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Spatially explicit life cycle assessments reveal hotspots of environmental impacts from renewable electricity generation

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Renewable energy generation has great potential to reduce greenhouse gas emissions, however, it may exacerbate other environmental impacts, such as water scarcity, elsewhere in the supply chain. Here, we reveal a wide range of global environmental impacts of concentrated solar power, run-of-river hydropower, and biomass burning compared to classical coal-fired power: Spatially explicit life cycle impact assessment is used to evaluate their supply chains with respect to demand for energy, land, material, and water, greenhouse gas emissions, and impacts on human health and ecosystem quality with a focus on mining. Hotspot analyses in terms of location and type of impact show that there is no clear preference for any of the technologies, mainly because water consumption is often critical on-site. The examined concentrated solar power plant is the least suitable for a sustainable energy transition: Its spatial hotspots are spreading the furthest globally and may exceed those of coal combustion in number and severity. The presented methodology is the basis to mitigate such environmental hotspots.

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Greenhouse gas emissions from electricity and heat production accounted for 25% of global greenhouse gas emissions in 2010[1]. Their reduction in order to counteract advancing climate change is a declared goal of the international community, set out in the Sustainable Development Goal 7 Clean and Affordable Energy[2]. Climate-friendly technologies to produce electricity are an important element of this endeavour, which has also been addressed by the International Resource Panel[3]. So far, society and politics have tended to focus less on other environmental impacts of such technologies than greenhouse gas emission. However, electricity production requires such large quantities of (cooling) water that, even under sustainable development scenarios, the demand can no longer be adequately covered as early as 2040 in many regions in the world[4]. It may contribute to regional water scarcity therefore. Moreover, demand for key mineral resources, the extraction, and processing of which in turn have a number of different environmental impacts, may probably increase. Lithium is an example for a resource in high demand by the renewable electricity sector, while its extraction can contribute to regional water scarcity in the High Andes[5]. Rare Earth Elements have meanwhile become critical to wind turbines, while their extraction and related processes can not only affect the surrounding environment negatively, but can also present severe risks to human health[6]. As the share of biofuels is expected to provide an important element of global energy mix with 20–30% of global requirement, not only demand for land, but also competition for fertile land between different users will increase[7]. Depending on the chosen scenarios 7–45% of global arable cropland would be required to satisfy increasing biofuel plant needs in 2050, which indicates that such developments have to be managed foresightedly[7].

Next to the selected examples, there are many other possible impacts and links between electricity generation and other sectors. As consequences of interactions between human and natural systems "have profound implications for global challenges"[8], the concept of telecoupling has been applied to describe interactions in human-environmental systems by integrating disciplinary concepts such as teleconnections and globalisation[8,9]. We use the term teleconnections, which was originally related to the linkages between distant climate systems[10], within this study to describe the environmental burden of electricity generation at certain locations on other locations all around the world. In order to uncover teleconnections in such a way that options for action can be derived, the degree of spatial resolution is crucial: A review of 251 Life Cycle Assessment (LCA) analyses has shown that there are still too few results and many regions of the world remain underrepresented[11]. To help close this gap, we conduct a comprehensive, spatially explicit assessment of various environmental effects through an advanced Life Cycle Impact Assessment (LCIA) hotspot analysis that takes spatial LCA further through a newly developed evaluation and presentation of hotspots to the best of our knowledge. For this purpose, a set of LCIA indicators is used to compare the potential environmental burden of the construction and operation phase of four case studies of electricity generation: run-of-river hydropower, concentrated solar power, burning of bagasse (sugar cane residues from manufacturing), and combustion of coal. Spatially explicit information regarding material supply is added to regionalise the upstream supply with eight relevant mineral commodities. Results are analysed with respect to most harmful activities in terms of locations and kind of activity to identify adverse teleconnections along the supply chains. Recommendations for energy production and further research priorities are derived.

Results

This study identifies teleconnections from four case studies of electricity generation (Fig. 1). Three systems of renewable electricity generation are considered: Run-of-river (ROR) hydropower at the Danube, Germany, consisting of six barrages between the cities Oberelchingen and Faimingen (a), concentrated parabolic through solar power (CSP) in Ouarzazate, Morocco (b), and incineration of sugar cane residues in the Rio dos Patos basin, Brazil (c), so-called bagasse. The latter is considered as product and as waste in comparison, which will be referred to as bagasse incineration and waste-bagasse incineration from here on. A coal-fired power plant (CPP) at the river Weser, Germany (d), serves as a reference for conventional systems.

LCA models of the construction and operation phase of the case studies are supplemented with case study-specific data. An extensive dataset with regionalised upstream supply chains for eight mineral commodities that are relevant for electricity generation systems, namely aluminium, copper, coal, cement, iron and steel, lithium, and phosphorus, is provided to support the spatial resolution of upstream supply beyond the used LCA database. The LCA models are comparatively and spatially explicitly assessed using a selection of LCIA indicators, in particular the climate and resource footprints that cover at least 80% of the variance of possible environmental impacts[12]. The indicators are divided into two groups: Group 1, environmental pressures, comprises indicators that refer to turnover of material flows determining the environmental burden close to driving actions (LCA midpoint), while group 2, environmental impacts, contains those indicators which evaluate more complex and more extensive impact pathways (LCA endpoint). If both are addressed, the term environmental burden is used. All indicator results are normalised by the median of all case studies and presented per 1 kWh of electricity delivered, specified for the construction and operation phase. A comparison of the cumulative results helps to evaluate the overall environmental performance of the case studies.

Moreover, hotspot analyses are carried out according to a newly developed method to the best of our knowledge. Hereby, the activities, i. e. all LCA processes that make up the modelled supply chain of a case study, are analysed both in terms of their location (a) and their type (b). Before, LCIA activity results are normalised per environmental pressure or impact by comparing them with common median values to make case study results directly comparable. Normalised values represent the ratio to a median environmental impact or pressure, respectively, and are classified into low, medium, high, and very high severity. The corresponding locations are regarded as teleconnections and considered as spatial hotspots increasingly from low to very high severity (a). Here, we use the terms on-site, i. e. the location of the case study under consideration, and remote, i. e. the location of all activities connected to a case study through the supply chain that are not executed at the location of the case study itself. Additionally, all activities are grouped into categories and their LCIA results are compared to the total environmental burden of each case study to derive activity hotspots in supply chains, i. e. those activities that are responsible for the highest burdens (b). A comparison with the spatial hotspots provides information about what kind of activities are behind spatial hotspots and where supply chain analyses must be prioritised.

Cumulative environmental pressures. In general, environmental pressures from renewable electricity generation are in most cases eminently lower than from coal combustion, where values are partly one order of magnitude larger (Figs. 2 and 3 and Supplementary Data 1). Among the renewable ones, the CSP causes highest pressures with results that are slightly above-average. Bagasse incineration causes higher environmental pressures than the waste-bagasse incineration, which ranks fourth overall. The

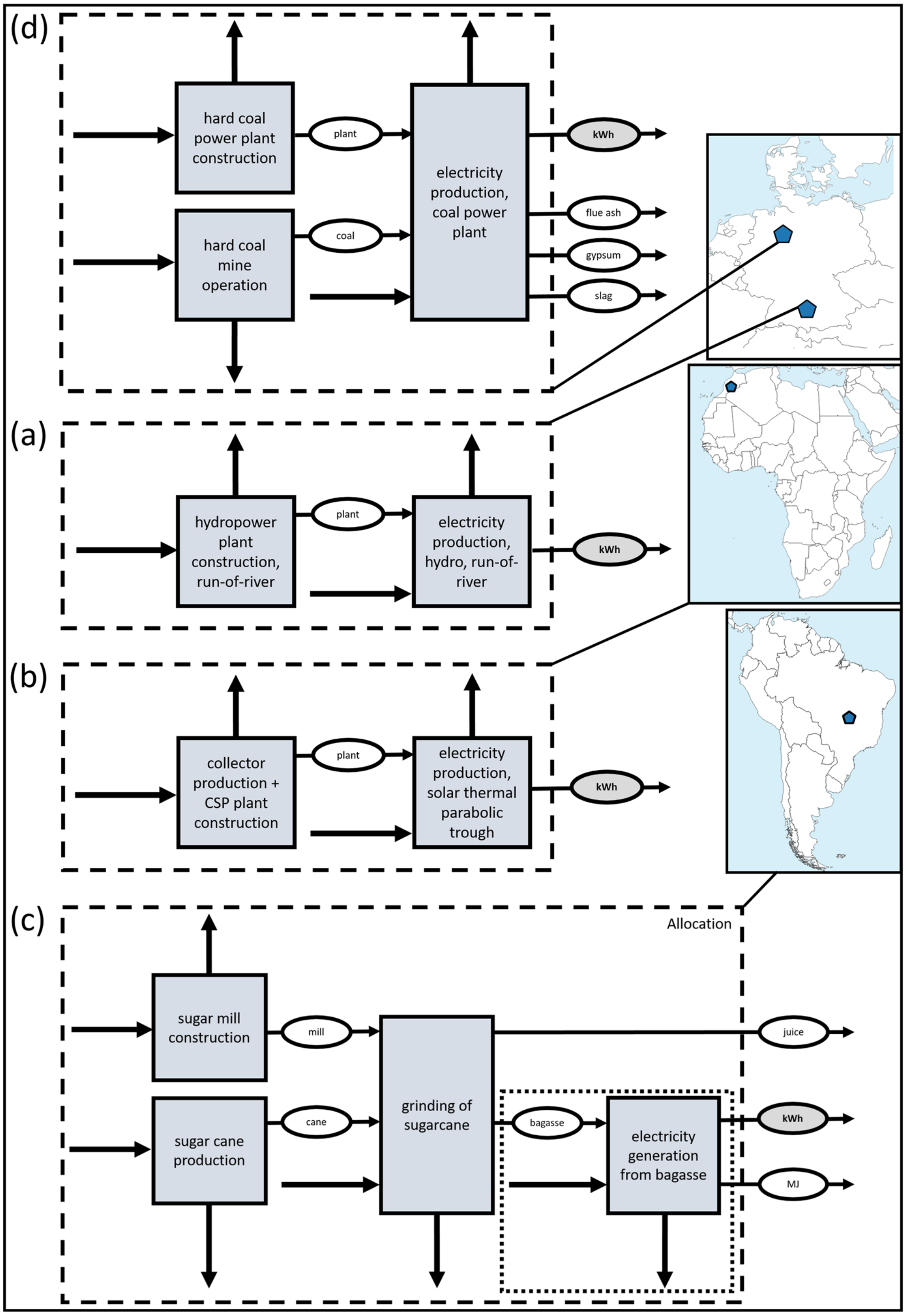

Fig. 1 Simplified LCA models and locations of the four case studies. The locations of the case studies are shown in the connected maps: **a** is located at the river Danube, Germany, **b** in Quarzazate, Morocco, **c** in the Rio dos Patos basin, Brazil, and **d** at the river Weser, Germany. For case study **c**, the sugar mill in Brazil, two different system boundaries are considered to account for waste-bagasse incineration (inner dotted boundary) and bagasse incineration (outer dashed boundary). Black arrows symbolise inputs and outputs, apart from the extra marked. In the figure, only the greatest contributions are considered in own processes (black boxes), respectively, other inputs are summarised via the black arrows.

lowest pressures are associated with the ROR hydropower. The first exception is the quantitative water scarcity footprint, i. e. the sum of evapotranspiration, product-incorporated water, and water transfer, with higher pressures than from coal combustion, especially with the CSP and the bagasse incineration. The second exception is land occupation which totals temporary occupation of physical space without any assessment in this study. It is intended to fulfil the function of an approximation to the land footprint based on physical land demand. Here, renewable electricity generation can be responsible for comparable pressures than the CPP, although for different reasons: In the case of CPP, the demand for construction timber in upstream mining plays a role, while the renewable electricity systems require land on-site. This does not apply to ROR hydropower, however, as its associated land occupation produces the lowest of all results.

In the construction phase, the highest environmental pressures are the total material requirement and raw material input of the CSP, which are mainly associated with gravel and sand

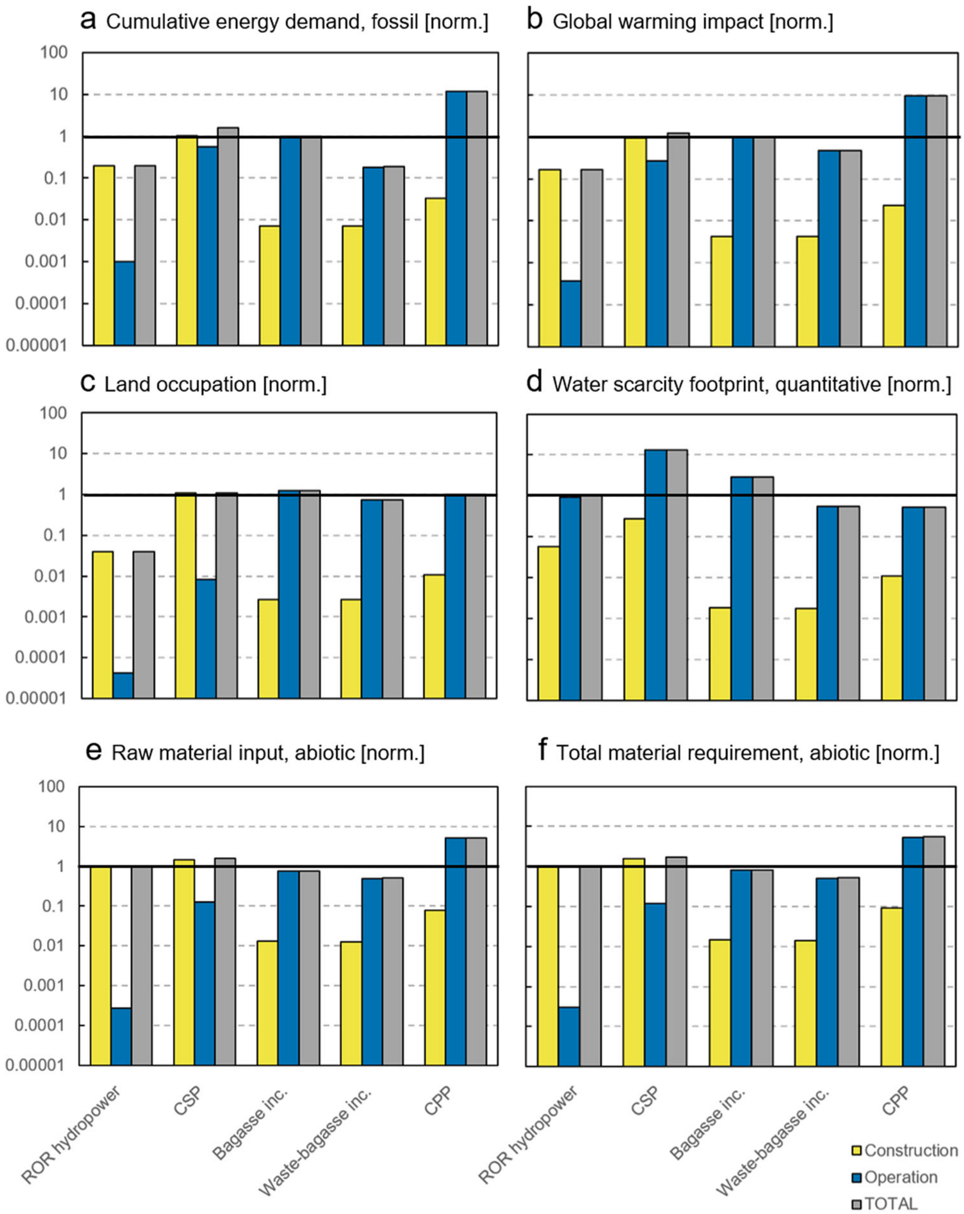

Fig. 2 Environmental pressures of electricity generation systems. Results are presented per environmental pressure **a**–**f** for the construction (yellow bars) and operation (blue bars) phase on a logarithmic scale per 1 kWh produced electricity, respectively. For each environmental pressure, LCIA results for operation, construction and total have been normalised by the median total result of all case studies. This approach ensures that the ratios between operation and construction are maintained and that the grey sum bar corresponds to the sum of the yellow and blue bar, respectively. Since a normalised value of 1 represents environmental pressures identical to the median, the corresponding grid line is highlighted in bold. ROR run-of-river, CSP concentrated solar power plant, Bagasse inc. Bagasse incineration, CPP coal-fired power plant.

requirement in the upstream supply (Supplementary Data 2–8). This is followed by the CSP's predominantly on-site land occupancy. Of medium severity are the qualitative water scarcity footprint of the CSP as well as its cumulative energy demand and global warming impact, among others because of coal demand and use in the supply chain. The raw material input and total material requirement of the ROR hydropower is also of medium severity due to gravel and sand requirement. Environmental pressures from bagasse incineration are always the lowest, regardless if it is considered a product or waste. The ratio of the indicators for the construction phases looks very similar for all case studies (Fig. 3).

The operation phase is environmentally more relevant than the construction phase for the CPP and bagasse incineration (by-product and waste), but for the ROR hydropower and the CSP, it is less relevant (Fig. 3) except for the quantitative water scarcity footprint. The highest environmental pressure is the on-site water demand of the CSP as a result of cooling and rinsing water losses in the Moroccan desert. Second highest is the fossil cumulative energy demand of the CPP. It is at 64% associated with hard coal mining in Russia, as the LCIA assesses energy carriers at the extraction stage. This is followed by other pressures associated with the CPP's demand for and use of coal, namely global warming impact, raw material input, total material requirement, and qualitative water scarcity footprint. The bagasse incineration has an above-average agricultural water demand on-site and its land occupation and global warming impact, which are also predominantly related to on-site activities, are of medium

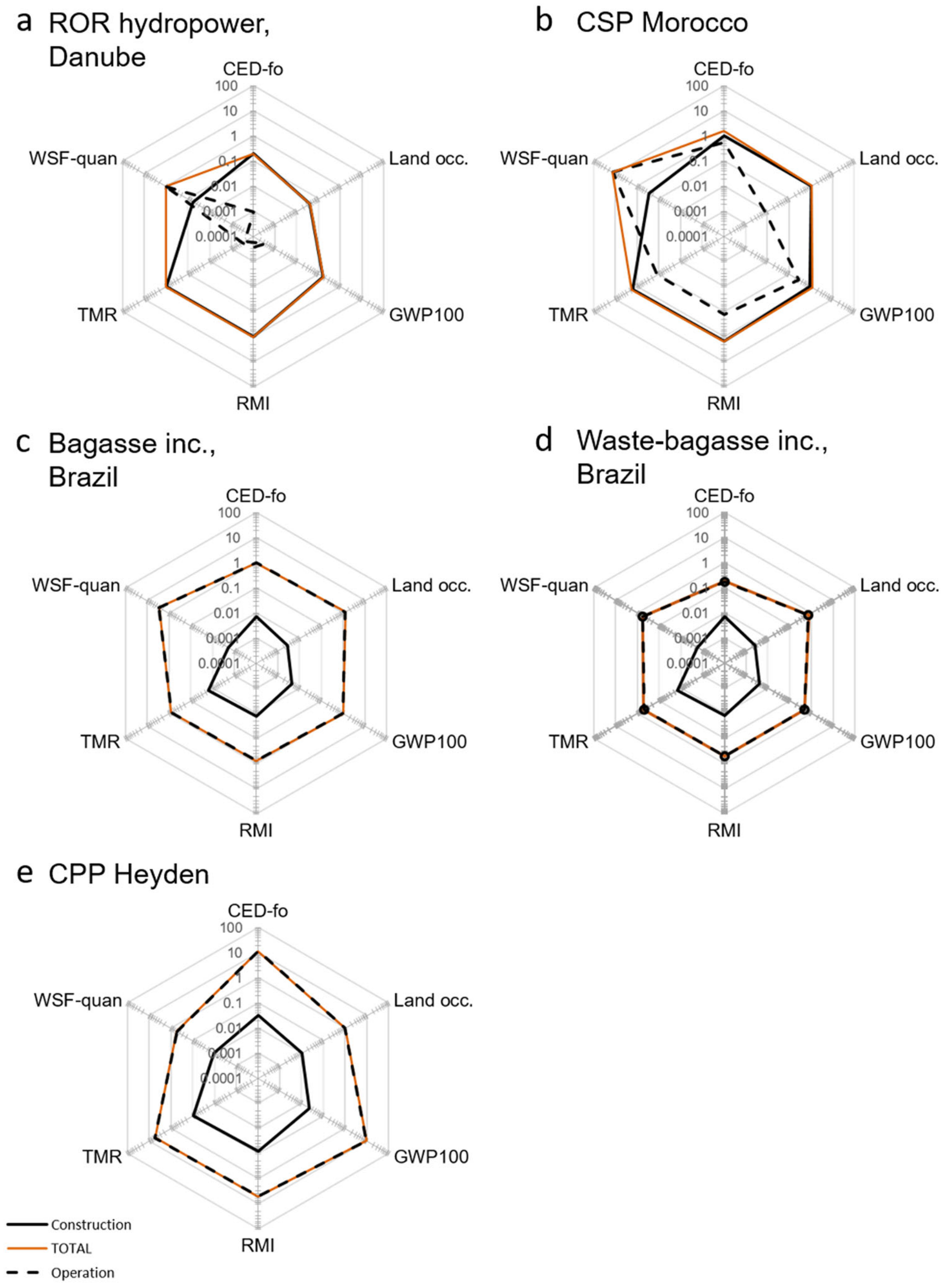

Fig. 3 Environmental pressures of electricity generation systems per case study. Results are presented by case studies for the construction and operation phase **a**–**e** on a logarithmic scale per 1 kWh produced electricity, respectively. For each environmental pressure, LCIA results for operation, construction, and total have been normalised by the median total result of all case studies (details Fig. 2). ROR run-of-river, CSP concentrated solar power plant, Bagasse inc. Bagasse incineration, CPP coal-fired power plant, CED-fo Cumulative Energy Demand, fossil, Land occ. Land occupation, GWP100 Global Warming Impact, RMI Raw Material Input and TMR Total Material Requirement and WSF-quan Quantitative Water Scarcity Footprint.

severity. The ROR hydropower is responsible for the lowest pressures.

Cumulative environmental impacts. As regards environmental impacts, the overall impact of bagasse incineration and the CSP on ecosystem quality is less than an order of magnitude lower compared to CPP (Fig. 4, Supplementary Tables 1 and 2, and Supplementary Data 9 and 10), meaning that there are only minor savings here compared to coal-fired power. For human health, only ROR hydropower is considerably less harmful. In the construction phase, the combustion of coal has the highest impact on human health, closely followed by the burning of bagasse (by-product and waste). In the operation phase, impacts on ecosystem quality are more relevant than on human health: The combustion of coal has the highest impacts, while sugar cane cultivation is responsible for only slightly lower results associated with bagasse incineration.

Hotspot analysis of the environmental burdens by locations. Spatial hotspots of a case study are the locations where the activities with the greatest environmental pressures take place. To identify these and evaluate hotspots comparatively, for each pressure, the results of individual activities are normalised by the median of the results of all activities in all case studies, summed

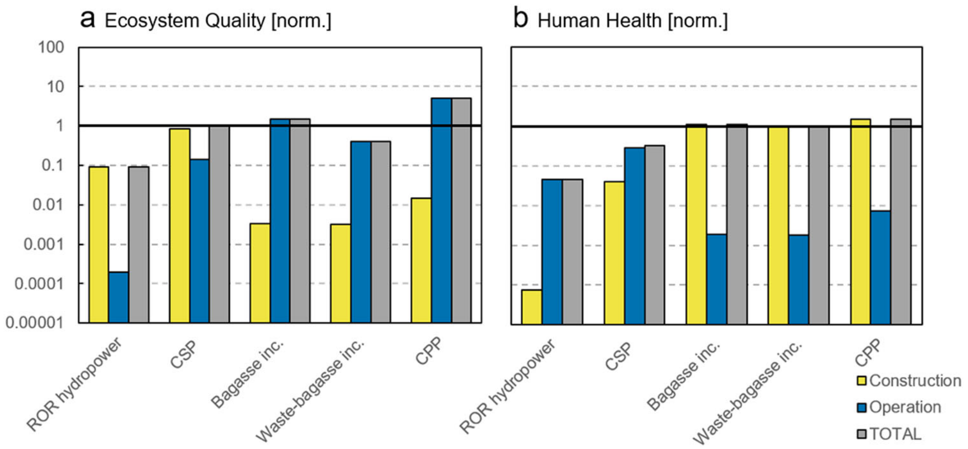

Fig. 4 Environmental impacts of electricity generation systems. Results are presented by indicators **a**, **b** for the construction (yellow bars) and operation (blue bars) phase, respectively, on a logarithmic scale (details Fig. 2). ROR run-of-river, CSP concentrated solar power plant, Bagasse inc. Bagasse incineration, CPP coal-fired power plant.

by location, and grouped by case study. The normalised results are presented on a scale from 1–100, meaning that the raw value is 1–100 times the median. Values below 1 are not regarded as hotspots and values above 100 are set to a maximum of 100. Hotspots can be countries or regions as well as individual points and can comprise several activities or several pressures of the same activity. Land occupation is not considered in the spatial hotspot analysis because it does not contain the necessary information for a meaningful spatial assessment of land occupancy and land use. Also, environmental impacts, which represent LCA endpoint approaches, are not included, as it can be assumed that in the endpoint perspective harmful effects occur beyond the locations belonging to the activities. The associated location does hence not necessarily represent the location of the harmful effect.

In general, the largest number of hotspots is due to the CSP (Fig. 5), while the most severe hotspots are found in the CPP with a few hotspots exceeding the maximum of 100 by far (Supplementary Data 11). The lowest number of hotspots is associated with bagasse incineration (by-product and waste), while the most minor hotspots are from waste-bagasse incineration. In the distribution of hotspots, the construction and operation phases differ strikingly.

In the construction phase, the CSP causes the most and most severe hotspots worldwide, predominantly related to primary extraction of energy carriers, potassium chloride for the electricity storage, and metals. In second place is the ROR hydropower, which has a large construction cost compared to the electricity yield. Medium severe hotspots of the ROR hydropower are associated with primary extraction of energy carriers and basic materials for construction, such as iron and clay. The construction of the CPP causes only hotspots of very low severity, mainly related to iron extraction and steel production. Bagasse incineration, regardless if bagasse is considered as by-product or as waste, is not really responsible for hotspots, since only small parts of the sugar mill facilities are attributed to the conversion of the bagasse into electricity.

In the operation phase, all case studies have roughly the same number of hotspots, excluding ROR hydropower, whereas those of the CPP are the most severe. These are predominantly the Russian coal mines from which the CPP obtains its coal, but production of natural gas in Russia, needed in the upstream supply, is also represented. Medium severe hotspots in China are related to coal mining. The on-site water demand for sugar cane cultivation is the most severe hotspot of the bagasse case study, followed by petroleum production in the Middle East and Russia. Medium severe hotspots are related to primary extraction of energy carriers and metals. In third place is the CSP with a dominant on-site hotspot, which is due to evaporation losses as a result of water cooling of the plant and cleaning of the mirrors and far exceeds 100 as the greatest of all hotspots. Medium hotspots are connected to the production of natural gas in the United States and Russia. For the waste-bagasse, the evaporation losses from the boiler system on-site are most important. Other hotspots are of medium severity, related to mining in China and Australia, and very low severity. Only one hotspot is attributable to ROR hydropower, which stems from the on-site evaporation of water as a result of the additional impoundment.

Level of regionalisation. The evaluation of spatial information is a core part of this work. However, the degree of regionalisation of activities can vary greatly: Activities that have been spatially disaggregated in this work are point-specific, whereas the spatial resolution of activities from the LCA database used can range from country level to region or continent level to global level, the latter meaning as much as unknown. In order to make the regionalisation transparent, a quality index is assigned to all locations, where quality 1 stands for point coordinates, quality 2 for countries, quality 3 for regions, quality 4 for unrealistic locations (e.g., clay from Switzerland for the bagasse case studies) and quality 5 for unknown locations. The level of regionalisation is the proportion of regionalised activities in a case study, i.e., of activities to which a location of quality 1–3 is assigned (Supplementary Table 3). It averages 56%, ranging from 41% (operation of ROR hydropower) to 88% (operation of CPP). Locations of quality 4–5 are not included in the hotspot analysis, although their share is 44% on average. It is to be assumed, that the spatial hotspots shown here represent a minimum, since activities at unknown locations are nevertheless part of the supply chain of a case study. Their spatial allocation will probably reinforce existing spatial hotspots or create new ones.

Hotspot analysis of the environmental burdens by activities. Next to the locations of activities in global supply chains, a consideration of the kind of activities is important, particularly to identify activities with weak or no spatial resolution. The most important activities that did not enter the hotspot analysis due to unknown or questionable regionalisation are the extraction of sand, gravel, uranium, petroleum, and gas, the processing of sinter, pig iron, ammonium, nitric acid, sodium nitrate, quicklime

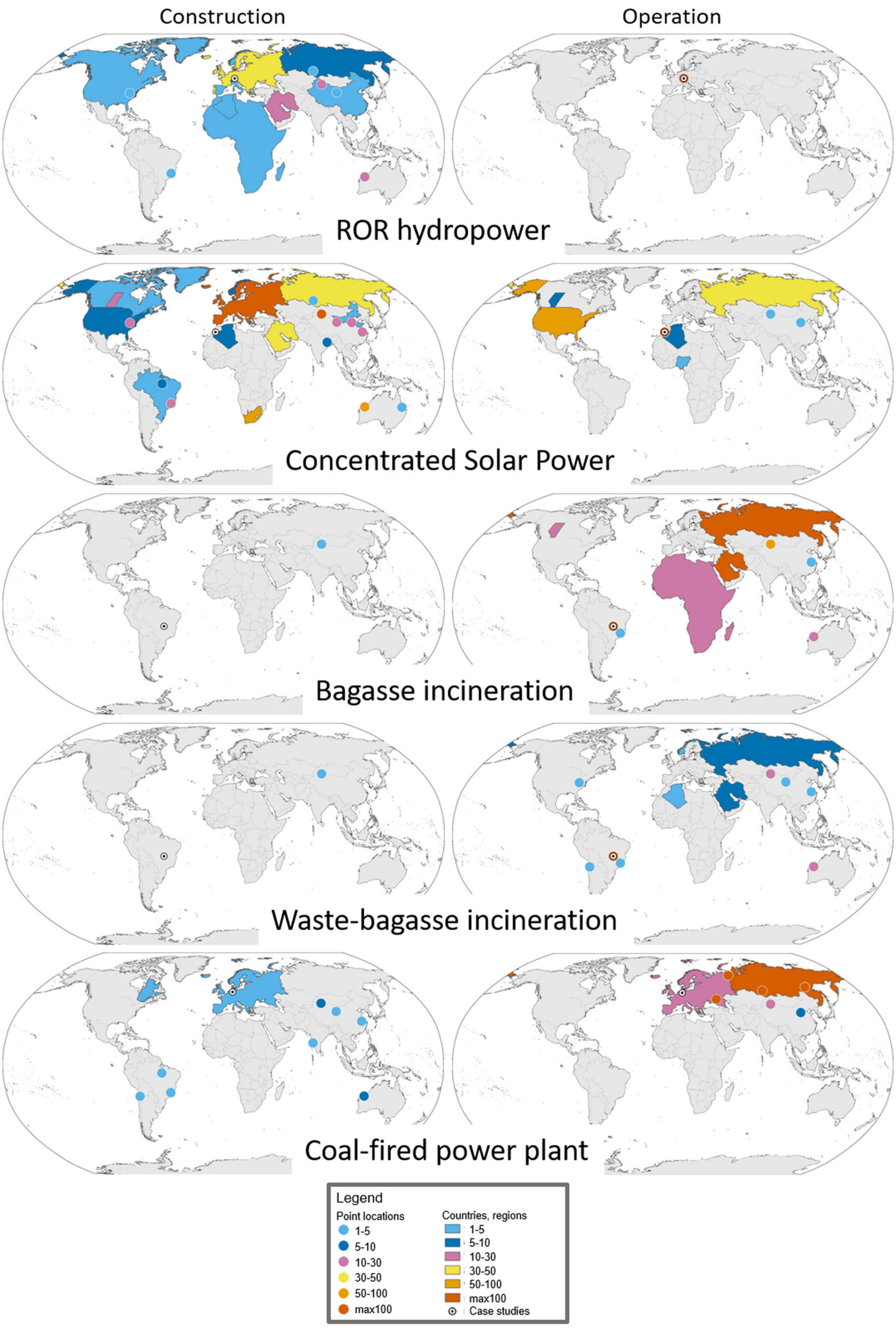

Fig. 5 Hotspots of environmental burdens of electricity generation systems in the construction and operation phase. Hotspots are marked in colour, they can be single points (represented by coloured circles), countries or regions (represented by coloured polygons). The colour indicates the ratio of a normalised hotspot results to the median of all case studies, whereas a value of 1–10 is regarded as a hotspot of low, 10–30 of medium, 30–50 of high and 50–100 as well as greater 100 of very high severity. High resolution maps of the single environmental pressures are available in Supplementary Figs. 1–7.

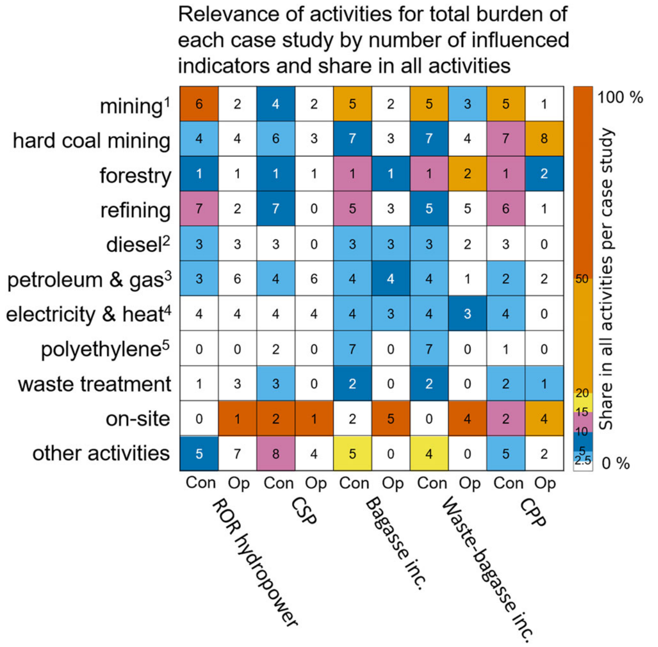

Fig. 6 Relevance of activity categories for total environmental burden of each case study by number of influenced indicators and share. Numbers represent the number of environmental pressures and impacts to which a category contributes. For example, in the construction phase of the ROR hydropower mining activities appear in the assessment of six LCIA indicators. Colours represent the share of a category in the total environmental burden of a case study. [1]Mining without hard coal mining, [2]burning of diesel, [3]production of petroleum and (natural) gas, [4]production of electricity and heat, [5]production of polyethylene. ROR run-of-river, CSP concentrated solar power plant, Bagasse inc. Bagasse incineration, CPP coal-fired power plant, Op Operation, Con Construction.

and clinker, polyethylene production, forestry, the use of diesel in building machines as well as the treatment of sulfidic tailings, spoil and waste.

The environmental burden of the construction phases is generally spread over several activities, while the operation phases are more specific (Fig. 6). Most relevant for the total environmental burden are on-site activities which influence less indicators. This means that there are specific severe environmental pressures and impacts on-site. The second most relevant are mining and coal mining, which is also reflected in the hotspot analysis. This is followed by forestry which is underrepresented in the spatial hotspot analysis but can make up to 24% of the total environmental burden (Supplementary Table 4). In fourth place is refining, which is also shown in the spatial hotspot analysis. Diesel, petroleum, and gas production, heat and electricity production and polyethylene production can contribute to the environmental burden as well, although the shares are mostly small in comparison. Behind the large share of other activities in the bagasse case studies are pressures in the upstream chain that result from the construction of the turbines for electricity generation.

Uncertainty analysis. Uncertainty analysis is performed by Monte Carlo Simulations using the software openLCA (see "Data availability"). Stochastic values (mean and median) are determined from the Monte Carlo Simulations for each indicator result of each case study, respectively for construction and operation. The distribution of the log of the ratio of mean to indicator results, referred to as static, and median to static is analysed for the midpoint indicator results of all case studies

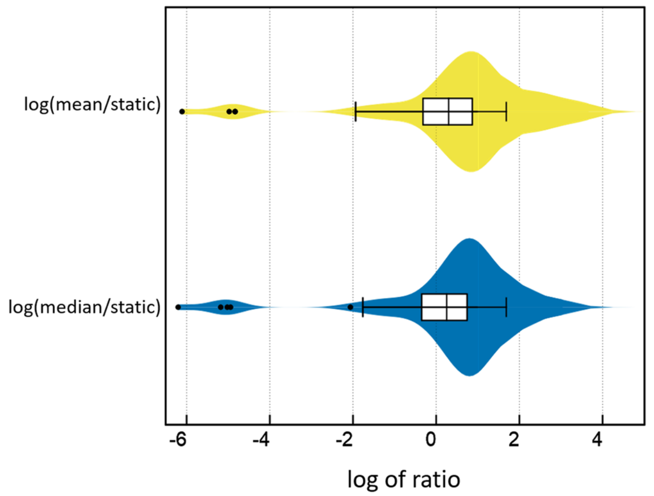

Fig. 7 Distribution of the ratios of stochastic to static values of all midpoint indicator results. These include the results of all case studies, respectively for construction and operation. The ratios are presented on a log-scale, meaning that the value is 0, if static and stochastic values (mean or median) are equal. Boxplots display the statistical analysis of the datasets (25th percentile, median, and 75th percentile), while black points represent outliers.

(Fig. 7, details and analysis for endpoint indicators see Supplementary Notes 2, Supplementary Data 12, and Supplementary Table 5). It shows a strong peak between 0 to 1, where the ratio of the parameters is 1–10, respectively. Overall, the stochastic values from the Monte Carlo Simulation tend to be larger than the static ones, which is typical for LCA models, if all input parameters are represented by lognormal distributions[13]. The shape of the distribution in Fig. 7 corresponds to what other authors have found for Monte Carlo Simulations of LCA models[13]. However, the uncertainties are considerably larger overall, what is to be expected for the analysis of extensive global supply chains[14]. The large negative outliers occur with the indicator RMI for the case studies waste-bagasse incineration and the CPP, i. e. the stochastic values are much smaller than the static ones. As the indicator TMR, which includes RMI, does not produce outliers for the same case studies, a statistical error can be assumed here.

Discussion

Environmental burden of renewable electricity generation technologies. The CPP is responsible for the greatest environmental pressures and impacts most often. Because of the demand for and use of coal, the fossil cumulative energy demand, global warming impact, raw material input, total material requirement, and impacts on ecosystem quality are the highest of all case studies. Associated hotspots are the most serious of all case studies.

However, this does not apply to all pressure and impact categories: All renewable case studies show a higher quantitative water scarcity footprint than the CPP, not in the upstream chain, but predominantly on-site. In particular, the CSP stands out, where water is used for cooling the plant and washing the mirrors. When calculating the water scarcity footprint, the high water stress level of the Moroccan desert, where water is about 60 times scarcer than in Germany[15], has a strong effect. The second highest water scarcity footprint has the cultivation of sugar cane in the Rio dos Patos basin, followed by the ROR hydropower due to evaporation from the backwater of the barrages on the Danube. If bagasse is used as waste, it has at least the same water demand than the CPP. In view of increasing regional water scarcity[16], the high water demand of the renewable case studies is a major problem for the studied technologies. Among others, a focus on wind power and photovoltaics, which may consume less water during operation, could turn this situation in favour of renewables. As regards land occupation, which summarises the pure physical land occupation of the case studies, the CSP, the bagasse case studies, and the CPP are at about the same level. The CSP has a great land requirement on-site, followed by the cultivation of sugar cane for the sugar mill which is comparable to the land occupation of coal mining, the largest consumer of land in the supply chain of the CPP.

Comparing only the systems of renewable electricity generation, the CSP is by far associated with the greatest environmental pressures and impacts due to its high resource demand with a multitude of hotspots from primary extraction all around the world. Its environmental performance is poor in comparison to the other renewable electricity technologies. In addition, savings are low compared to coal-fired electricity. We thus conclude that the CSP technology as considered here should be seen critical. Efforts to develop concentrated solar power plants in countries with high solar radiation, also for export[17], are likely to shift environmental problems, if it does not succeed in making their construction less resource intensive and greatly reduce water consumption. Dry cooling is a promising concept here, while water desalination is an option if it can be ensured that it does not entail other problems, e.g., damage to marine life by rejecting brine[18]. The high land requirement may also become a problem if the technology is further expanded. However, physical land occupancy, taken into account here to represent the land footprint, can only serve as an initial estimation of related environmental effects.

Environmental relief of renewable electricity generation technologies. None of the case studies examined provides important savings in actually all categories compared to coal-fired power generation. Most often, ROR hydropower has the lowest environmental pressures and impacts with a wide margin to the CPP, however, the material input to construct six barrages with a comparatively low energy yield is high and no water is saved compared to the coal-fired power plant. In addition, there are other known impacts on river systems, e.g., alteration of the natural flow regime and impairment of the fluvial ecosystem[19], which were not considered here. Electricity from waste-bagasse has the second lowest environmental burden, followed by bagasse incineration which causes median burdens. The bagasse case studies are particulary convincing in the construction phase where savings are possible in comparison to the construction of the other systems. This is testimony to the idea that integrated systems can have great environmental benefits. The results help to assess the suitability of biomass for sustainable electricity generation: the greatest savings are in integrated use, when the biomass used is a genuine waste product and is not specifically grown for the purpose of electricity generation. The CSP is closest to the burden of the CPP and provides no important savings as discussed before.

We see these results as an important indication that only the consideration of a broad range of environmental impacts when evaluating possible technologies can contribute to making the energy transition more sustainable. This is still being done too little[11]. The focus of the German energy concept, for example, is on climate protection[20] and also the International Renewable Energy Agency (IRENA) considers this to be central (https://www.irena.org/energytransition). However, climate protection alone is not enough for a sustainable global energy transition as the results of this study indicate. Environmental impacts of appropriate technologies should be small across a wide range of sustainability criteria[21] so as not to merely shift problems. To evaluate the environmental performance of different technologies, an LCIA of the entire supply chain according to various sustainability criteria is indicated.

Application of the hotspot analysis to reduce environmental burdens. Because regional scarcity or regional impacts can play a role for certain resources, environmental pressures and impacts should be spatially located, in addition. Since detailed spatial LCA analyses are not yet a standard procedure[11], the methodology and applications presented here are intended to contribute to the progress of the approach. Our LCIA hotspot analysis can (1) present a multitude of LCIA results of different case studies comparably on a unified scale, (2) identify supply chain-related environmental pressures according to location and to kind of activity, and (3) can show where and at which points in the supply chains there is a need for what kind of action. The most important hotspots of the case studies examined and their implications are as follows:

(1) The majority of spatial hotspots are related to material and energy carrier supply from mining activities, which are distributed all over the world with a special focus on Russia, the Middle East, the United States, Africa, and China. Mining activities are important for the total environmental burden of all case studies, even the ROR hydropower, and always contribute to several environmental pressures and impacts. Depending on the type of mining resource, these can be for example reduced by decreasing raw material input through savings, using secondary resources through recycling or urban mining, or by moving teleconnections to less critical regions, in descending order. In the case of CSP, for example, a combination of the three possibilities is conceivable, which should initially be examined and anchored in the planning phase.

(2) For resources with varying regional availability, the investigated case studies of renewable electricity generation partly consume more than the CPP, especially in case of water. There is little that can be done about the existing plants; at the very least, opportunities for savings through technological retrofits should be explored. Since the water consumption of the case studies investigated leads to on-site hotspots, in the case of new planning of barrages, sugar mills, and CSP plants, the critical resource should always be addressed during site selection. If there is no possibility to mitigate the environmental impacts, one must ask whether the corresponding technology can really contribute to sustainable electricity production. Based on the results of this work, such a critical impact is water consumption in the Moroccan desert.

Further research is needed to overcome the current limitations of the analysis: (1) Physical land occupancy can only serve as a basis for the land footprint and should in perspective be connected to a proper assessment with respect to impacts on biodiversity. (2) The comparison should be extended to include other essential renewable technologies for electricity generation, such as photovoltaics or wind power, as well as the disposal stage, which can be important in terms of human toxicity, eco toxicity, or metal resource depletion. (3) The efforts made in this study to spatially differentiate mineral supply chains and the entailed environmental burdens cover only a few commodities and can only be a first step towards a transparent representation of the teleconnections. There is a number of activities with weakly localised upstream supply chains, namely gravel and sand quarrying, waste treatment, petroleum and gas extraction, the production of basic chemical products and building materials, forestry as well as diesel production and use. Where high environmental impacts meet weak regionalisation, further efforts should be made, to detect the most severe impacts of international supply chains. In the long term, regionalised datasets for all primary resources on sub-country level need to be created, integrated into LCA databases, and considered in supply chain analyses in order to be able to regionally represent and assess the environmental impacts of human extraction. This can initially be done by modelling world markets using a combination of datasets and assumptions as shown in this study, but the long-term goal should be to accurately determine the origin of resources, e.g., using supply chain tracing, fingerprint analysis, and the like. This is not only an ongoing task of the LCA community, but policymakers, manufacturers, and suppliers are also called upon to ensure a spatially explicit environmental assessment of upstream supply, next to the assessment of economic questions and CO_2 emissions.

Materials and methods

Phases of the life cycle assessment. The LCA is carried out in four steps in accordance with DIN ISO EN 14040[22]. Phase 1 includes the determination of the goal and scope of the analyses. The functional unit provided by the four case studies is defined as 1 kWh of net electricity produced and results are related to this. The system boundary is defined to determine which processes along the process chain of the four case studies are considered in the LCA. Figure 1 shows that the electricity-producing processes are considered as well as the associated supply chains, respectively (only a selection shown in Fig. 1). If necessary, an allocation with respect to different output products is performed (bagasse). For the bagasse, two different system boundaries are considered in comparison which is described in detail below. The overall objective is to compare the different case studies in a meaningful way with regard to a broad range of environmental impacts and to identify hotspots of environmental burdens, which also defines the scope.

In the second phase, inventory analysis, the LCA models are designed in the software openLCA. They are based on existing datasets from the LCA database ecoinvent 3.5[23] which are extended or modified with the help of case study-specific data, as the focus of this study is not on the presentation of an extensive life cycle inventory. After a collection, description, and review of case study-specific data elementary flows from and to the environment are derived and added to the models as inputs and outputs. Taking into account the great differences between the case studies, an attempt was made to process the inventories with the same degree of accuracy and to consider the same elementary flows, where possible. Moreover, the inventory is adapted to include elementary flows relevant for the assessment phase. Product systems are created, linking the models of the case studies to the LCA database and providing the supply chain. In the case of eight mineral resources, the upstream chains in the database have been modified in advance.

In the third phase, the impact assessment, the product systems are evaluated using selected indicators. In the steps characterisation and (optionally) normalisation and weighting, the contribution of the product system to different impact categories is determined.

In the last phase, evaluation, the contributions are analysed spatially explicit and uncertainty analyses are carried out against the background of the framework conditions from phase 1. Mid-point approaches refer directly to the environmental impact categories, whereas end-point approaches describe impacts on the protected goods Human Health, Ecosystem Quality, and Resources. Both approaches are used in this study, whereas end-point impacts on Human Health and Ecosystem Quality are assessed. LCA is considered here from the use of raw materials to production (cradle to gate). The results for the construction phase of the facilities (buildings, infrastructure, machinery) and the operation phase (production) are presented separately, which is well suited for the comparison of energy systems[24]. The construction phase is also related to the functional unit of 1 kWh.

Life cycle inventory analysis. In the following, the LCA models of the four case studies are described comprising general information, the used ecoinvent 3.5[23] dataset, modifications for the construction and operation phase, a definition of the functional unit as well as the allocation approach along with information about special data handling (access of life cycle inventory see "Data availability" statement). The four case studies have been selected in the course of a research project which was carried out in cooperation with local practice partners. The practice partner have provided internal knowledge and data at first hand which has opened up the possibility of comparing the four case studies in terms of a wide range of environmental impacts based on real data.

Case study (a), the ROR hydropower plant at the Danube, consists of six barrages between the Bavarian cities Oberelchingen and Faimingen. The plants have been built from 1960 to 1965 and are each equipped with two double-regulated Kaplan turbines with stationary shaft and one directly mounted synchronous generator each. Drop heights are 5–7 m, the capacities are 7–10 MW and an average of approximately 50 GWh is annually generated per barrage (information from the website of the operator Bayerische Elektrizitätswerke GmbH). An ecoinvent 3.5 dataset for an average European ROR hydropower plant is taken as basis to model the case study. For the construction phase, areas that were transformed during construction or are occupied with case study facilities are analysed by evaluating freely accessible satellite images. So called transformation from wetland, from water bodies, to industrial area, to traffic area, and to water bodies (visible in satellite images from bulges, Supplementary Notes 3 and Supplementary Fig. 8) as well as the occupation of river are considered as elementary flows. For the other case studies, a similar approach was taken according to the available information from the operators and satellite image evaluations. For the operation phase, a turbine water use of 111 $m^3\ kWh^{-1}$ is calculated using the equation $P = Q \times h \times c_1$ (P: capacity in W, Q: water flow rate in $m^3\ s^{-1}$, h: drop height in m, $c_1 = 8.5\ KN\ m^{-3}$, the latter including gravity, density of water and a plant efficiency of 85%). Evaporation losses from additional impoundment during the operation phase are calculated at 0.02 $m^3\ kWh^{-1}$ taking into account a total transformation to water bodies by the six barrages of approximately 1 million m^2 and an evaporation rate of $643\ l\ m^{-2}\ a^{-1}$ as described in literature for similar latitudes[25]. The difference to the input water, i. e. the water flowing through minus the evaporation losses, is modelled as emission to water. Due to their close spatial proximity, the six barrages were balanced together. The functional unit of the operation phase is 1 kWh for all case studies. The inventory of the construction phase is also related to 1 kWh using a factor which is derived from the total capacity of the six barrages of 52 MW, an annual production of 50 million kWh, and a life time of 80 years[26] for the cement in dams, tunnels and control units (the latter only considered in the conversion for the construction phase). A shorter lifetime for the steel for turbines and tubes of 40 years is already considered in the original ecoinvent 3.5 process.

Case study (b), the CSP Noor I, which started operation in 2016 is located in the Moroccan desert near the city Ouarzazate. The location has one of the highest solar radiation levels in the world with 2635 kWh m^{-2} annually. The sun is shining almost 365 days. The 160 MW plant consists of a solar field, a power block, and a thermal energy storage. In the solar field, parabolic trough collectors use the solar radiation to heat up a heat transfer fluid. The power block, consisting of steam generation system, super-heater, turbine, re-heater, condenser, pre-heater, optional boiler, heat-exchangers, cooling tower, and pumps, receives this fluid to convert it into electricity. The thermal storage, to produce electricity in the absence of solar radiation, is based on molten salt, a mixture of 60% sodium nitrate and 40% potassium nitrate[27]. In contrast to the follow-up Noor projects in the region, the cooling system of Noor I still relies on water, and water is also needed to remove sand from the solar panels. It is taken from the nearby reservoir El Mansour Eddahbi. An ecoinvent 3.5 dataset for a 50 MW CSP is taken as basis to model the case study. For the construction phase, occupation of approximately 40 million m^2 by industrial area is considered and a total water use of 0.3 million m^3 reported by the operator is added to the inventory. For the operation phase, the elementary flow energy, solar, converted is added to account for the energy input from the sun. It is calculated by dividing the energy output of 1 kWh by 25%, which corresponds to the thermal-energy-to-electricity efficiency[28]. For the LCA analysis, not the total energy input is taken into account, but the efficiency of the system after the conversion of the solar heat into thermal energy. If the efficiency of the conversion of solar energy to thermal energy of about 59%[28] is considered, the overall efficiency of the conversion of solar energy to electricity would be 15%, which is also used in other studies[29]. The water demand was modelled in accordance with the information provided by the operator: A water use of approximately 0.005 $m^3\ kWh^{-1}$ is considered for cooling purposes and cleaning of the solar panels to remove sand. The water input is accounted for as evaporation loss as no water is recharged to the reservoir but collected on-site in evaporation ponds or reused if possible. The inventory of the construction phase is related to 1 kWh using a factor that is derived from the total capacity of 160 MW, a net annual production of 370 million kWh (information kindly provided by the operator), and a life time of 30 years[30] (the latter only considered in the conversion for the construction phase).

In the Rio dos Patos basin, Brazil, sugarcane is cultivated on a total available area of 65,000 ha of formerly degraded pasture (case study (c)). The sugar cane is processed during nine months of the year by the sugar mill units Jalles Machado and Otávio Lage which are both located in Goianésia and started operating in 1980 and 2011. At first, the fresh plants are grinded to separate plant fibres from sugar cane water, which is further processed to produce primarily sugar and ethanol as well as yeast as a by-product. Distillery wastewater, so-called vinasse, is returned to the fields as irrigation and fertiliser to complete the cycle. The pressed plant fibres, so-called bagasse, are burned to produce electricity via a system of boilers, steam turbine, and generator. The electricity is partly used for self-supply and otherwise fed into the electricity grid. Additionally, generated heat is fed into the sugar fermentation process. As 54% of the yearly produced sugar cane is irrigated and the region may frequently be exposed to water scarcity during the dry season, the operator makes extensive efforts to steadily reduce water consumption in agriculture and industry: In addition to elaborated planting and harvesting strategies or the use of efficient plants, the focus is on strategic water management: While in 2018 45% of irrigation consisted of salvage irrigation (one single application of approximately 40 mm of surface water with a boom traveller during the growth period), 17% was deficit irrigation with between 25 and 50% of the plant water deficit supplied. The return of vinasse and residual process water from the mill to the fields is another key element of the irrigation strategy and accounted for 37% of total irrigation in 2018. Dryer years may demand more salvage irrigation which can results in a shift of shares. This information was kindly provided by the operator Jalles Machado S/A Açúcar e Álcool. The LCA model was applied with two different allocation approaches for the analysis of electricity production from bagasse (Fig. 1) which differ in that (1) bagasse is considered as a by-product of sugar and ethanol production and (2) as a waste product thereof. From an LCA perspective, this is a critical question: In the Brazilian case study, the bagasse is seen as pure waste product as sugar cane is grown exclusively for the production of sugar and ethanol. Furthermore, there are no disposal costs for the bagasse which would classify it perfectly as waste. But since the electricity is sold, bagasse could also be assigned an economic value as an energy source. Therefore, many authors are performing a by-product allocation from the outset (for example Botha and Blottnitz 2006[31], Lopes Silva et al. 2014[32], Mashoko et al. 2013[33] and Ramjeawon 2008[34]). In order to be able to deal with different realities, especially in an international comparison, both approaches have been considered in this study comparatively. The LCA by-product approach is based on a dataset from ecoinvent 3.5 for electricity from sugarcane[35]. For the construction phase, a 40 MW gas turbine and elementary flows for transformation from approximately 500.000 m^2 pasture to industrial area and occupation of industrial area are added. For the operation phase, the calorific value of sugarcane of 5 MJ kg^{-1}, transformation from pasture to irrigated and non-irrigated annual crop, occupation by irrigated and non-irrigated annual crop and an evapotranspiration of 0.38 m^3 kg are considered in the process step sugar cane production (information kindly provided by operator). In the process step electricity generation, a net water demand of 0.008 m^3 kWh^{-1} due to evaporation losses from the boiler system is considered (information kindly provided by operator). For the by-product model, an economic allocation of sugar cane juice, which serves as starting material for the production of sugar and ethanol, and sugar cane fibres, i. e. bagasse, is performed in an upstream production step with respect to current market prices (Supplementary Data 13). The amount of bagasse used per kWh produced is calculated from its high heating value[36] of 16 MJ kg^{-1} at 0.22 kg kWh^{-1}. The LCA waste model is based on the same ecoinvent 3.5 data. For the construction phase, only the 40 MW gas turbine is considered without modifications. For the operation phase, only the process step electricity generation is considered with a net water demand of 0.008 m^3 kWh^{-1} (see above). The inventory of the construction phase is related to 1 kWh using a factor that is derived from a net annual production of bagasse of 700 million kg, a turbine capacity of 40 MW, a lifetime of 50 years (information kindly provided by the operator) and an estimated share of bagasse processing infrastructure in the total sugar mill of 5%.

Case study (d), the CPP Heyden in Petershagen, at the Weser River serves as reference for conventional electricity generation within this study. Commissioned in 1987 it is still Germany's most powerful power plant with a net capacity of 875 MW that will probably operate until the end of 2025. The fuel is hard coal which is delivered mainly from Russia. Waste gases from combustion are purified by passing them through denitrification, dust removal, and desulphurisation plants gradually. Waste water is also treated, including one of the world's first ultrafiltration plants. During operation, the CPP produces by-products such as flue ash, gypsum, and slag which are reused for different purposes. This information was kindly provided by the operator Uniper Kraftwerke GmbH. An ecoinvent 3.5 dataset for an average European CPP is taken as basis to model the case study and no modifications are made for the construction phase. For the operation phase, the net water demand is put at 0.001 m^3 kWh^{-1} which represents the loss from cooling water input, and a multitude of material inputs and emissions to air and water, such as cadmium and mercury, are added (kindly provided by the operator). The economic allocation of electricity and the by-products is neglected, as their economic value is too low. The inventory of the construction phase is related to 1 kWh using a factor which is derived from a total electricity production of 10^{11} kWh over a lifetime of 35 years with the German coal phase-out also considered and a capacity of 920 MW (information kindly provided by the operator).

Regionalisation of supply chains of selected mineral commodities. The supply chains of the mineral commodities aluminium, copper, coal, cement, iron and steel, lithium, and phosphorus are regionalised at mine site level and inserted into the LCA database ecoinvent 3.5. A detailed description of the procedure and the associated data is presented in Supplementary Notes 7. Essentially, global production data for the selected mineral commodities are taken (see "Data availability" statement) to select those countries which account for the largest share of world production, so that overall 80% of world production was covered. Mine sites in the selected countries (see data availability statement) are clustered using a hotspot analysis, taking into account distance and regional water stress, resulting in a maximum of five mine sites per country, each representing an entire mining region. These sites are added to the LCA database as single processes and linked to the existing supply chains in the database according to their share of world production. For example, for the CPP, it is known that the hard coal is sourced exclusively from Russia, but where no case study-specific data are available, the upstream chains regionalised in the described way are linked to the case studies. These supply chains represent the most likely origin of a particular mineral commodity, based on global production volumes.

Life cycle impact assessment. In order to cover a wide range of environmental impacts, a number of LCIA indicators are considered. Primarily the resource footprints, which already cover more than 80% of all environmental impacts[12], are to be taken into account. For the climate[37], energy, land, material, and water footprint methods are selected, that quantify and assess elementary flows, as footprint is understood here as a value weighted according to certain criteria. In addition, the indicator set should meet the requirements of the German environmental impact assessment, which is an environmental policy instrument in Germany to evaluate environmentally relevant projects for possible environmental impacts before approval, is also included. In contrast to it, the LCA assessment is not restricted to the planning phase. Moreover, LCA analyses also evaluate remote environmental impacts associated with the upstream supply chain which is missing in the German environmental impact assessment. The approach presented here is seen as a possible interface between science-based indicators and practical applications.

Based on the Cumulative Energy Requirements Analysis[38,39] the sub-indicator Fossil Cumulative Energy Demand (CED_{fo}) from the LCA implementation of Hischier et al. 2010[40] is used within this study as energy footprint: It summarises the energy provided by the fossil energy carriers hard coal, lignite, crude oil, natural gas, coal mining off-gas as well as peat, uranium and wood and biomass from primary forests along the supply chain[40] and assesses them according to the energy content in MJ equivalents m^{-3}, kg^{-1} or MJ^{-1}. This is implemented by multiplication with corresponding characterisation factors.

For the climate footprint[37], the global warming impact is calculated according to the LCA implementation IPCC 2013 using the impact category climate change GWP100a (GWP_{100})[40]. The elementary flows of carbon dioxide, carbon monoxide, chloroform, dinitrogen monoxide, different ethane and methane compounds, nitric oxide, nitrogen fluoride, sulphur hexafluoride as well as volatile organic compounds are summarised along the supply chain and assessed with respect to their global warming potential in kg CO_2-equivalents kg^{-1}.

Two indicators represent the product material footprint[41]: For the Raw Material Input (RMI) the input of a multitude of abiotic materials from aluminium to zirconium is summarised along the supply chain and assessed with respect to "the ratio of the mass of the extracted raw material (used extraction) to the mass of the respective abiotic material in the extracted raw material in kg kg^{-1}"[42]. The Total Material Requirement (TMR) comprises the input of similar abiotic materials, which are assessed with respect to "the ratio of the mass of unused extraction and the mass of the extracted primary material for the production of the material measured in kg kg^{-1}"[42].

The water consumption is determined and evaluated as midpoint LCA water scarcity footprint[14]. It "assesses the on-site and remote probability of natural freshwater scarcity for humans and nature caused by water use along human supply chains in a spatially explicit way"[14]. The Quantitative Water Scarcity Footprint (WSF_{quan}) represents the quantitative water consumption through evapotranspiration, product-incorporated water and water transfer across basin boundaries in regionally weighted m^3 of water. The weighting, which relates to the water stress level in a country, is carried out with the LCIA method AWARE[15], respectively. The Qualitative Water Scarcity Footprint (WSF_{qual}), which is the regionally weighted virtual volume of water in m^3 required to dilute process-related aluminium emissions into water bodies to safe concentrations, is not included in this study. Schomberg et al. 2021[14] have already pointed out that the WSF_{qual} is mainly due to waste treatment in global supply chains, because of high aluminium emissions. Since we cannot provide any new information on these upstream chains, especially not spatially explicit, the WSF_{qual} would not provide any new insights.

To assess land use impacts on biodiversity there is currently no midpoint LCIA available that is suitable for the examined case studies. The Life Cycle Initiative made an interim recommendation for the indicator potential species loss from land use[43] in 2016, but also stated, that it is not suitable for comparative assertions. In a newer report from 2019, the LANCA®[44] approach is recommended to assess land use impacts on soil quality. However, for the purpose of this study, it is rather the total area occupied in the context of the case studies and the encroachment on the natural ecosystem by land use that are of interest. Hence, the pure land occupation is summed up along the supply chains of the case studies in $m^2 \times a$ without any weighting in order to provide first information on possible teleconnections as already Kaiser et al. 2021[45]. Land use changes are not evaluated in the absence of a suitable method so far.

The endpoint LCA method ReCiPe Endpoint (H,A)[46] is used to reveal damages on the LCA protected goods human health and ecosystem quality. The sub-indicator Human Health (HuHe) summarises impacts in the categories climate change, human toxicity, ionising radiation, ozone depletion, particulate matter formation, and photochemical oxidant formation and assesses them according to modelled and harmonised impact pathways in points kg^{-1} or m^{-2} or m^{-2} a^{-1}, respectively. The sub-indicator Ecosystem Quality (ECO) summarises impacts in the categories agricultural land occupation, climate change, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, natural land transformation, terrestrial acidification, and terrestrial ecotoxicity and assesses them analogously.

For LCIA indicators with sub-categories, the results of the single sub-categories are added up to receive the total indicator results: The indicator CED_{fo} for example consists of the sub-categories fossil, nuclear and primary forest, whose individual results were added together. Occasionally, especially for the WSF_{quan}, this approach removed negative values that can for example occur when datasets in the LCA database contain rounding errors.

Hotspot analysis of LCIA results. An LCIA not only provides an overall result for an environmental pressure or impact, but also shows the contributions of individual activities. The term activity refers to the processes that make up the upstream chain of a case study. A systematic analysis of the extensive information provided by the LCIA is the main focus of this study and several methodological steps are carried out to present relevant information in a comparative manner:

(1) As an average supply chain can be made of ~100,000 single activities, only processes that contribute more than 1% to the total result of an environmental pressure or impact per case study are selected. This represents at least 48%, but on average 79%, of a total indicator result (Supplementary Data 14). The difference to 100% is mostly due to many thousands of processes that contribute very little, respectively, the analysis of which would go beyond the scope and distract from focal points.

(2) To make activities of different environmental pressures and impacts, which have different units, comparable, a normalisation step is carried out. For each environmental pressure or impact p, single activity results of a case study c, $x_{p,c,i}$, are normalised by the median med_p of all activities of all case studies[47]. The sample for determining this median includes all activity results of all case studies of an environmental pressure or impact (Eq. 1, ROR: run-of-river hydropower, CSP: concentrated solar power, BBY: bagasse as by-product, BWA: bagasse as waste, CPP: coal-fired power plant, operation, and construction phase not listed separately). The normalised values are calculated per environmental pressure or impact p by dividing single activity results by the median (Eq. 2).

$$med_p \in (x_{p,ROR,1}, x_{p,ROR,2}, \cdots, x_{p,ROR,n}, x_{p,CSP,1}, x_{p,CSP,2}, \cdots, x_{p,CSP,n}, x_{p,BBY,1}, x_{p,BBY,2}, \cdots, x_{p,BBY,n}, x_{p,BWA,1}, x_{p,BWA,2}, \cdots, x_{p,BWA,n}, x_{p,CPP,1}, x_{p,CPP,2}, \cdots, x_{p,CPP,n}) \quad (1)$$

$$norm_{p,c,i} = \frac{x_{p,c,i}}{med_p} \quad (2)$$

(3) A normalised value represents the ratio of the activity result to the median, meaning that the activity result is $norm_{p,c,i}$ times as large as the median. For the spatial hotspot analysis, normalised values are presented on a scale from 1 to 100. Values below 1 represent activity results smaller than the median which are hence no hotspots, values above 100 are set to a maximum of 100 (dark orange hotspots in Fig. 5) to keep the scale manageable. It can be assumed that a result that is more than one hundred times the median is a hotspot in any case. This approach is inspired by the calculation approach of the water stress indicator AWARE[15], which is already widely accepted in the LCA community. A colour scale is used to provide orientation and to distinguish hotspots of different severity according to their normalised value: 1–5 light blue, 5–10 dark blue, 10–30 pink, 30–50 yellow, 50–100 orange, >100 dark orange. Land occupation and environmental impacts, which represent LCIA endpoint approaches are not included in the spatial hotspot analysis. As regards land occupation, spatial information is lacking for a correct assessment; in case of the environmental impacts, it must be assumed that, as a result of the endpoint perspective, impacts do not also occur at the location of the associated activities.

(4) Locations can occur more than once because different activities take place in the same place or an activity causes more than one pressure. Hence, for each location, all single normalised activity results are summed up per case study.

(5) The level of regionalisation strongly depends on the input data and can reach from point coordinates to global, which is equivalent to unknown. Due to the large volume of data involved in the analysis of international supply chains, the data may contain inaccuracies in the regionalisation. To address this issue and to be able to see the level of regionalisation at a glance, a quality index is provided for locations: Locations of quality 1 are point coordinates. Locations of quality 2 represent country or sub-country level, while locations of quality 3 are regions of two or more countries. Spatial allocations that are at least questionable, e. g. treatment of waste in Switzerland which is part of the supply chain of the sugar mill in Brazil, are assigned quality 4, while unknown locations, referred to as global or rest-of-world, are assigned quality 5. Locations of quality 1 are added in the course of this study, locations of quality 2–5 are taken from the ecoinvent 3.5 database. Locations of quality 4 and 5 are excluded from the spatial hotspot analysis. Quality indices are provided for all analysed processes in the Supplementary Information and are used to identify activity groups with poor regionalisation.

(6) To assess the relevance of single activities for the total environmental burden of the case studies independent of the presence of spatial information, they are grouped in the categories mining, hard coal mining, forestry, refining, burning of diesel, production of petroleum and (natural) gas, production of electricity and heat, production of polyethylene, treatment of waste, on-site activities (that take place at the location of the case studies) and other activities. A representation as a matrix allows a quick evaluation of the relevance of a category for the respective case study (Fig. 6) to identify particularly important environmental burdens. In addition, for each activity the number of LCIA indicators the respective activity influences, i.e., is responsible for impacts in the categories of the indicator, is given by numbers from 1 to 8. A comparison of the matrix to activities with poor regionalisation, identified in step 5 of the hotspot analysis, allows to estimate the relevance of activities with a poor regionalisation.

Data quality evaluation, assumptions, and limitations. As close cooperation is established with the operators of the case studies, many data are directly provided by the operators (see data availability statement). In these cases, no evaluation of the data sources is carried out. This may result in discrepancies with other studies: For example, Aqachmar et al. 2019[27] reported approximately 0.006 $m^3\ kWh^{-1}$ water use for the Moroccan CSP, in contrast to 0.005 $m^3\ kWh^{-1}$ reported by the operator within this study. Moreover, Verán-Leigh & Vázquez-Rowe 2019[48] considered a lifetime of 50 years for the permanent structural items and a reservoir water evaporation of 0.003 $m^3\ kWh^{-1}$, however, the examined case studies differ from this study in location and technical equipment so that the values are not transferable. As the reservoir water evaporation of 0.03 $m^3\ kWh^{-1}$ used in ecoinvent 3.5 for German non-alpine reservoirs, could not be verified, a value of 0.02 $m^3\ kWh^{-1}$ was calculated for this study. The measurement of additional impoundment areas from satellite images is subject to a great deal of uncertainty, as the images only represent a snapshot and it is unclear whether the images were taken at a time of high or low water levels (Supplementary Fig. 1). In the absence of more precise data, they are intended to give an idea of the possible magnitude of water consumption through evaporation. Biogenic greenhouse gas emissions from biogenic decay in reservoirs[49], which has been calculated for ROR hydropower plants with reservoirs[48], is not considered within this study, as the methodology is explicitly reported for dams and not additional impoundment areas. All other data used are taken from scientific publications. For all values that are added to the LCA models in the course of this study, a logarithmic normal distribution is assumed for the error distribution. These are included in the Monte Carlo simulations of the uncertainty analysis.

Data availability

All inventory data are available from Mendeley Data[50]. Case study specific data that were kindly provided by MASEN, Jalles Machado S/A Açúcar e Álcool and Uniper Kraftwerke GmbH are not accessible directly. Data that are used to regionalise mineral supply chains are freely available from USGS (https://mrdata.usgs.gov/mineral-operations/ and https://mrdata.usgs.gov/mineplant/) and can be purchased from Mining Intelligence (https://www.miningintelligence.com/, license for Mining Intelligence 2018 purchased by University of Kassel). LCIA methods are available from Schomberg et al. 2021[14] and https://www.openlca.org/, while the ecoinvent 3.5 database is available from ecoinvent (license for ecoinvent 3.5 purchased by University of Kassel).

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Author contributions

Anna Schomberg has set up the framework for the evaluation of the case studies, elaborated the methodology, developed the LCA models, operationalised the methodology, calculated and evaluated the results, created the figures, wrote the main text and Supplementary Information. Stefan Bringezu elaborated the methodology and extensively revised the manuscript and the methodology. Martina Flörke supervised the project WANDEL, has set up the framework for the evaluation of the case studies, and supported the elaboration of the methodology. Hannes Biederbick has supported the regionalisation of the upstream chains through data research and analysis. All authors discussed the results and implications and commented on the manuscript at all stages.

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