV-Wind, PV and Wind LCOE and CO₂ extracted from ambient air in the year 2020.
- Fig. 7.4-12:** Renewable power methane production cost in dependence on input hybrid PV-Wind, PV and Wind LCOE and CO₂ accessible by CCS in the year 2020.
- Fig. 7.4-13:** Total LCOE of hybrid RES-RPM-CCGT power plants for hybrid PV-Wind, PV and wind supplied by CO₂ from ambient air and operated 5,000 FLh in the year 2020.
- Fig. 7.4-14:** Total LCOE of hybrid RES-RPM-CCGT power plants for hybrid PV-Wind, PV and wind supplied by CO₂ accessible from CCS and operated 5,000 FLh in the year 2020.
- Fig. 7.4-15:** Total LCOE of hybrid PV-NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-16:** Total LCOE of hybrid Wind-NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-17:** Total LCOE of hybrid PV-Wind-NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-18:** LCOE benefit of hybrid PV-RPM-CCGT power plants extracting CO₂ from ambient air versus NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-19:** LCOE benefit of hybrid Wind-RPM-CCGT power plants extracting CO₂ from ambient air versus NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-20:** LCOE benefit of hybrid PV-Wind-RPM-CCGT power plants extracting CO₂ from ambient air versus NG-CCGT-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-21:** Hybrid RES-RPM-CCGT power plant option of least local LCOE and respective absolute LCOE.
- Fig. 7.4-22:** Least local LCOE of hybrid RES-RPM-CCGT, NG-CCGT-CCS and coal-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-23:** Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in the US (33.5°N/ 101.5°W) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 and an overview on annually new installed power plant capacity in the US.
- Fig. 7.4-24:** Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in Chile (27.5°S/ 69.5°W) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 and an overview on annually new installed power plant capacity in Chile.
- Fig. 7.4-25:** Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in Germany (50.5°N/ 11.5°E) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 and an overview on annually new installed power plant capacity in Germany.
- Fig. 7.4-26:** Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in Saudi Arabia (18.5°N/ 45.5°E) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 and an overview on annually new installed power plant capacity in Saudi Arabia.

- Fig. 7.4-27:** Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in India (25.5°N/ 72.5°E) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 and an overview on annually new installed power plant capacity in India.
- Fig. 7.4-28:** Hybrid RES-RPM-CCGT and fossil fuel fired power plant LCOE dynamics for a site in China (45.5°N/ 115.5°W) for 6,000 FLh and a fossil fuel price range of 50 – 250 USD/barrel in the year 2020 and an overview on annually new installed power plant capacity in China.
- Fig. 7.4-29:** DESERTEC vision for the EU-MENA rim and for Asia-Pacific might result in a global power grid based on renewable energies.
- Fig. 7.4-30:** Population accessible by solar power in dependence on distance to sites of excellent solar conditions.
- Fig. 7.4-31:** Hybrid RES-RPM-CCGT power plants of least local LCOE in competition to NG-CCGT-CCS and coal-CCS power plants for fossil fuel prices of 150 USD/barrel, 50 USD/barrel, 100 USD/barrel, 200 USD/barrel and 250 USD/barrel operated 5,000 FLh in the year 2020.
- Fig. 7.4-32:** People living in regions of least cost 100% renewable power supply and respective distance to these regions in dependence on fossil fuel prices in the range of 50 – 250 USD/barrel in the year 2020.
- Fig. 7.4-33:** Aggregated people living in regions of least cost 100% renewable power supply and respective distance to these regions in dependence on fossil fuel prices in the range of 50 – 250 USD/barrel in the year 2020.

List of Tables

- Table 2.3-1:** Solar resources for all major regions in the world.
- Table 2.4-1:** Various population weighted solar resources for moderate (Germany) and excellent (Egypt) solar conditions.
- Table 3.1-1:** Corporate R&D investments of public listed PV companies for the years 2003 – 2009, sorted by R&D investments in 2009.
- Table 3.1-2:** Corporate PV R&D investments estimated for the year 2009.
- Table 3.1-3:** Leading PV and inverter patent assignees in the year 2008.
- Table 3.1-4:** Leading PV and inverter patent assignees for the years 2000 – 2008.
- Table 3.1-5:** International PCT applications, corporate R&D investments and R&D investments per PCT for the 20 leading PCT assignees.
- Table 3.1-6:** Estimates of annual production potential of CdTe and CIGS PV technology due to resource limitation.
- Table 3.1-7:** Overview on specific greenhouse gas emissions and the energy return on energy invested for the major power technologies.
- Table 3.2-1:** Scenario assumptions for PV power plant economics.
- Table 3.4-1:** Ethiopian cumulated off-grid PV addressable markets for solar home systems.
- Table 3.4-2:** Cost and lifetime assumptions for PS and SHS and typical local energy needs in off-grid regions.
- Table 3.4-3:** Examples for existing and proposed hybrid PV-(Wind-Battery)-Diesel systems in the world.
- Table 4.1-1:** Scenario assumptions for STEG plant economics.
- Table 4.2-1:** Scenario assumptions for wind power plant economics.
- Table 4.3-1:** Qualitative comparison of PV, STEG and wind power.
- Table 5.0-1:** Overview on power plant technologies and their treatment in this thesis.
- Table 5.1-1:** Global power plant capacity by power plant technology and decade of commissioning by early 2009 in absolute capacity.
- Table 5.1-2:** Global power plant capacity by power plant technology and decade of commissioning by early 2009 in relative numbers.
- Table 6.1-1:** Overview on hybrid power systems discussed in this thesis.
- Table 6.1-2:** Characteristics of fossil and nuclear fuelled thermal power plants.
- Table 6.2-1:** Scenario assumptions for oil power plant economics.
- Table 6.2-2:** Oil LCOE for 2,000 to 4,000 FLh, power plant conversion efficiencies of 35%, 40%, 45%, 50% and 55%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}.
- Table 6.3-1:** Scenario assumptions for gas power plant economics.
- Table 6.3-2:** Total cost of natural gas in dependence on gas field type related production cost and transport cost constraints.
- Table 6.3-3:** Gas LCOE for 2,000 to 4,000 FLh, power plant conversion efficiencies of 40%, 50% and 60%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, natural gas to crude oil coupling of 0.8 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}.
- Table 6.3-4:** Gas LCOE for 2,000 to 4,000 FLh, power plant conversion efficiencies of 40%, 50% and 60%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, natural gas to crude oil coupling of 0.7 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}.
- Table 6.4-1:** Scenario assumptions for coal power plant economics.
- Table 6.4-2:** Coal LCOE for 3,000 to 6,000 FLh, power plant conversion efficiencies of 35%, 40% and 45%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, coal to crude oil coupling of 0.3 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}.
- Table 6.4-3:** Coal LCOE for 3,000 to 6,000 FLh, power plant conversion efficiencies of 35%, 40% and 45%, crude oil prices of 45, 80, 120, 160 and 200 USD/barrel, coal to crude oil coupling of 0.2 and carbon emission prices of 0, 30, 50 and 70 €/t_{CO2}.
- Table 7.1-1:** Breakeven cost for PV sub-plant of hybrid PV-Hydro power plant in dependence of oil price, discount rate and carbon credits for several developing countries.
- Table 7.3-1:** Technical potential of PV and wind power versus the current global energy demand.
- Table 7.4-1:** Scenario assumptions for hybrid PV-Wind-RPM-CCGT power plant economics in the year 2020.
- Table 7.4-2:** Global energy supply potential of hybrid RES-RPM-CCGT power plants based on least local LCOE.
- App. Table 1:** Dataset of population weighted mean irradiation values of various solar resources for all countries, continents and major regions in the world.

App. Table 2: Global overview on PV capacities installed, general and social progress indicators.

App. Table 3: List of 161 countries and respective data for grid-parity events, electricity prices, irradiation on fixed optimally tilted module surface, population, gross domestic product, greenhouse gas emissions, electricity generation and electrification rate.

App. Table 4: List of country codes of top level web domain.

List of Equations

- Eq. 2.1-1: Composition of GHI.
- Eq. 2.2-1: Total radiation on a tilted surface according to Hay-Davis-Klucher-Reindl model.
- Eq. 2.2-2: Geometric factor and its contributing functions.
- Eq. 2.2-3: Decomposition of daily into hourly irradiation data.
- Eq. 2.2-4: Specific geometric considerations for fixed optimally tilted non-tracking PV systems.
- Eq. 2.2-5: Specific geometric considerations for 1-axis horizontal east-west continuous tracking PV systems.
- Eq. 2.2-6: Specific geometric considerations for 1-axis horizontal north-south continuous tracking PV systems.
- Eq. 2.2-7: Specific geometric considerations for 1-axis vertical optimally tilted continuous tracking PV systems.
- Eq. 2.2-8: Specific geometric considerations for 1-axis optimally tilted north-south continuous tracking PV systems.
- Eq. 2.2-9: Specific geometric considerations for 2-axes non-concentrating continuous tracking PV systems.
- Eq. 2.2-10: Total radiation on a tilted concentrating surface according to Hay-Davis-Klucher-Reindl model and specific geometric considerations for 2-axes concentrating continuous tracking PV systems.
- Eq. 2.3-1: Population and area weighted irradiation values per considered entity.
- Eq. 3.1-1: Empirical law of experience curves.
- Eq. 3.1-2: Energy payback time of PV systems.
- Eq. 3.1-3: Energy return on energy investment.
- Eq. 3.1-4: Lifetime of PV modules and respective power output.
- Eq. 3.2-1: Levelized cost of electricity for PV systems.
- Eq. 3.2-2: Total life cycle cost for PV systems.
- Eq. 3.2-3: Levelized cost of electricity including annual PV system degradation rate.
- Eq. 3.2-4: Ground cover ratio.
- Eq. 4.1-1: STEG performance model.
- Eq. 4.1-2: Levelized cost of electricity for STEG plants.
- Eq. 4.2-1: Transformation of wind speed to different heights.
- Eq. 4.2-2: Weibull distribution and the routine for extracting the Weibull parameters.
- Eq. 4.2-3: Power output of wind power plants.
- Eq. 4.2-4: Levelized cost of electricity for wind power plants.
- Eq. 6.1-1: Hybrid energy hub model equation.
- Eq. 6.2-1: Levelized cost of electricity for oil power plants.
- Eq. 6.3-1: Levelized cost of electricity for gas power plants.
- Eq. 6.4-1: Levelized cost of electricity for coal power plants.
- Eq. 7.3-1: Definition of overlap and critical overlap full load hours.
- Eq. 7.4-1: Levelized cost of electricity for hybrid PV-Wind-RPM-CCGT power plants.

List of Publications

Journals

- Breyer Ch. and Gerlach A., Global Overview on Grid-Parity, Progress in Photovoltaics: Research and Applications, submitted, June 24, 2011; accepted
- Breyer Ch., Vogel M., Mohr M., Johnev B., Fostiropoulos K., Influence of exciton distribution on external quantum efficiency in bilayer organic solar cells, *physica statatus solidi (b)*, **243**, 3176, 2006
- Vogel M., Doka S., Breyer Ch., Lux-Steiner M.Ch., Fostiropoulos K., On the function of a bathocuproine buffer layer in organic photovoltaic cells, *Applied Physics Letters*, **89**, 163501, 2006

International Scientific Conferences

- Hlusiak M., Arnhold O., Breyer Ch., Optimising a Renewables Based Island Grid and Integrating a Battery Electric Vehicles Concept on the Example of Graciosa Island, 6th European Conference on PV-Hybrids and Mini-Grids, Chambéry 2012, April 26-27, accepted
- Blechinger P., Bogner K., Hlusiak M., Breyer Ch., Energy Supply in Mini-Grids Regarding Renewable Energies: An Optimization for Petite Martinique, 6th European Conference on PV-Hybrids and Mini-Grids, Chambéry 2012, April 26-27, accepted
- Werner C. and Breyer Ch., Analysis of Mini-Grid Installations: An Overview on System Configurations, 6th European Conference on PV-Hybrids and Mini-Grids, Chambéry 2012, April 26-27, accepted
- Gerlach A.-K. and Breyer Ch., PV und Windkraft: Sich hervorragend ergänzende Energietechnologien am Beispiel Mitteldeutschlands, 27. Symposium Photovoltaische Solarenergie, Bad Staffelstein 2012, February 2 - March 2, accepted
- Breyer Ch., Rieke S., Sterner M., Schmid J., Hybrid PV-Wind-Renewable Power Methane Plants – An Economic Outlook, 6th International Renewable Energy Storage Conference, Berlin 2011, November 28-30
- Arnhold O., Hlusiak M., Möhrke F., Breyer Ch., Mobility Concepts Using Excess Power from Proposed Renewable Energy Supply System on Graciosa Island, Azores Archipelago, , 6th International Renewable Energy Storage Conference, Berlin 2011, November 28-30
- Breyer Ch., Rieke S., Sterner M., Schmid J., Hybrid PV-Wind-Renewable Methane Power Plants – A Potential Cornerstone of Global Energy Supply, 26th EU PVSEC, Hamburg 2011, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.31; ISES Solar World Congress 2011, Kassel, 2011, August 28 – September 2
- Breyer Ch., Görig M., Gerlach A.-K., Schmid J., Economics of Hybrid PV-Fossil Power Plants, 26th EU PVSEC, Hamburg 2011, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6DO.13.2; ISES Solar World Congress 2011, Kassel, 2011, August 28 – September 2
- Gerlach A.-K., Stetter D., Schmid J., Breyer Ch., PV and Wind Power – Complementary Technologies, 26th EU PVSEC, Hamburg 2011, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.32; ISES Solar World Congress 2011, Kassel, 2011, August 28 – September 2

- Breyer Ch., Werner C., Rolland S., Adelmann P., Off-Grid Photovoltaic Applications in Regions of Low Electrification: High Demand, Fast Financial Amortization and Large Market Potential, 26th EU PVSEC, Hamburg 2011, September 5-9, DOI: 10.4229/26thEUPVSEC2011-5BV.1.45
- Werner C., Gerlach A., Adelmann P., Breyer Ch., Global Cumulative Installed Photovoltaic Capacity and Respective International Trade Flows, 26th EU PVSEC, Hamburg 2011, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.8
- Breyer Ch., The Photovoltaic Reality Ahead: Terawatt Scale Market Potential Powered by Pico to Gigawatt PV Systems and Enabled by High Learning and Growth Rates, 26th EU PVSEC, Hamburg 2011, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6EP.1.2
- Kersten F., Doll R., Kux A., Huljić D.M., Görig M.A., Breyer Ch., Müller J., Wawer P., PV-Learning Curves: Past and Future Drivers of Cost Reduction, 26th EU PVSEC, Hamburg 2011, September 5-9, DOI: 10.4229/26thEUPVSEC2011-6CV.1.63
- Breyer Ch., PV Market Potential in the Terawatt Scale: Fuel-Parity in PV Power Plant Business, Grid-Parity for End-user PV Applications and Off-grid PV in Rural Regions, ISES Solar World Congress 2011, Kassel, 2011, August 28 – September 2
- Breyer Ch., Werner C., Adelmann P., Small Photovoltaic Applications in Regions of low Electrification: High Demand, fast financial Amortization and large Market Potential, 2nd Symposium Small PV-Applications, Ulm 2011, June 6-7
- Werner C., Gerlach A., Adelmann P., Breyer Ch., Global Overview on cumulative installed Photovoltaic Power, 2nd Symposium Small PV-Applications, Ulm 2011, June 6-7
- Breyer Ch., Görig M., Schmid J., Fuel-Parity: Impact of Photovoltaic on global fossil fuel fired power plant business, 26. Symposium Photovoltaische Solarenergie, Bad Staffelstein 2011, März 2-4
- Breyer Ch., Gerlach A., Beckel O., Schmid J., Value of Solar PV Electricity in MENA Region, IEEE EnergyCon, Manama, 2010, December 18-22
- Breyer Ch., Gerlach A., Schäfer D., Schmid J., Fuel-Parity: New Very Large and Sustainable Market Segments for PV Systems, IEEE EnergyCon, Manama, 2010, December 18-22
- Breyer Ch. and Gerlach A., Global Overview on Grid-Parity Event Dynamics, 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6-10, DOI: 10.4229/25thEUPVSEC2010-6CV.4.11
- Breyer Ch., Birkner Ch., Kersten F., Gerlach A., Stryi-Hipp G., Goldschmidt J.Ch., Montoro D.F., Riede M., Research and Development Investments in PV – A limiting Factor for a fast PV Diffusion?, 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6-10, DOI: 10.4229/25thEUPVSEC2010-6CV.5.22
- Breyer Ch., Schmid J., Population Density and Area weighted Solar Irradiation: global Overview on Solar Resource Conditions for fixed tilted, 1-axis and 2-axes PV Systems, 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6-10, DOI: 10.4229/25thEUPVSEC2010-4BV.1.91
- Breyer Ch., Schmid J., Global Distribution of optimal Tilt Angles for fixed tilted PV Systems, 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6-10, DOI: 10.4229/25thEUPVSEC2010-4BV.1.93
- Breyer Ch., Vogel M., Fostiropoulos K., Lux-Steiner M.Ch., Contribution of C₆₀ to Short-Circuit Current Density in bilayer Organic Solar Cells, 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6-10, DOI: 10.4229/25thEUPVSEC2010-1DV.4.59
- Breyer Ch., Vogel M., Fostiropoulos K., Limitations in Donor-Acceptor Photovoltaic Devices calculated for a novel organic multi-layer Stack Model, 25th EU PVSEC/ WCPEC-5, Valencia 2010, September 6-10, DOI: 10.4229/25thEUPVSEC2010-1DV.4.58

- Breyer Ch., Gerlach A., Hlusiak M., Peters C., Adelmann P., Winiecki J., Schützeichel H., Tsegaye S., Gashie W., Electrifying the Poor: Highly economic off-grid PV Systems in Ethiopia – A Basis for sustainable rural Development, 24th EU PVSEC, Hamburg 2009, September 21-25, DOI: 10.4229/24thEUPVSEC2009-5EP.2.3
- Breyer Ch., Gerlach A., Mueller J., Behacker H., Milner A., Grid-Parity Analysis for EU and US regions and market segments – Dynamics of Grid-Parity and Dependence on Solar Irradiance, local Electricity Prices and PV Progress Ratio, 24th EU PVSEC, Hamburg 2009, September 21-25, DOI:10.4229/24thEUPVSEC2009-6DV.2.34
- Breyer Ch., Knies G., Global Energy Supply Potential of Concentrating Solar Power, SolarPACES 2009, Berlin, September 15-18
- Vogel M., Breyer Ch., Johnev B., Mohr M., Rusu M., Mete T., Lux-Steiner M.Ch., Fostiropoulos K., The function of buffer layers in phthalocyanine/C₆₀-based solar cells, MRS Spring Meeting, San Francisco 2006, April 17-21
- Breyer Ch., Vogel M., Mohr M., Johnev B., Lux-Steiner M.Ch., Fostiropoulos K., Simulation of Exciton Distribution in Bilayer Organic Solar Cells, 20th IWEPM Euroconference on Electronic Properties of Novel Materials, Kirchberg 2006, March 4-11

Symposia/ Workshops/ National or non Scientific Conferences

- Breyer Ch., Photovoltaik Marktpotenzial im Terawatt Bereich, 12. Forum Solarpraxis, Berlin, 2011, November 17-18
- Breyer Ch., PV Market Potential in the Terawatt Scale, 3. Photovoltaik-Symposium, Bitterfeld-Wolfen 2011, November 3-4
- Breyer Ch., Market Potential for Off-Grid PV in Developing Countries, 4th ARE Market and Investment Workshop, 26th EU PVSEC, Hamburg, 2011, September 7
- Breyer Ch., Global PV Market Potential by 2020 and Consequences for the Power Business, Photon's 6th Solar Electric Utility Conference, Berlin, April 14
- Breyer Ch., Utility scale PV Systems and their Market Potential, SRC/ Masdar Institute Forum on Solar-Electric Energy Systems (SEES), Abu Dhabi, March 27-28
- Breyer Ch., Solar Photovoltaics – A Sustainable and Low Cost Power Technology, Sustainability: Our Common Future, University of Leipzig, Leipzig, January 21
- Breyer Ch., Value of Solar PV Electricity in MENA Region, Casablanca Forum: Large-Scale Solar Power in MENA: Vision and Reality, Casablanca 2010, June 15-16
- Breyer Ch., Global Photovoltaic Diffusion: Regions, Market Segments and Cost, 8th Workshop Students Chapters GEE, Gesellschaft für Energiewirtschaft und Energiepolitik e.V., Mannheim 2009, May 7
- Breyer Ch., How favourable is PV?, Frühjahrssitzung Arbeitskreis Energie der DPG, Deutsche Physikalische Gesellschaft e.V., Bad Honnef 2009, May 6
- Breyer Ch., Photovoltaic, Workshop for a Third Industrial Revolution Energy Plan for the Province of Utrecht Distributed Renewable Energy, organized by The Foundation on Economic Trends/ Rifkin J., Utrecht 2010, February 4-6
- Breyer Ch., Reiß J., Wie günstig ist Photovoltaik?, 2. Photovoltaik-Symposium, Bitterfeld-Wolfen 2009, November 5-6
- Breyer Ch., How cheap is Photovoltaic?, German-Russian Week Environment, Kassel 2009, May 15
- Knies G., Breyer Ch., Trans-Mediterrane EE-Zusammenarbeit für Energie- und Klimasicherheit, Loccumer Tagung zu Energiesicherheit in und für Europa, Loccum 2007, January 19-21

Patent

- Breyer Ch., Hlusiak M., Huljic D., Kraftwerk, German Patent and Trademark Office, AZ102010017762.8, filed in 2010, July 6

Other Publications

- Breyer Ch., Gerlach A., Werner C., Grid Parity: Coming Sooner Than You Think, Future Photovoltaics, 2011(4), December
- Breyer Ch., Über solarthermische Kraftwerke und deren globales Energieversorgungspotenzial, In: Gerechtigkeit und Verantwortung in der Klima- und Energiepolitik, Aufenanger V., Friedrichsen N., Koch S. (Hrsg.), Verlagshaus Monsenstein und Vannerdat OHG, Münster, 2010
- Breyer Ch., Wie günstig ist Photovoltaik?, In: Gerechtigkeit und Verantwortung in der Klima- und Energiepolitik, Aufenanger V., Friedrichsen N., Koch S. (Hrsg.), Verlagshaus Monsenstein und Vannerdat OHG, Münster, 2010
- Huber V., Breyer Ch., Ursachen und Folgen des Klimawandels, In: Energie, Macht, Vernunft – Der umfassende Blick auf die Energiewende, Creutzig F., Goldschmidt J.C. (Hrsg.), Shaker Media, Aachen, 2008

Danksagung

Viele haben ihren besonderen und ganz individuellen Beitrag geleistet, damit diese Arbeit in der vorliegenden Form entstehen konnte.

Besonderer Dank gebührt Herrn Prof. Jürgen Schmid für die Ermöglichung der Dissertation und das Vertrauen in das Gelingen meiner individuellen Forschungsansätze. Vielen Dank an Herrn Prof. Ingo Stadler für die Übernahme der Zweitbegutachtung dieser Arbeit.

Ohne den weitblickenden strategischen Blick von Verantwortlichen bei Q-Cells wäre sicherlich nicht der organisatorische Freiraum denkbar gewesen, der die grundsätzliche Betrachtung von in Zukunft zu realisierenden Geschäftsmodellen ermöglichte. Mein ganz besonderer Dank gebührt hier in chronologischer Reihenfolge Jörg Müller, Marko Schulz, Achim Reiß, Till Utermöhlen und Ina von Spies.

Mit leidenschaftlichem Einsatz haben „meine“ Studenten Fleißarbeiten, Details und Seitenpfade dieser Arbeit ermöglicht. Gemeinsam haben wir erstaunliche Ergebnisse zu Tage gefördert, die es im Regelfall zuvor in der jeweiligen Form noch nicht gegeben hat. Alexander Gerlach, Friederike Kersten, Marzella Görig, Ann-Katrin Gerlach, Chris Werner und Robert Olyschläger – es war mir eine Freude und Ehre mit Euch gemeinsam Terra Incognita zu betreten und die süßen Früchte der Erkenntnis zu genießen.

Ich hatte das große Glück mit den verschiedensten Kollegen aus verschiedenen Ländern, Disziplinen, Unternehmen, Instituten und NGOs unterschiedliche Aspekte der Photovoltaik und noch einiges mehr kennen zu lernen. Mein herzlicher Dank gebührt Anton Milner, Christian Birkner, Christina Peters, Daniel Montoro, Daniel Schäfer, Gerhard Stryi-Hipp, Daniel Stetter, Hannes Behacker, Harald Schützeichel, Jacob Winiecki, Moritz Riede, Jan-Christoph Goldschmidt, Markus Hlusiak, Michael Sterner, Oliver Beckel, Peter Adelman, Samson Tsegaye, Stephan Rieke, Simon Rolland, Workeneh Gashie und Yves-Marie Saint-Drenant. Daneben haben weitere Helfer im Hintergrund zum Gelingen dieser Arbeiten beigetragen. Die Anerkennung hierfür gebührt Alexander Schwank, Andreas Mohr, Christoph Gerhards, Dominik Huljić, Falk Reimann, Frank Strümpfel, Guido Glania, Kersten Mangado, Franz Trieb, Martin Schädel, Max Lee, Saioa Tardon, Andreas Wade und Peter Engelhart.

Kollegen in unterschiedlichen Teams haben einerseits mit ihrem unverstellten Blick auf meine Themen, aber auch mit faszinierter Verwunderung meinen leidenschaftlichen Drang zu neuen Erkenntnissen begleitet. Herzlichen Dank hierfür an Alberta Rohardt, Alexander Goldmaier, Andreas Kux, Angelika Möbius, Christian Minge, Christoph Jordaan, Daniel Fricke, Florian Benz, Jochen Endle, Paul Schreiter, Roland Doll, Uli Neumann und Wolfgang Brugger.

Mit Begegnungen, Erlebnissen oder auch Ratschlägen haben höchst unterschiedliche Menschen in meinem bisherigen Leben dazu beigetragen, dass ausnahmslos unbeabsichtigt aber dennoch als Folge davon diese Arbeit entstehen konnte. Ein ganz herzliches Dankeschön an Christian Walther, Edith Gallenmüller, Gerhard Knies, Hans Neuberger, Hans Roscher, Hermann Scheer, Irmgard Lux, Johannes Breyer, Raimund Lux und Stefan Rahmstorf.

Ohne die großartige Unterstützung meiner Familie wäre diese Arbeit gar nicht denkbar gewesen. Liebe, Wertschätzung und Toleranz ermöglichen erst die gedankliche Freiheit aber auch den zeitlichen Freiraum für das Betreten neuer Welten. Mein liebevoller Dank gilt Angelika und Jonas. Möge für Dich einmal selbstverständlich sein, was ich in dieser Arbeit noch als eine mögliche Zukunft zum Besseren beschreibe.