UNIKASSEL VERSITÄT
CENTER FOR ENVIRONMENTAL SYSTEMS RESEARCH

Multicriteria Analysis Methods for enhanced Result Interpretation in Life Cycle Assessment

Case Study: Processes of CO_2-Utilization

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Table of Content

List of Figures

List of Tables

1 Introduction

The production and consumption of goods is related to pressures on the environment due to the extraction of resources from and the emission of waste flows into the environment. Those pressures can lead to a degradation of the environment and may require action to reduce the risk of conflicts or hazards, e.g., due to a scarcity of resources.

To assess the environmental impacts of processes and products in a holistic way, Life Cycle Assessment (LCA) studies are used. In LCA studies all life cycle stages from resource extraction until waste management are analysed in combination with an assessment of the corresponding environmental impacts. They can be also used to compare existing technologies with promising alternatives still in the developing stage (e.g., technologies for CO_2 utilization). In order to measure and assess the technology specific impacts, suitable indicators are required. Since generally more than one environmental impact is caused by economic activities the use of more than one indicator is necessary which can reveal trade-offs. To accommodate such trade-offs, the application of methods for Multi Criteria Analysis (MCA) can be a helpful tool.

In this document the problem of trade-offs between indicators in LCA studies is explained in more detail as well as the requirement of MCA methods to accommodate them. Furthermore, the four environmental footprints in combinations with certain other indicators are proposed as a common minimum-set of indicators to harmonize LCA-studies and to ensure their comparability. Important rules for the conduction of an LCA for CO_2 utilization technologies are also explained. In the next step, MCA methods are described, and their application is shown. As a worked example, the results of an LCA-study for the CO_2-based production of base chemicals and polymers are used. It is shown how those methods enable the accommodation of trade-offs and therefore enhance the explanatory power of LCA-studies. Furthermore, their differences and critical points for their application are explained.

2 System Perspective

A sustainable development involves the responsible production and consumption of goods in a way that the involved natural and socioeconomic systems do not lose their capability of regeneration (United Nations, 1987). The sustainability is measured in the three dimensions, namely environment, economy and social (BMZ, 2017). Together, these three dimensions form a target triangle which serves as an evaluation basis for the sustainability of decisions from different actors (nations, organizations, companies) on different scales (global, national, regional, local). The dimensions are closely linked by their very nature and can influence each other which is important for holistic sustainability assessments (Egenolf and Bringezu, 2019). In the following section the link between the ecological and economic dimensions is described in more detail.

2.1 The DPSIR-Model

The ecological dimension of sustainability describes the state of the natural environment at different scales. Its state is connected to the economic action of actors via numerous impact pathways. With the help of the DPSIR concept (Driving Forces, Pressures, State, Impacts, Response) (Figure 1) the relation between production and consumption, the related environmental impacts as well as the resulting feedback loops are explained.

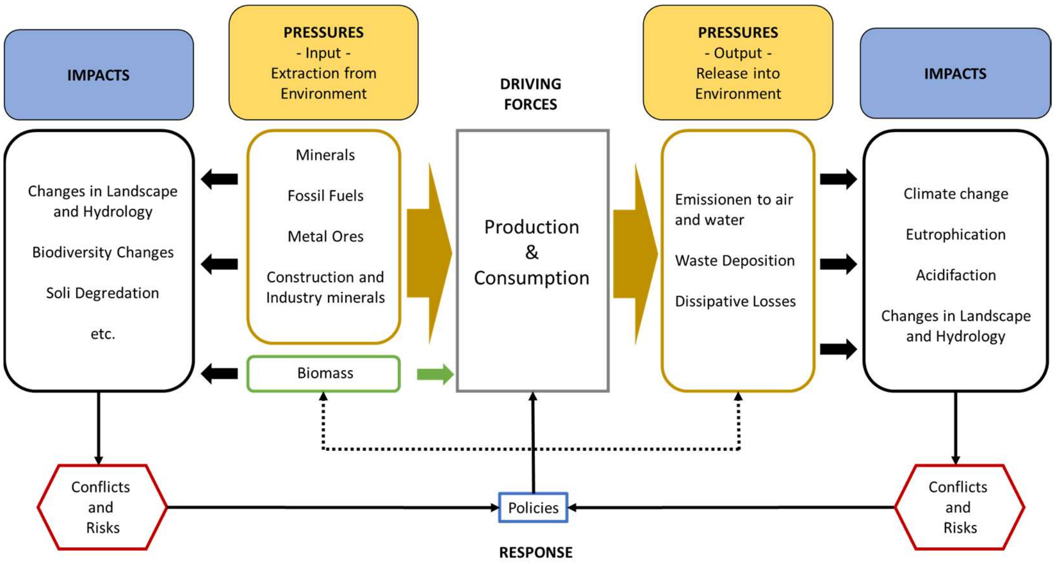

Figure 1: DPSIR-Model according to (Bringezu, 2015) without the illustration of the „State“.

The production and consumption of goods lead to environmental pressures at the input and output side of the technosphere due to different material flows. These are for example, the extraction of resources out of the earth’s crust to generate material input into manufacturing processes as well as emission or disposal flows as output of waste management processes. This uptake, utilization and disposal of natural resources caused by economic activity is called socioeconomic metabolism. The resulting impacts on the environment raise the risk of conflicts or hazards, e.g. caused by resource scarcity or pollution. Therefore, political actions are necessary to provoke an adjustment of production and consumption patterns.

While the DPSIR-concept serves as a basic framework, a specific system definition and quantitative indicators are required to assess the environmental impacts of products and processes. Therefore, the following section will give an introduction into the methodology of Life Cycle Assessment.

2.2 Life Cycle Assessment

2.2.1 Methodology

A quantitative comparison of processes or products requires consistent system boundaries to define the research object as well as assessment methods. Therefore, the general LCA methods are standardized in the DIN-ISO-Norms 14040 and 14044. Those norms are internationally accepted and define clear accounting and assessment rules (DIN, (2016), DIN, (2018)). The framework of an LCA is subdivided into three phases (Figure 2).

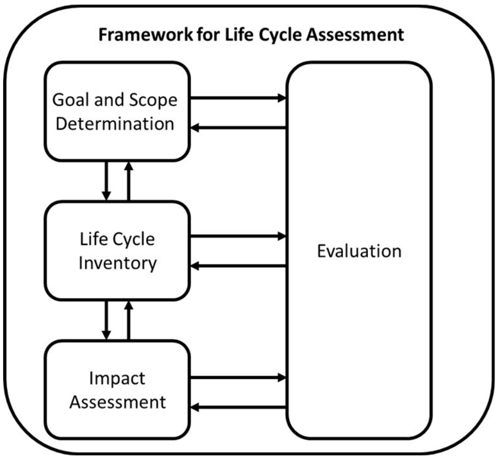

Figure 2: Framework for Life Cycle Assessment (adapted from DIN EN ISO 14040).

The first phase consists in the definition of the goal and scope of the study as well as the system definition. In this phase, extent, content, and indicators of the LCA are determined. In the second phase a life cycle inventory is developed which includes all material and energy flows between the environment the production system. In the third phase the environmental impacts of these flows are determined using suitable indicators. After each of the phases an evaluation of the results is conducted.

The following rules must be regarded while conduction an LCA study:

- A precise definition of the goal and the respective scope of the study is elementary for a target aimed assessment
- In general, the whole life cycle of a product must be considered. The neglection of certain life-cycle stages is only acceptable if it is done in accordance with the goal and scope of the study
- The LCA is conducted for a functional unit (FU) to which all calculations and statements refer. The FU serves as a quantification of the product’s value and is used as the central

comparison unit. The value can consist in a certain purpose of a product, like the provision of packaging for one litre of liquid or a transportation service, like the transportation of one ton of goods for one kilometre.

The scope as well as the respective effort of an LCA study can differ according to the type of the study. The following types can be differentiated (Table 1):

Table 1: Description of different types of LCA.

LCA-Type	Description
Screening LCA	A Screening LCA enables a relatively fast and efficient estimation of the environmental pressures of technologies/products considering average values for the most important material flows along the whole life cycle. It is suitable if detailed process data is lacking, e.g., for technologies in early research stages.
Full-scale LCA	A full-scale LCA enables a detailed calculation of the environmental pressures of technologies/products considering specific values for all material flows along the whole life cycle. It requires detailed data of the examined processes.

2.2.2 Indicators, impact categories and measuring points in Life Cycle Assessment

Indicators are usually derived from basis data and provide a more aggregated information on a certain topic. Every indicator serves to answer a target question. As target questions may be specific (e.g. what pressures on climate are exerted) or more general (e.g. what is the overall performance of the economy) the indicators have to be rather specific (e.g. Global Warming Impact Impact (GWI) or provide more aggregated overview information as "headline indicators" (e.g. Gross Domestic Product). Such pyramids of information aggregation exist for multiple scale levels (Figure 3).

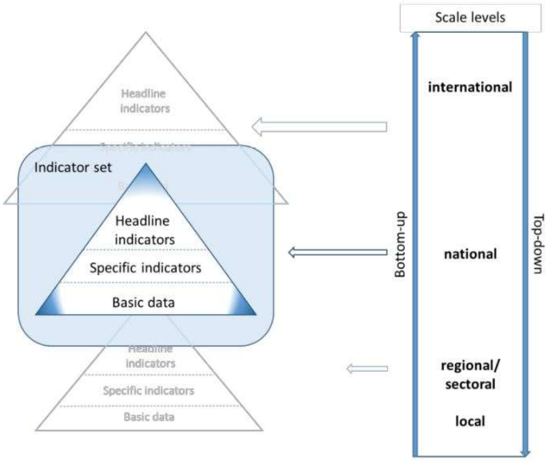

Figure 3: Different scales for indicators (Egenolf und Bringezu 2019).

If indicator based targets on a higher level shall be implemented by action on a lower level this will require a consistency of indicators across these levels. For instance, if the national target for the reduction of Greenhouse Gase (GHG) emissions shall be implemented at local scale, the same indicator (GWI) must be applied for the planning, monitoring and evaluation of the measures. A correct choice of the system boundary is very important to identify a possible problem shift towards other geographical areas or scale levels. Life-cycle-based system boundaries are usually applied across scales because they cover the whole supply chain. Hence, to compare LCA results with specific targets, a compatibility of the applied indicators is very important.

Possible environmental impacts are qualitatively categorized according to their effect on the environment and grouped with the help of different *impact categories,* such as *Climate Change*, *Eutrophication* or *Ozon Depletion*. The calculation of the magnitude of an environmental impact can then be conducted at different points along the cause-effect chain between the cause (e.g. Resource extraction or GHG-Emission) and the final impact on the areas of protection (AoP) which are *Human Health, Natural Environment and Natural Resources .* Figure 4 exemplifies the possible estimation points with the help of the cause-effect chain of GHG-emissions.

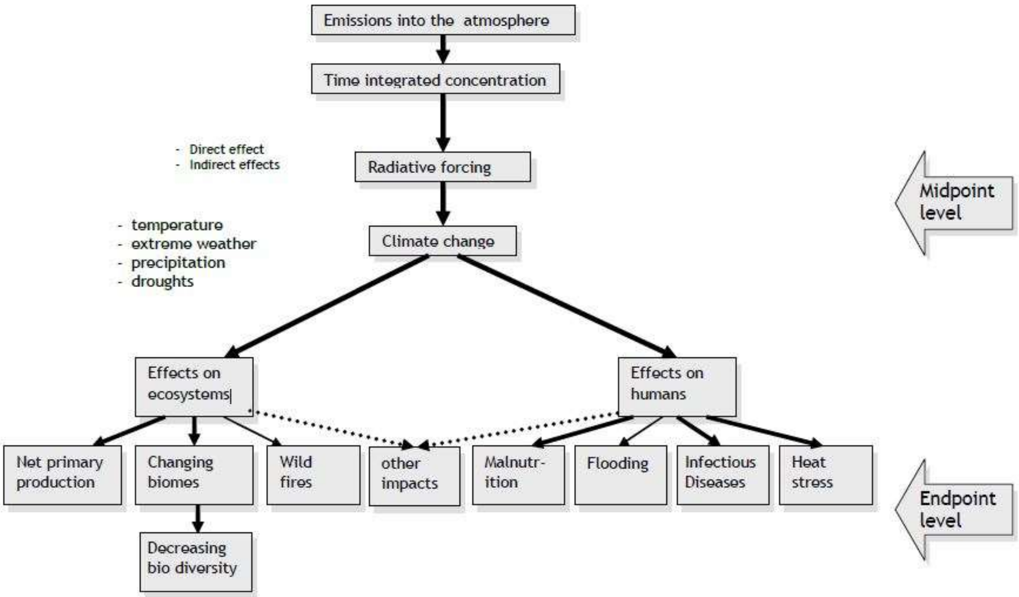

Figure 4: Cause-Effect-Chain of GHG-Emissions (ILCD 2010a).

The estimation point can be located directly at the pressure (sum of emitted GHG), at one point between pressure and final impact (GWI) or at the final impact (Danger for Human Health) (ILCD, 2010a).

Basically, indicators are more tangible the closer their estimation point is to the proximate pressure (e.g. the GHG emissions) which is caused by a driving force (e.g. demand for fossil fuel consumption). The farther the cause-effect chain is followed the higher the number of required assumptions and the higher the uncertainty of parameter estimations. At the same time, every additionally aggregated information raises the risk of measuring errors and uncertainties which then propagate along the cause-effect chain (ILCD, 2010b). This effect leads to a loss of precision and significance of an indicator and must be regarded within the scoping phase of a study as well as in the impact assessment. Consequently, midpoint indicators are generally more reliable than endpoint indicators since they accumulate less uncertainty.

2.2.3 Choice of suitable Indicators

The relations between human activities and the caused environmental impacts are complex and diverse. Therefore, more than one indicator is generally required to be able to evaluate the respective impacts comprehensively (Bringezu and Bleischwitz, 2009). Suitable indicators should be chosen with respect to the goal, scope, and the target group of a study. Their choice needs to be derived from the target questions and should be made transparent.

The multiple approaches of impact assessment methods and indicators currently in use hamper the comparability and the communication of the LCA results. Therefore, measures for complexity reduction and harmonization would facilitate the comparability. While the observation of several impact categories in LCA-studies is generally recommended due to the complexity of production processes and the risk of ecological problem shifting, several studies have shown that a comparably small set of four resource-based indicators is sufficient to represent a large share of the possible environmental pressures. Such a reduction is possible mainly because of correlating indicators in larger indicator sets. Steinmann et al. (2016) showed that 84 % of possible variances in the results of specific LCA impact categories can be explained with the help of four resource footprints namely Fossil Energy/Carbon, Land, Material and Water. Another study showed that the same indicator set offers explanatory power for more than 90 % of the variation in the damage categories human health and biodiversity damage (Steinmann et al., 2017). However, to completely cover the environmental impacts of a product or a technology the use of additional indicators is recommended (Steinmann et al., 2018). Nevertheless, time and costs for a full-scale LCA may be saved, when concentrating on the assessment of few key indicators, which already offer a large explanatory power.

2.2.4 Proposed indicator-set in CO_2-Win

Within the funding measure CO_2-Win a minimum-set of four midpoint indicators, three resource footprints[1] and one climate footprint, are proposed for the LCA-based assessment of the projects. The set does not aim to be exhaustive but to secure the comparability of the different LCA-studies within the funding measure. Hence, it is important that all of them are calculated and that applied characterization factors used for the calculation of the indicators are identical. There are only midpoint indicators within the set because this approach is seen as more straightforward due to reduced analytical effort, and less uncertainties involved. Nevertheless, in cases where knowledge is available indicating that there may be specific other risks (e.g., emission of fluorinated substances which may result in ozone depletion) these need to be accounted as well.

The choice of the Four Footprints and their characterization factors is mainly derived from the findings of Steinmann et al. (2016), and it is also in line with the actual work of and the respective recommendations from the *Life Cycle Initiative*, initiated by the United Nations Environment Program. The initiative aims to harmonize the life cycle assessment procedures (UNEP, 2016, 2019). The majority of the chosen indicators is part of indicators sets used for product declarations on the national or

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[1] A footprint serves to quantify the life-cycle wide pressure on the environment, caused by human actions Vanham et al. (2019).

European level (DIN, (2020); Finkbeiner et al., (2018)). Furthermore, the use of environmental footprints enables a connection between the ecological assessment of products and the national monitoring systems such as in integrated environmental and economic accounting[2], the regular reporting of progress towards the SDGs, and on the Resource Efficiency Program in Germany. When applying the same indicators across scales, the contribution of new technologies to environmental targets like GHG-reduction or resource efficiency can be measured in a consistent manner.

Three of the Four Footprint indicators are input based and one of them is output based (Table 2). Input-based indicators are used to cover the pressures on the environment based on the amount of natural resources which are required as input per FU. At the same time, output-based indicators cover the environmental pressures caused by the output-flows (e.g., GHG emissions) of the product system. As resource footprints the *Material Footprint, Water Footprint*, and *Land Footprint* are considered in combination with the Global Warming Impact (GWI) caused by GHG emissions as *Climate Footprint*. An explicit assessment of the used energy is not necessary since the impact of the utilization of different kinds of energy sources is already assessed through the application of the four footprints. For example, the use of fossil energy sources is covered with the help of the climate footprint, while the use of renewable sources like wind or PV is covered by the material footprint.

2.2.5 Trade-offs

The use of more than one indicator comes along with the possibility of revealing trade-offs between the different impact categories. A trade-off is shown if indicators point into “different directions”. This means that a relief in one impact category can only be reached by a raised pressure in another impact category. An example for a trade-off is the substitution of fossil resources by a) energy plants or b) CO_2 use in combination with renewable-based hydrogen. In both cases the GHG-emissions compared to the fossil alternative are reduced but at the same time other environmental pressures may increase. In case a) the agricultural land use may be expanded due the occupation of agricultural land accompanied by higher pressures on biodiversity (Di Fulvio et al., 2019) and in case b) the higher requirement for energy infrastructures causes a higher primary raw material demand (Hoppe et al., 2018). Therefore, the impact assessment requires a multi-criteria analysis of the results. Appropriate methods to deal with this challenge are described and exemplified in section 4.

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[2] In Germany: Umweltökonomische Gesamtrechnungen (UGR)

Table 2: Proposed minimum set of Footprint indicators

Indicator	**Indicator name/ Sub-indicators**	**Input-or Output based**	**Measured Impact**	**Obligatory/Optional**	**More Information/download-link**
Climate Footprint	Global Warming Impact (20 years) Global Warming Impact (100 years)	Output	Global Warming caused by the emission of greenhouse gases	Obligatory	UNEP (2016) https://www.lifecycleinitiative.org/training-resources/lcia-cfs/
Water Footprint	AWaRe (Available Water Remaining)	Input	Water scarcity in the areas of water withdrawal	Obligatory on country level Optional on basin level	UNEP (2016) https://www.lifecycleinitiative.org/training-resources/lcia-cfs/ Boulay et al. (2018) and Schomberg et al. (2021)
Material Footprint	(a) Raw Material Input (RMI) (b) Total Material Requirement (TMR)	Input	Environmental impacts due to (a) turnover of primary raw materials used along the subsequent process chain (b) the overall excavation, translocation, and deposition of primary material in nature	Obligatory	Mostert and Bringezu (2019) https://www.mdpi.com/2079-9276/8/2/61
Land Footprint	Land Occupation Land Transformation	Input	Effects on biodiversity by land use and land use change	Obligatory	UNEP (2019) https://www.lifecycleinitiative.org/training-resources/lcia-cfs/

3 CO_2 Utilization and Life Cycle Assessment

The utilization of CO_2 as raw material, also called *Carbon Capture and Utilization* (CCU), aims at the substitution of fossil carbon sources or geogenic carbonates which may lead to a mitigation of CO_2-emissions and in particular to a more circular use of carbon. In general two application fields can be described (Figure 5): 1) the use of CO_2 as carbon source in organic chemistry for the production of base chemicals, polymers or fuels, and 2) the mineralization of CO_2 using inorganic elements like calcium or magnesium to produce carbonates which can be used, for instance, as construction material.

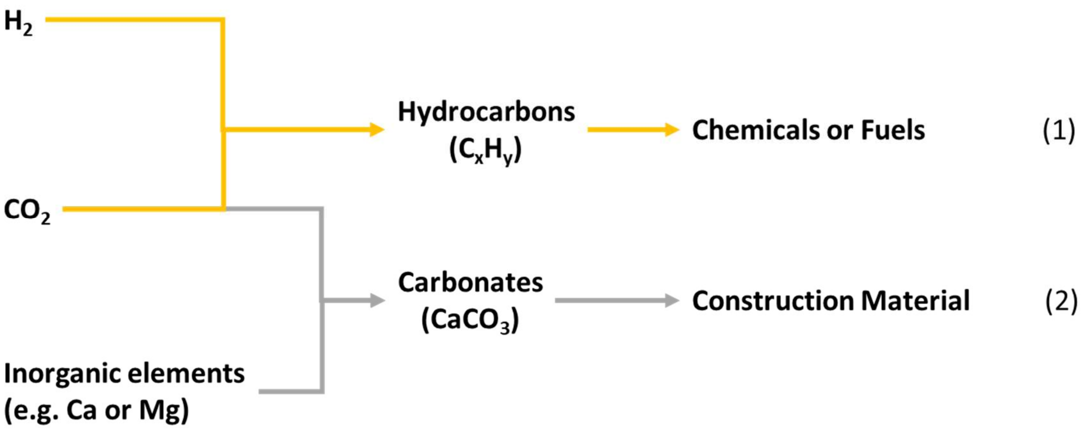

Figure 5: Schematic description of CO_2-based processes.

Both application fields differ with respect to the production processes as well as the use and end-of-life phase of the respective CO_2-based products. To evaluate the sustainability of CO_2-based processes and products life cycle assessment is required in order to measure the respective environmental impacts. The following section will give a broad overview of the existing literature of LCA-based assessment of CCU processes.

3.1 Literature Examples

For the utilization of CO_2 in the production of base chemicals and polymers multiple examples for life cycle assessment exist. Assen et al. (2013) analysed the global warming impact of CO_2-based methanol. They showed that the CO_2-based production can reduce the environmental impacts but also that the settings of the LCA method can have a big impact on the results for multifunctional systems. Therefore, the authors recommend to use a system expansion to cover all functions or to allocate the environmental burden between the different functions based on economic values. Hoppe et al. (2018) and Sternberg et al. (2017) showed with the help of cradle-to-gate LCAs, that the CO_2-based production of base chemicals like methanol or polymers like polyethylene (PE) shows a reduced climate footprint when renewable electricity is used for the necessary hydrogen production. Hoppe et al. (2018) concluded that the mitigation of CO_2-emissions also leads to an increased material footprint. Furthermore**,** Meys et al. (2019) and Thonemann and Pizzol (2019) showed in different studies that the utilization of CO_2 as a building block within the production of polyols significantly reduces the climate footprint as well as the utilization of fossil resources. A more detailed overview of LCAs for CO_2-based chemical production can be found in Thonemann (2020).

In the field of CO_2-mineralization several LCA have been conducted. Khoo et al. (2011) and Nduagu et al. (2012) analysed the cradle-to-gate climate footprint of a carbonate production using CO_2 from point sources and newly mined silicates. They showed that a net negative CO_2-balance can be achieved in the manufacturing stage of CO_2-based of construction material despite the energy requirement for mining activities and CO_2-sequestration. Pan et al. (2016) calculated the potential for emission mitigation using steel slag or wastewater as a mineral source and CO_2 emissions from a steel plant. Ostovari et al. (2020) compared multiple mineralization technologies using slag from a steel mill or additionally mined olivine and serpentine as a source for the inorganic elements. Both studies concluded that CO_2-mineralization can reduce the climate footprint in two ways. First via the storage of CO_2 in the product and second via the substitution of cement using the product.

The mentioned studies show that CCU technologies have the potential to reduce climate impacts of various products and processes and how they differ with respect to the produced products and their application fields. At the same time, a direct comparison of the studies is not possible since they use different settings (e.g. system boundaries, impact categories, allocation rules) or different FUs. In the next sections existing guidelines and rules for the LCA of CCU processes are presented to show current best practices.

3.2 Specific Guidelines and Rules

3.2.1 Existing Guidelines

Beside the publication of scientific articles, there have been several documents and guidelines in which the application of general LCA methods and norms is described to answer specific questions in the field of CCU technologies.

A detailed guideline for a LCA of CCU technologies was published by Zimmermann et al. (2020). The authors explain step by step how to perform the LCA with respect to the existing norms and present case studies for several process routes without a focus on specific indicators. Fehrenbach et al. (2016) describe the right accounting methods of GHG emissions as well as the calculation of the technology's climate impact (GWI) regarding different CO_2-sources. Furthermore, Bringezu et al. (2019) explain how environmental impacts of raw material use can be calculated for CCU technologies with the help of the material footprint. They show how this impact assessment method can be applied with respect to the existing LCA norms. Based on the mentioned literature, the most important rules and recommendations for best practice of LCA studies for CCU processes are explained in the following section.

3.2.2 Overview of basic LCA rules

Goal Determination

Generally, the utilization of CO_2 as raw material base aims to reduce environmental impacts of existing products, such as polymers or construction material. Therefore, the goal of the study should aim at the quantification of environmental impacts of CCU processes and their conventional counterparts including a comparison of the results.

The definition of the target question(s) of the study is a key element of the goal determination since they have an impact on the depth of detail as well as the impact categories, which should be considered. Table 3 shows exemplary target questions and the respective LCA type and impact categories.

Table 3: Exemplary target questions for LCA Studies

Target Question	**LCA-Type**	**Impact Categories/Indicators**
Can the CO_2-based production of polymers lead to lower environmental impacts compared to conventional production?	Screening LCA	Four environmental footprints
Which environmental pressures are reduced or raised by a CO_2-based process compared to the conventional process?	Full-scale LCA	Environmental footprints as well as further indicators like eutrophication, toxicity, or ozone depletion
How could a CO_2-based process contribute to (inter-)national environmental or sustainability targets?	Screening or Full-scale LCA for a certain reference region	Choice according to the considered environmental targets. Determination of the total impact value of the reference system and period is necessary.

Functional Unit and Reference Flow

To allow meaningful statements, the environmental impacts of CCU and conventional products calculated via LCA must be put into relation with a certain and well-defined FU. The choice of a suitable FU depends on the purpose, chemical structure, and composition of the CCU product as well as the conventional benchmark. Six different FU can be used for CCU products:

- *1 kg,* if the CCU product is used as material with the same chemical structure and composition (e.g. polymer or cement substitute)
- *1 MJ / kWh,* if the CCU product is used as energy carrier with the same chemical structure and composition (e.g. fuel)

- *Quantification of material service,* if the CCU product is used as material with a different chemical structure and composition (e.g. comparison of detergents based on their cleaning performance)
- *Quantification of energy service,* if the CCU product is used as energy carrier with a different chemical structure and composition (e.g. Transport service)
- *Coverage of time specific energy demand,* if the CCU product is used as energy storage to timely decouple energy conversion and use (e.g. seasonal storage of renewable energy)
- *Economic value,* if an integrated comparison of different functions, quality levels or products is necessary (e.g. recycling vs. virgin materials)

In addition to the FU the spatial and temporal (base year and period) scope must be defined. They give information about the timespan and the geographic region for which the study is representative. Especially if the results of the LCA study will be compared to target values it is very important that the parameters are chosen consistently.

System boundary

In general, an LCA requires a life-cycle-wide system boundary from cradle-to-grave. Nevertheless, a narrower definition may be sensible depending on the target question. The choice of the concrete system boundary depends on differences between the life cycle stages of the CCU and the conventional product. Life cycle stages which are identical can be excluded from the system boundary. For example, if a fossil-based polymer is substituted by a CO_2-based polymer with the same chemical structure and composition, it can be assumed that the use and end-of-life stage are identical. Therefore, a system boundary containing the manufacturing stage only is sufficient.

If products differ in their chemical structure and composition, the whole life cycle must be included into the system boundary to assess all possible environmental advantages and disadvantages of CCU processes. This is the case e.g. for construction materials, which substitute cement but have a different chemical composition.

Impacts of the capturing process of CO_2

In general, CO_2 can hardly be seen as a scarce resource since it is either considered as waste flow if CO_2 point sources are used or as abundant in case it is captured out of the atmosphere. According to LCA-rules the environmental impacts caused by the energy and material demand to capture the CO_2 represent the environmental impacts of the capturing process in both cases. If, however, the capturing process is part of an integrated plant delivering different products and services, then an allocation of upstream processes and their resources and emissions to the different products may be required (Müller et al., 2020).

Allocation methods

If the modelled system is a multifunctional system (e.g. a CCU process with more than one valuable output) the following hierarchy of analysis methods is proposed. In order to reach the highest possible accuracy compared to the real process, a lower option may only be chosen when the previous option is not feasible.

1. Subdivision → division of the product system into smaller parts
2. System expansion → expansion of the reference system by the production of all outputs
3. Allocation → allocation of inputs and environmental impacts of a product system on its outputs based on an underlying relationship (e.g., physical causality, mass, or economic factors)

Interpretation of bound CO_2

The capturing of a CO_2 molecule and its use as a material base or building block for a new product can lead to negative CO_2-emissions within the manufacturing stage if energy with a low carbon intensity is used. However, for a sound interpretation the GHG balance of the whole product life cycle, the used source of the CO_2 as well as the carbon storage must be considered. For the life cycle wide GHG balance, three possible outcomes exist (Table 4). It is very important that a CCU process chain can only be qualified as a carbon sink, in case of life cycle-wide net negative emissions. Additionally, the term "sink" should only be used if there will be permanent CO_2 removal from both atmosphere and anthroposphere.

Table 4: Possible outcomes for life cycle wide GHG-balances of CCU technologies.

Term	**Interpretation**	**Life-cycle wide GHG Balance**
Climate Mitigation	Reduced negative climate impact	Positive: Input < Output
Carbon Neutrality	No climate impact	Neutral: Input = Output
Net negative Emissions	Positive climate impact	Negative: Input > Output

The sustainability of the CO_2 source must be considered in terms of long-term availability. Fossil point sources based on technologies which can be substituted now or soon (e.g., coal-fired power plants) should be classified as unsustainable. Additionally, biomass-based sources should be treated with caution by considering potential problem shifts (e.g., increased land use when primary biomass is used for energy purposes). In contrast, sources which represent a decisive part in the social metabolism and are not avoidable (e.g. cement or waste incineration plants) should be regarded as sustainably available, as well as the CO_2-capture from the atmosphere (Kaiser and Bringezu, 2020).

The storage of CO_2 in products and the related climate mitigation effect is neglectable when products with a short life span are directly disposed and incinerated (e.g., plastic packaging or fuels) or are dispersed in the environment (e.g., chemicals such as paintings) after the use-phase. If the carbon originated from the CO_2 input is recycled or used in cascades and therefore kept in the anthroposphere for a longer time, a storage effect can be achieved due to the multiple life cycles of the carbon. Therefore, the combination of a CO_2-based production with carbon recycling technologies can lead to storage of CO_2 within the anthroposphere also for products with a short lifetime. At the same time, for products with a long lifetime (e.g., construction material) a storage effect can be achieved in the first life cycle already and should be regarded in the LCA considering the effect of delayed emission on the global warming impact.

Data Quality

The quality of the input data must be assessed because it plays a significant role for the validity of the results. The higher the data quality the higher is the validity of the results. In contrast, if the data quality is too low, a sound interpretation and comparison of the results is not possible. To enable a transparent assessment of the data quality, the used input data should be evaluated by the LCA practitioner or an independent expert in an extra part of the LCA study. A common method for such an quality assessment is the *Pedigree Matrix*, which evaluates the input data in five categories (Weidema et al., 2013) (Annex 1). Based on the resulting quality matrix the overall data quality of the LCA study is evaluated. Hence, these procedures identify data sets with good and poor quality and uncover further research requirements. If distribution parameters are available for the input data, the existing variance can be adjusted accordingly to take the higher uncertainty into account (Weidema et al., 2013).

4 Multi Criteria Analysis in LCA

A *Multi Criteria Analysis* (MCA) serves to evaluate and compare one or more objects (e.g. a product) or the states of a system regarding more than one criterion. If a decision is to be made based on the results of an MCA, it is called *Multi Criteria Decision Analysis (MCDA).* The evaluation is done in reference to a defined target or target system and with the help of pre-defined criteria each with one defined measured variable (Geldemann and Lerche, 2014). The main goal of the analysis is to identify the best alternative or the best set of alternatives with respect to the defined target or target system (Zimmermann et al., 2020).

In LCA studies, different product systems for the same product or different products with the same functional value are compared to each other. The goal is to calculate and evaluate the environmental impacts of the different alternatives in order to identify the one with the least environmental impacts while providing the same FU. Since the results of LCA studies are not always unambiguous, the application of MCA methods for the interpretation of the results more and more increased in the recent past (Zanghelini et al., 2018). Figure 6 shows an exemplary target system of an MCA for an LCA study.

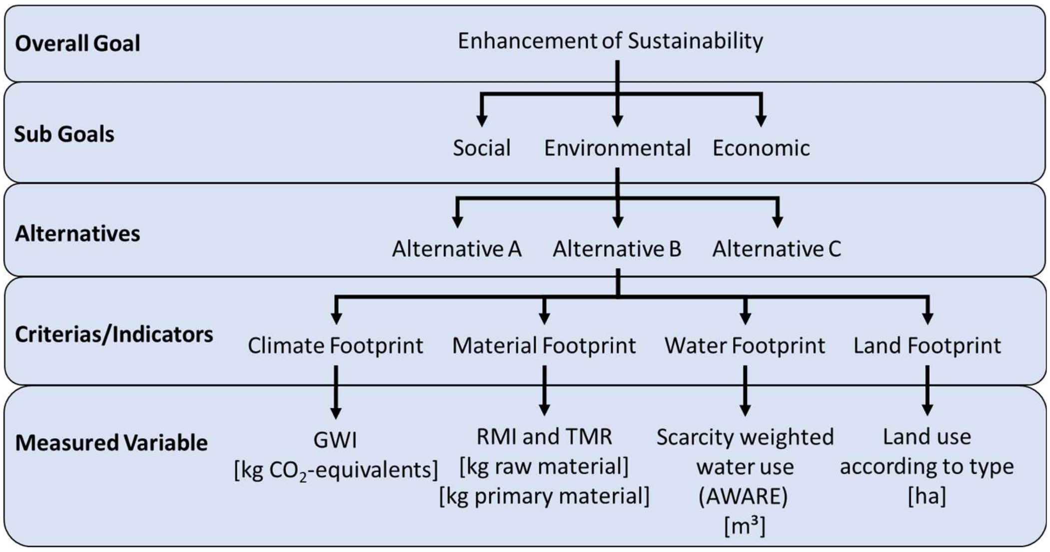

Figure 6: Structure of a Multi Criteria Analysis for Life Cycle Assessment. (GWI = Global Warming Impact, RMI = Raw Material Input, TMR = Total Material Requirement, AWARE = Available Water Remaining).

The use of MCA in LCA studies enables a comparison of alternatives even if the considered indicators do not show a clear result. It is considered as an optional but meaningful step in the interpretation phase of an LCA-study (DIN, 2018). Possible MCA methods will be presented and explained in the following section.

4.1 Description of the case study

Hoppe et al. (2018) showed that the utilization of CO_2 as raw material to produce base chemicals or polymers leads to a trade-off between two impact categories. On the one hand, the LCA results

(Cradle-to-gate) show that the Global Warming Impact (GWI) can be reduced in nearly all cases compared to the fossil reference (Figure 7).

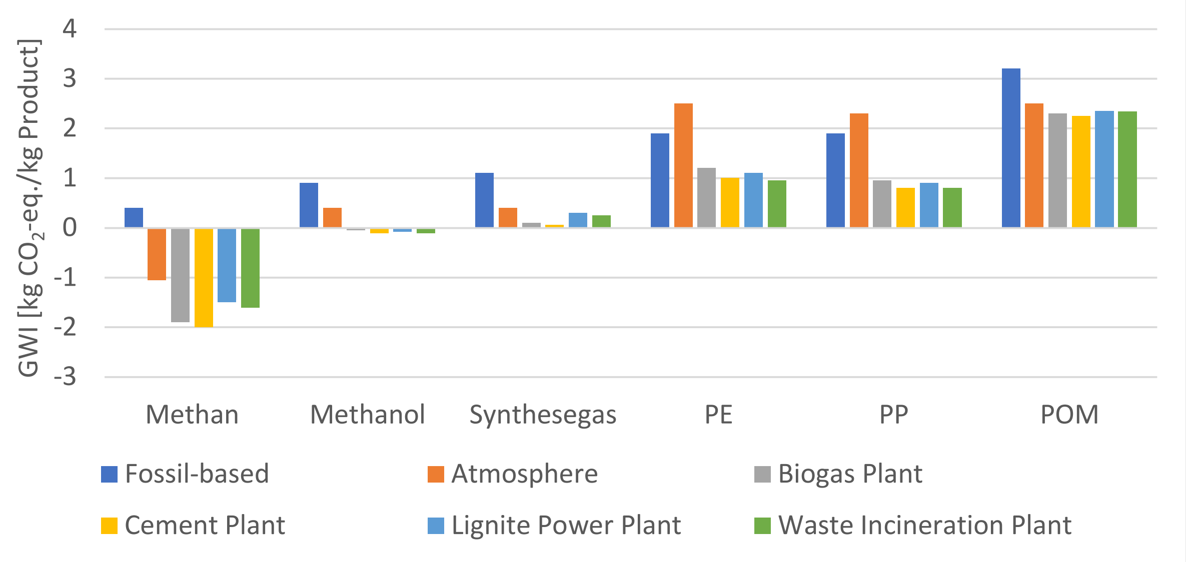

Figure 7: Global Warming Impact (GWI) for the fossil- and CO_2-based production of base chemicals and polymers, depending on the considered CO_2 source (PE = Polyethylene, PP = Polypropylene, POM = Polyoxymethylene) (Hoppe et al., 2018).

On the other hand, the Raw Material Input (RMI) is increasing for all cases, due to the high energy requirements of electrolysis and the resource requirements for the renewable power infrastructure[3]. (Figure 8).

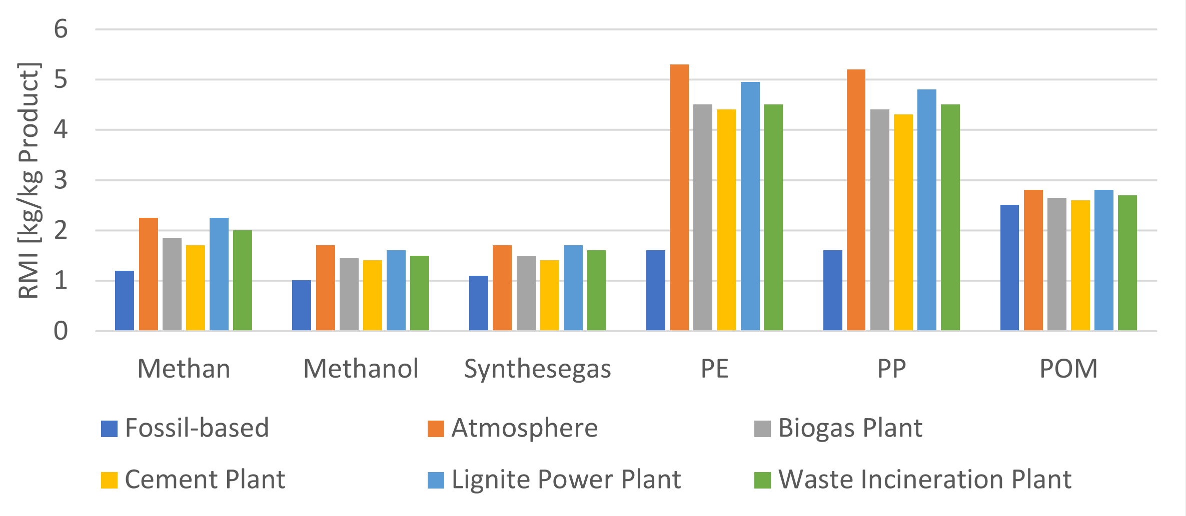

Figure 8: Raw Material Input (RMI) for the fossil- and CO_2-based production of base chemicals and polymers, depending on the considered CO_2 source. (PE = Polyethylene, PP = Polypropylene, POM = Polyoxymethylene) (Hoppe et al., 2018).

Based on the technologies studied, a reduction of the GWI could only be achieved by increasing the RMI, which constitutes a trade-off, regardless of the considered chemical or CO_2-source. Hence, a sound evaluation of the different alternatives is only possible with the help of MCA. Based on the shown example different MCA methods will be described and discussed in the following sections.

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[3] Recent analysis showed that there are CCU technologies which avoid that trade-off and are favorable both with regard to climate and material footprints (Kaiser et al., (2021).

4.2 Prioritization

4.2.1 Background

With the help of prioritization ambiguous results can be interpreted based on a target hierarchy (DIN, 2018). In LCAs the chosen target hierarchy must be in line with the goal and scope as well as the target group of the study. For example, if a clear grading of political targets exists, these could be used for such a target hierarchy of environmental impact categories of an LCA. After the prioritization of the results the alternative which dominates the highest ranked impact category can be identified as the best solution (Geldemann and Lerche, 2014). Since a target hierarchy always contains subjective preferences its structure must be transparent and well documented. Additionally, the effect of an alternation of the priorities should be examined via a sensitivity analysis.

4.2.2 Method

The following steps are necessary to sort and evaluate the results of a LCA with the help of prioritization. The method can be used for normalized or non-normalized results[4].

1. **Determination of a target hierarchy**

In the first step, a pre-defined target hierarchy is used to ordinally scale the different impact categories. The hierarchy is determined based on the subjective opinion of the target group and the goal of the study. This could be done with the help of a stakeholder survey. The process of target determination must be transparent and well documented. Since there is no pre-defined hierarchy in the case study, two possible variants are examined. For instance, in *Variant A* the reduction of the climate impact has the highest priority while in *Variant B* the reduction of the material requirement is the top priority.

2. **Ranking of the LCA-results**

In the second step, the alternatives are scaled based on their indicator value in the impact category with the top priority. In this example, the alternatives with the lowest environmental impact are ranked the highest. For the ranking, one is considered as the highest and five as the lowest rank.

Figure 9 shows the classification of the LCA results for the production of CO_2-based Methanol regarding different CO_2 sources. For *Variant A* the use of a waste incineration or cement plant dominate the other alternatives. This constitutes a special case since both CO_2-sources show the same value. For *Variant B* the use of a cement plant dominates the other alternatives. Depending on the used target hierarchy the mean rank alternation is ± 1.

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[4] For an explanation of the normalization method see section 4.3

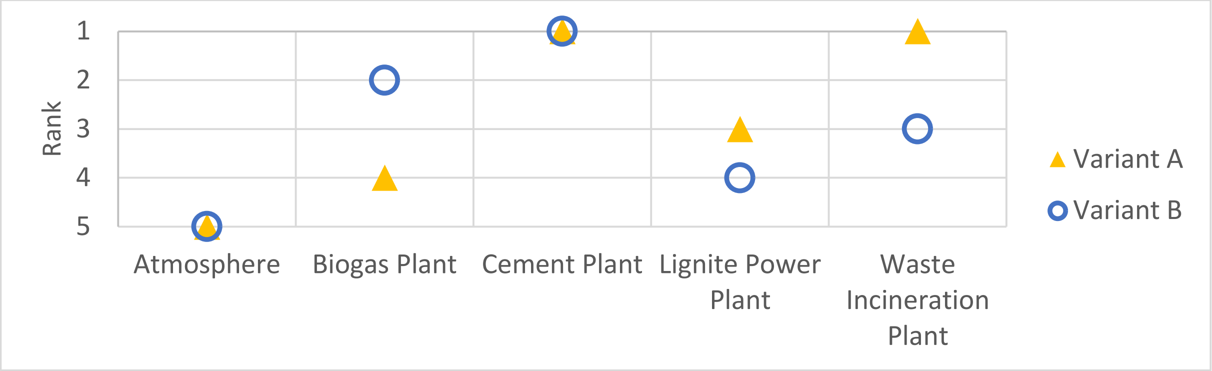

Figure 9: Classification of LCA results for different alternatives to produce CO_2-based Methanol under consideration of different target hierarchies (Variant A: Reduction of Climate Impact; Variant B: Reduction of Material Requirement).

4.2.3 Interpretation

The differences between the alternatives cause an alternation of the rank order depending on the chosen target hierarchy. For example, the alternative *Waste Incineration Plant* is ranked highest for the reduction of climate impact and fourth for the reduction of the material footprint. In contrast, the *Cement Plant* is ranked highest for both variants. The focus on just one impact category leads to the neglection of information and a possible one-sided presentation of the LCA-results. This could lead to a situation where an alternative is recommended as best option which is top ranked in only one impact category but at the same time shows unfavourable values in the other categories. Therefore, a comparison of different target hierarchies should be conducted to get a more differentiated picture. Furthermore, a more differentiated weighting of the impact categories takes all categories as well as their relation to each other into account.

4.3 Normalization

4.3.1 Background

The normalization of values helps to interpret the magnitude of indicator values in relation to a certain reference values (DIN 2018). This reference data, also called normalization base, represents the total value of an environmental impact for a definite reference system (e.g. region, nation, continent, etc.) during a definite period (e.g. yearly). The choice of the normalization base depends on the goal and target questions of the study, where and when the decision to be supported will take place and who is the target group. Hence, it is determined by the scale on which the comparison of alternatives takes place and has to be aligned with the scope of the study. Furthermore, it is very important that reference system and period are identical for every indicator (ILCD, 2010b). The normalization step allows direct comparison of the results with respect to their effect on the overall situation of the reference system and therefore creates a common comparison base for the different indicators.

4.3.2 Method

The following steps are necessary to normalize the results of an LCA-study.

1. Definition of the reference system and period.

The spatial and temporal frame of an LCA is defined in the scope of the study and serves as a basis for the choice of the reference system and period. In the case study, the examined processes are assumed to be located in Germany. Therefore, the German economy is defined as a reference system with system boundaries according the federal statistical office. As a meaningful time-period, one year is chosen, according to the time periods of GHG-inventories for the German economy.

2. Calculation of the normalization base

To calculate the total value of an environmental impact category of the reference system, the cumulated impacts for one period are considered. Thereby, the system boundaries of the reference system must not differ between the impact categories. In the presented example, cumulated values are chosen based on official statistics published by the German Federal Environmental Agency (Table 5).

Table 5: Normalization bases for the regarded impact categories (GWI = Global Warming Impact; RMI = Raw Material Input).

Impact Category	**Indicator**	**Value**	**Source**
Climate Impact	GWI [kg CO_2 equivalents per year]	$9.07 \cdot 10^{11}$	UBA (2019)
Resource Use	RMI [[kg Raw Material equivalents per year]	$2.64 \cdot 10^{12}$	UBA (2018)

3. Calculation of the relative change of the environmental impact

Since the normalization base is calculated for a certain period, a production volume must be assumed for the FU for the same period in order to be mathematically correct. In this handout, a production volume of one kg per year is assumed, out of reasons for simplicity. To compare the environmental impacts of the alternatives the difference between the new (GWI_x) and the conventional (GWI_c) alternative is calculated and put into relation with the total value the impact category $(\mathrm{GWI}_{\mathrm{Germany\ 2017}})$. The following formula exemplarily shows the calculation of a normalized value for the climate impact of alternative x $(\mathrm{GWI}_{\mathrm{xN}})$. The procedure for the RMI is identical.

$$\mathrm{GWI}_{\mathrm{xN}} = \frac{\mathrm{GWI}_{x} - \mathrm{GWI}_{\mathrm{c}}}{\mathrm{GWI}_{\mathrm{Germany\ 2017}}}$$

4.3.3 Interpretation

The evaluation of the normalized indicator results shows in which impact category a net improvement or aggravation is achieved for each alternative and how high it is relative to the status quo in the reference system. Figure 10 shows the normalized value for the example.

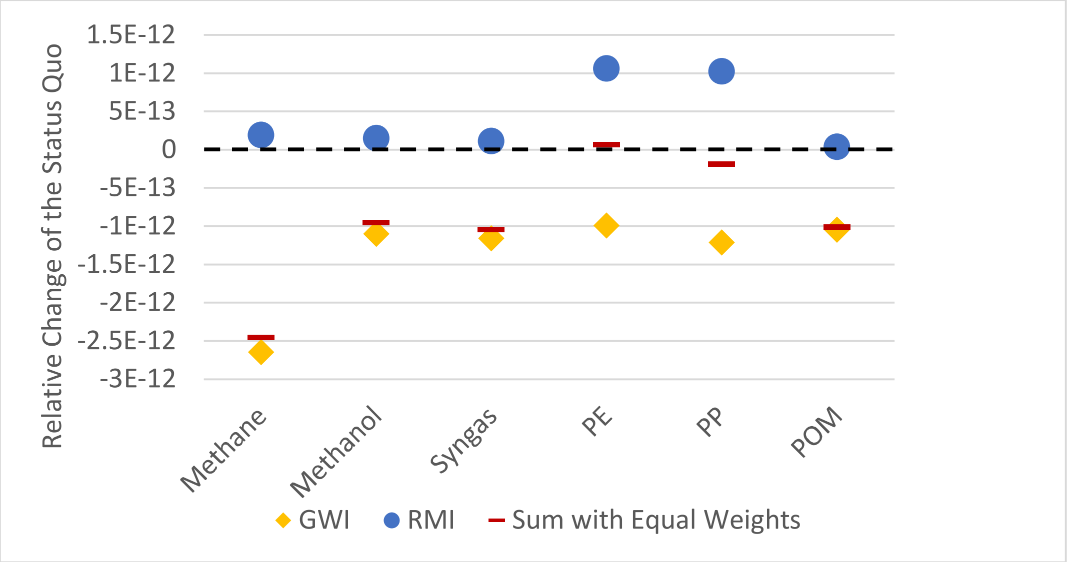

Figure 10: Normalized indicator values for the CO_2-based production of base chemicals and polymers considering a cement plant as the CO_2 source. The figure serves to illustrate the different results of normalization for each alternative. A negative value means an overall improvement of the status quo. Because of the different functional values of the different products a comparison among the alternatives is not easily possible. (GWI = Global Warming Impact, RMI = Raw Material Input, Sum with equal weights = Sum of equally weighted values for GWI and RMI; PE = Polyethylene, PP = Polypropylene, POM = Polyoxymethylene; Data source: (Hoppe et al., 2018)).

It becomes clear, that the CO_2-based production leads to an improvement in the impact category of climate impact for every case while there is an aggravation for the material footprint. However, a direct comparison of two impact categories is not possible without additional information. Normalized results can only be aggregated across impact categories after an additional weighting step because of the different reference values of the impact categories (UNEP, 2019). To demonstrate the results of the aggregation of normalized values, equal weights are assumed for both impact categories in the presented example. The effects of applying non-equal weights are described in section 4.4. It becomes clear that the CO_2-based production would lead to a net improvement of the status quo in nearly all cases, except for studied route of PE production. Therefore, the trade-off can be accommodated via the normalization of the results but only with the help of a simplified weighing step, which in general cannot be fully objective.

4.3.4 Pareto Optima

The required workload of an MCA can be decreased by a meaningful reduction of the number of alternatives which must be evaluated. To maintain the validity of the study, only redundant alternatives can be excluded. To do this, pareto optima are identified. An alternative represents a pareto optimum if the result in one dimension can only by improved if the result in another dimension is worsened. This means that the environmental impact can only be reduced in one impact category if the impact in another category is raised or a lower reduction is yielded. If more than one alternative represents such an optimum, they are called a pareto front. To identify the most promising alternatives with the help of MCA methods, the examination of those alternatives lying on the pareto-front would be sufficient.

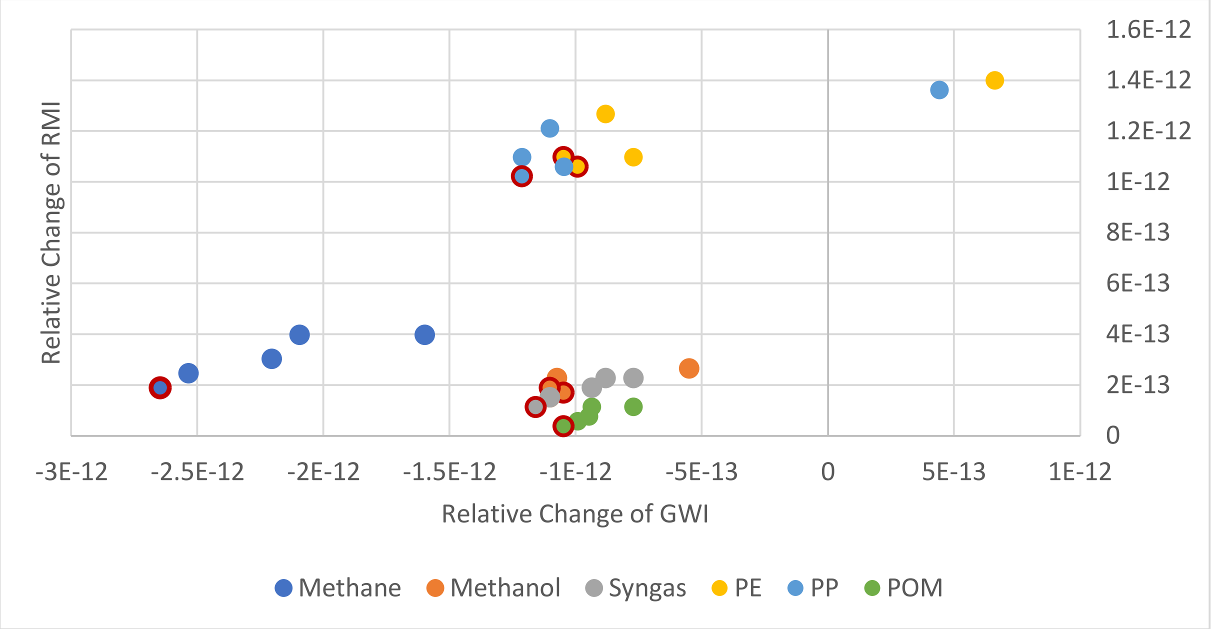

Figure 11: Pareto optima (red circle) for different alternatives for the CO_2-based production of chemicals and polymers, considering different CO_2-sources and normalized values for two different environmental impact categories (GWI = Global Warming Impact; RMI = Raw Material Input; PE = Polyethylen, PP = Polypropylen; POM = Polyoxymethylen).

In the example, a total of 36 alternatives (six products times six different carbon sources) can be compared. Due to the identification of pareto optima, the number of alternatives can be reduced by identifying the optimal CO_2 source for each product. Figure 11 shows the different alternatives regarding the normalized environmental impacts (according to section 4.3.2) in the two impact categories. The pareto optima are marked in red. In this case, the 30 alternatives can be reduced to only 8 alternatives. A further reduction is not possible since a cross-comparison between the different products is invalid due to their different functional value. In theory, the conventional production also represents a pareto optimal solution for all six products because of the lower resource requirements. Since this analysis aims at the identification of pareto optimal CO_2-based processes this option is not regarded any further. According to

Table 6, the use of a cement plant as the CO_2-source represents a pareto optimal solution for all products with methanol and polyethylene having two pareto optimal CO_2-source.

Table 6: Pareto optimal CO_2-sources for the different CO_2-based chemicals and polymers.

Product	**CO_2-sources**
Methane	Cement Plant
Methanol	Biogas and Cement Plant
Syngas	Cement Plant
Polyethylene	Cement and Waste Incineration Plant
Polypropylene	Cement Plant
Polyoxymethylene	Cement Plant

4.4 Weighting

4.4.1 Background

In weighting methods, a specific weight is assigned to every impact category which should resemble its relevance (ILCD, 2010b). Like the case for prioritization, weighting methods are based on subjective information and therefore are normative (Sala et al., 2018). The definition of weights shall be done in accordance with the scope of the study and the preferences of the target group, ideally involving experts and representatives of different stakeholders. The weights can be defined considering scientific expertise as well as political and societal values. The process of choosing weights has to be well-justified and documented (ILCD, 2010b). Furthermore, the definition of specific weights for the considered impact categories based on the stakeholder's opinion or values are generally complex, time consuming and involve additional uncertainty. Therefore, a weighting based on externally defined target values (s. section 4.5.1) is also a recommendable option (Sala et al., 2018). A practical example for this weighting method are the *Swiss Eco-factors*. This method is based on the concept of ecological scarcity and uses national normalization and target values to weight and compare different environmental impacts (Frischknecht and Büsser Knöpfel, 2013).

In all cases, an additional sensitivity analysis should be used to show the influence of different stakeholder values on the result (DIN, 2018). If a normalization step was conducted in the forefront it is very important that reference system and period are identical in the weighing process.

4.4.2 Method

The following steps are necessary to conduct a weighting method.

1. Definition of weights

In the first step, a weight w_j is defined for every impact cateory j according to the identified preferences of the target group. Since the preferences of the target group were not explicitly identified in the case study the weights will be defined based on own assumptions. They will also be varied to depict different sets of weights (Table 7).

Table 7: Assumed weights (GWI = Global Warming Impacts; RMI = Raw Material Requirement).

Weighting Set	Climate extreme	Climate moderate	Equal weights	Resources moderate	Resources extreme
w_{GWI}	10	2	1	1	1
w_{RMI}	1	1	1	2	10

2. Calculation of weighted indicator values

After the definition of the weights the absolute x_{ij} and normalized x_{ijN} indicator values of every alternative i are multiplied with the weights w_j for each impact category. The results are the values x'_{ij} (xn'_{ij}) which can then be compared and evaluated.

$$x'_{ij} = x_{ij} \cdot w_j \qquad \text{for } j = 1, \ldots, \text{m and } i = 0, \ldots, k$$

$$x'_{ijN} = x_{ijN} \cdot w_j \qquad \text{for } j = 1, \ldots, \text{m and } i = 0, \ldots, k$$

3. Calculation of the aggregated score

If the indicator values have the same unit or were normalized in foregoing steps, the calculation of an aggregated score for each alternative is possible. Due to the different units of the indicators in the case study, this step requires the normalization of the indicator values. To calculate the Weighted and Aggregated score (AS) the following formular is used:

$$\mathrm{AS}_i = \sum_{j=1}^{m} (x_{ijN} \cdot w_j)$$

In an LCA-study, the AS resembles the weighted effect for each alternative. Therefore, it allows the comparison of different alternatives as well as the results of different weighting sets.

4.4.3 Interpretation

The net environmental impacts of the alternative are reduced if $\mathrm{AS}_i < 0$. If $\mathrm{AS}_i > 0$, they are increased. Figure 12 shows the AS for the eight pareto optimal results and the four weighting sets. It becomes clear, that the number of alternatives with a positive AS differs according to the different sets. For the *Equal Weights* calculation both alternatives for PE show a positive AS. Using the sets with higher weights on the climate impact all alternatives show a negative AS and therefore imply an improvement of the status quo. In case of the higher weighting of the impact category *Resource use,* three alternatives (Methane, Syngas, Polyoxymethylene (POM) have a negative AS for both sets. In addition, the two alternatives for methanol show a negative value for the moderate weighting set. On the one hand this shows the robustness of the results for Methane, Syngas and POM caused by a high reduction of the climate impact. On the other hand, the different number of negative AS shows the sensitivity towards the used weights which underlines the importance of transparency and sensitivity checks when weighting methods are applied.

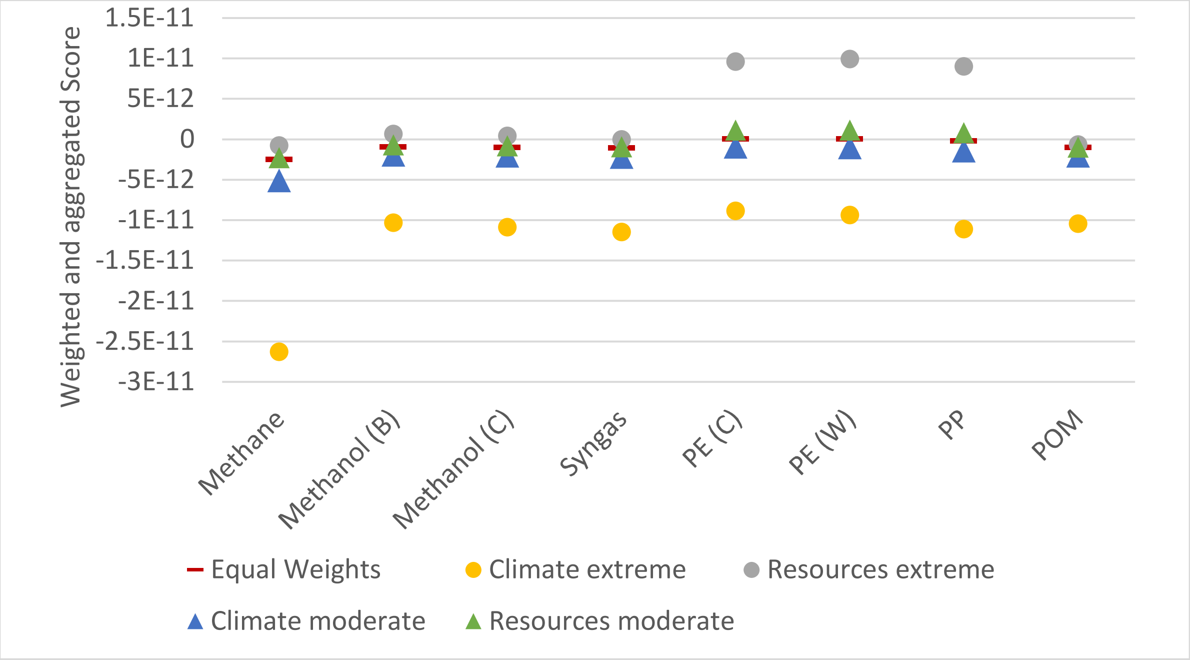

Figure 12: Aggregated score of the CO_2-based alternatives with different weights (PE = Polyethylene, PP = Polypropylene, POM = Polyoxymethylene; B = Biogas Plant, C = Cement Plant, W = Waste Incineration).

4.5 Combined Methods

4.5.1 Distance-to-Target

4.5.1.1 Background

The *Distance-to-Target (DTT)* method represents a special case for a combination of normalization and weighting methods with target values (e.g. the reduction of GHG-emissions). The DTT method is considered as a transparent and reproducible method which helps to interpret the results of an LCA in an efficient way (Song and Moon, 2019). It enables the normalization of indicator values according to the distance between the target value and the status quo. The target values must be related to the same reference system and target year for every impact category. This method allows the normalization of indicator values based on the distance to a defined target value in combination with a weighting step which does not directly rely on subjective stakeholder information but on the current distance from the target value. Therefore, it enables the calculation of the contribution of an alternative to reach a defined goal in combination with the calculation of the AS (Castellani et al., (2016); Weiss et al., (2007)).

4.5.1.2 Method

1. Normalization

For the DTT normalization two parameters are necessary for every impact category *j*. First the normalization base N_j which represent the current aggregated impact in this category and second the target value T_j, both for the reference system, e.g. a national economy. The target value expresses an aimed state of the reference system in a certain year. Its determination is not part of the study but exogenously given, for example by policy. It is very important, that the target year and reference system are consistent for all impact categories. Based on the German Strategy for sustainable development the target values and weights given in Table 8 can be calculated for the target year 2030 (German Federal Government, 2018). The accordingly normalized value xt'_{ij} is calculated also using the indicator values for the new x_{ij} and the conventional alternative x_c:

$$xt'_{ij} = \frac{x_{ij} - x_{cj}}{N_j - T_j} \qquad \text{for } j = 1, \ldots, m \text{ and } i = 0, \ldots, k$$

The results can now be compared and may be interpreted directly. The reader will note that this approach of normalization de facto already represents an implicit weighting: the impact differences in every impact category are expressed as their specific contribution to close the gap between status quo and the target at the higher scale level.

2. Calculation of weights

After the normalization, an additional explicit weighting step may be introduced. The weights for a DTT may be determined for every impact category *j* with the help of the same two parameters N_j and T_j used in the normalization step (Castellani et al., 2016).

$$w_j = \frac{N_j}{T_j}$$

To calculate the additionally weighted aggregated score (AS) the following formular is used:

$$AS_i = \sum_{j=1}^{m} (xt_{ij} \cdot w_j)$$

The AS allows the comparison of different alternatives based on their weighted contribution to reach certain targets. The results can be ranked or compared to different weighting sets.

Table 8: Normalization and Target values as well as calculated weights for the Distance-to-Target Method.

Impact Category *j*	**Indicator**	N_j	T_j	w_j	**Target**
Climate Impact	GWI [kg CO_2 equivalents per year]	$9.07 \cdot 10^{11}$	$6.88 \cdot 10^{11}$	1.32	55 % reduction compared to 1990
Resource Use	RMI [kg raw material equivalents per year]	$2.64 \cdot 10^{12}$	$2.24 \cdot 10^{12}$	1.18	Extrapolation of the trend between 2000 and 2010 to the year 2030

4.5.1.3 Interpretation

Figure 13 shows the results of the application of DTT using only implicit as well as implicit and explicit weights. The results were calculated using the parameters from Table 8 and are compared to conventionally normalized results using different weighting sets (Section 4.4). A score below zero can be interpreted as an overall improvement of the status quo considering the conditions described by the normalization and target values. In contrast a score greater than zero shows an overall worsening compared to the status quo. A score of zero means that the situation is unaltered.

The values calculated with this DTT approach show comparable results as for the higher weighting of the climate impact for Methane, Methanol, Syngas and POM. For olefins the AS is greater than zero for the DTT method. This is caused by the significantly higher resource requirement for those alternatives in combination with a smaller reduction of the climate impact. Therefore, by considering actual target values the LCA results can be differentiated more precisely between the alternatives. Furthermore, a comparison of the implicitly (i) weighted values with the implicitly and explicitly (i+e) weighted values shows that the use of the explicit weights w_j leads to a lower AS and therefore to a higher impact of the GWI reduction on the overall result for all alternatives but the production of PE. In those two cases the relatively high values for an additional resource requirement compensate the now higher weighting of GWI reduction. Furthermore, the additional explicit weighting step does not change the results of the different alternatives with respect to their positioning.

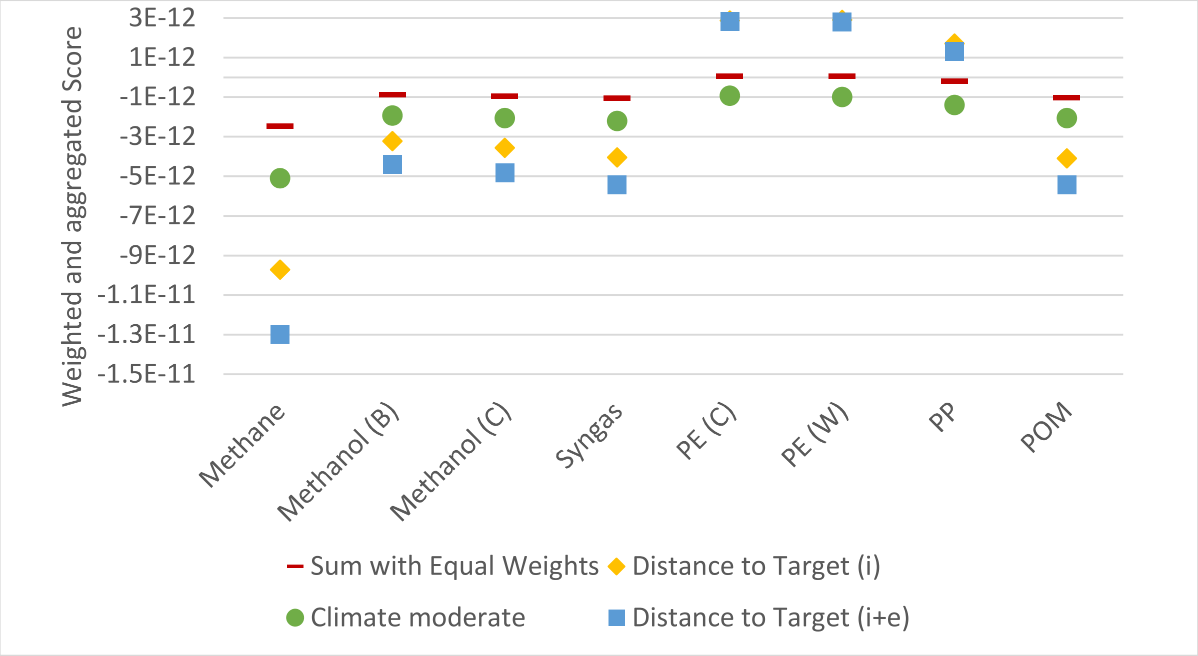

Figure 13: Aggregated score calculated by a Distance-to-Target method for implicit (i) as well as implicit and explicit (i+e) weighting. The results are compared to conventionally normalized results weighted with equal weights as well as the weighting set "climate moderate". As impact categories the Global Warming Impact and the Raw Material Requirement were considered (PE = Polyethylene, PP = Polypropylene, POM = Polyoxymethylene; B = Biogas Plant, C = Cement Plant, W = Waste Incineration).

4.5.2 Outranking Methods

So called *Outranking Methods* combine methods for prioritization and weighting. To do so the alternatives are pairwise compared with each other in every impact category and prioritized based on a pre-defined preference function of the decision maker. Additionally, weights are defined for every impact category. Hence, an overall dominant solution can be identified according to the existing preferences (Geldemann and Lerche, 2014). Prerequisite for this method is the knowledge of the decision maker's preference function in order to develop the weights and priorities. This function has to be defined in an extra working step, for example via stakeholder surveys. Because of the higher effort, outranking methods are not considered as an optional part of LCA studies in the ISO-Norms 14040 and 14044 but could be helpful to identify stakeholder-specific optimal solutions. More information can be found in Zopounidis and Pardalos (2010).

4.6 Recommendations

For the life cycle impact assessment (LCIA) in the CO_2-Win BMBF program, a three-step procedure is recommended. This procedure aims to enable a sound calculation of the environmental potential of the technologies developed in the different projects as well as the whole funding measure with respect to national environmental targets.

1. **Step:** Calculation and comparison of the four footprints in a non-aggregated analysis (without normalization or weighting steps).

2. **Step:** Normalization and non-weighted comparison of the climate and material footprint based on the reference values given in this document. The reference values for a normalization of the water and land footprint are under development and not yet published. Therefore, a normalization based on national values is not yet possible for these two footprints.
3. **Step:** Weighting and normalization of the climate and material footprint with the Distance-to-Target method using the given normalization and target values in this document.

The development and use of a specific weighting for single projects is not considered appropriate since it would hamper comparability and further calculations of economy-wide effects. Nevertheless, an additional individual weighting set in combination with a sensitivity analysis may be helpful to accommodate tradeoffs between impact categories and to identify optimal alternatives for single projects.

5 Conclusions

Methods for MCA enable the comparison of different alternatives based on more than one assessment criterion. The methods described in this document showed that MCA methods can be meaningful support for LCA-studies to enhance their explanatory power, e.g., by ranking the results or dissolving trade-offs in a rational, quantitative, and transparent manner.

MCA methods differ with respect to their complexity and the level of subjectivity, which is involved in the process. Normalization and Distance-to-Target methods allow relatively quick and clear statements about the effect of alternatives on the status quo or on reaching certain policy targets. The involved subjective information is particularly related to the choice of the reference system. In contrast, prioritization or weighting methods require a higher effort to identify the preferences of the stakeholders and limit the explanatory power to the target group of the study. Furthermore, it was shown that the results differ significantly depending on the applied method. Therefore, transparency and proper documentation of assumptions is very important when MCA methods are applied. To enable a sound calculation of the environmental potential of processes and products developed within the BMBF programme CO_2-Win the three-step procedure presented should be followed.

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Annex

Table 9: Pedigree Matrix to assess data quality according to (Weidema et al., 2013).

Criteria	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions ***or*** non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g., by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from > 50 % of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50 %) relevant for the market considered **or** > 50 % of sites but from shorter periods	Representative data from only one site relevant for the market considered **or** some sites but from shorter periods	Representativeness unknown or data from a small number of sites **and** from shorter periods
Temporal correlation	Less than 3 years of difference to the period of the dataset	Less than 6 years of difference to the period of the dataset	Less than 10 years of difference to the period of the dataset	Less than 15 years of difference to the period of the dataset	Age of data unknown or more than 15 years of difference to the period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study (i.e., identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale ***or*** from different technology

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