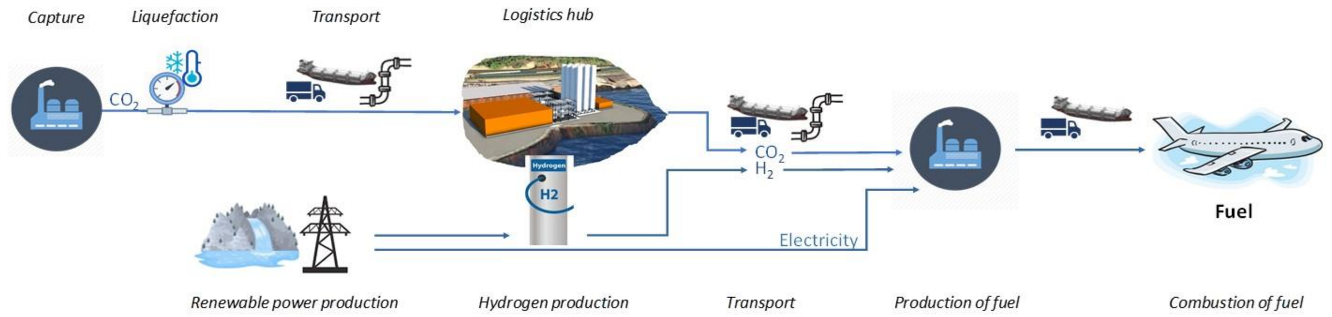
Guidelines for Life Cycle Assessment (LCA) of CCU systems



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Summary

Carbon capture and storage (CCS) is a way of reducing greenhouse gas emissions by capturing and subsequently storing carbon dioxide (CO_2). CCU (carbon capture and utilization), on the other hand, represents a way of recycling the carbon in the captured CO_2 by converting it to fuels or other products. The acronym CCUS describes systems including both utilization and storage of captured CO_2.

This report gives an overview of the three potential CO_2 emissions sources to be captured: direct air capture, geothermal power generation and industrial point sources with regard to their potential of being considered fossil or non-fossil CO_2. Furthermore, the main pathways for utilising captured CO_2 are presented.

CCU systems connect two (or more) product systems; the first being the source of the CO_2 and the second being the CO_2-based production system which uses CO_2 as feedstock. Hence, CCU systems represent multifunctional systems due to the double role of CO_2, representing both emission and feedstock. The report presents Life Cycle Assessment (LCA) methodology in general with a deeper focus on how to solve multifunctionality. The recommendation is to apply system expansion without substitution and compare the CCU system with a reference system. It is crucial to establish relevant system boundaries for the compared systems to ensure that all systems provide the same functions to society.

A practical LCA guideline for CCU value chains is finally presented in Appendix 1.

Contents

1 Carbon Capture and Storage, and Carbon Capture and Utilisation

Carbon capture and storage (CCS) is a way of reducing greenhouse gas emissions by capturing and subsequently storing carbon dioxide (CO_2). CCU (carbon capture and utilization), on the other hand, represents a way of recycling the carbon in the captured CO_2 by converting it to fuels or other products. The acronym CCUS describes systems including both utilization and storage of captured CO_2.

CO_2 is usually considered to be captured from fossil or biogenic point sources or directly from the atmosphere via direct air capture (DAC). Fossil point sources release carbon previously stored in underground compartments, while biogenic point sources release carbon previously consumed from the atmosphere. Figure 1 shows that CCS technologies can theoretically be carbon neutral over the entire life cycle if:

- CO_2 is captured from the atmosphere (via biogenic point sources or direct air capture) and the CO_2 is released at the end-of-life (Figure 1 a).
- CO_2 is captured from fossil point sources and CO_2 is sequestered (Figure 1 b).

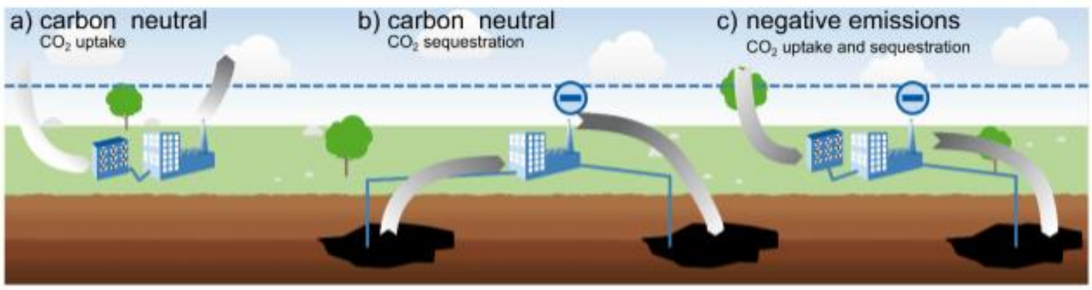

Figure 1 **Principal flow diagrams for CO_2 neutrality and negative emissions (from Zimmermann et al. (2018)**

It can be seen from Figure 1 c that negative emissions will only occur for the cases when CO_2 is taken from a biogenic point source or by direct air capture and sequestered. Furthermore, negative emissions only occur if the emissions over the entire lifecycle are less than 1 kg CO_2-eq. per kg CO_2 sequestered. It should be emphasised that, for case a and b in Figure 1 to be fully carbon neutral, all other GHG emissions must be zero over the life cycle.

Figure 2 shows corresponding flow diagrams for CCU cases.

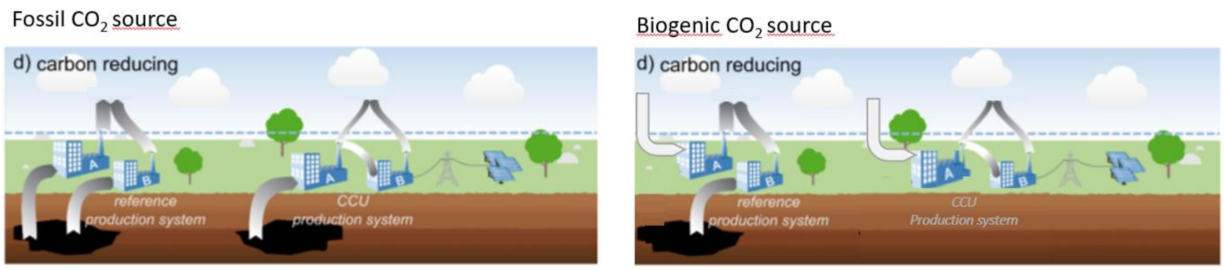

Figure 2 **Principal flow diagrams for reduced CO_2 emissions, in CCU systems (adapted from Zimmermann et al. (2018))**

For all CCU cases, except for a potential case when the captured CO_2 is permanently stored in a product, CCU technologies will have positive CO_2 emissions (burdens) over the life cycle, independent of whether the CO_2 source is fossil or biogenic. However, the emissions from the CCU case might be lower than for a competing Reference case based on conventional processes. In this case, the CCU process might contribute to reduced climate change through substituting conventional processes. Even though such processes lead to lower CO_2 emissions compared to a reference case, they are not carbon negative.

2 Potential CO_2 emissions sources

2.1 Direct air capture

Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere (IEA, 2021). The two most common technology approaches are liquid and solid DAC. Liquid systems pass air through chemical solutions (e.g., a hydroxide solution), which removes the CO_2. While returning the rest of the air to the environment, the system reintegrates the chemicals back into the process by applying high-temperature heat to release the captured CO_2. The CO_2 is now concentrated and can be stored or used (polishing might be necessary, depending on the requirements for transport etc). The CO_2 emissions are treated the same way as biogenic CO_2 emissions regarding the potential of achieving negative emissions or carbon removal.

2.2 Geothermal power generation

Geothermal power plants use steam from nature to produce electricity. The steam comes from reservoirs of hot water found a few miles or more below the earth's surface (NREL, n.d). The steam rotates a turbine that activates a generator, which produces electricity.

The main GHG emitted by geothermal operations is CO_2 (Goldstein et al., 2011). In general, geothermal fluids contain minerals leached from the reservoir rock and variable quantities of gas, mainly CO_2, and a smaller amount of hydrogen sulphide. The gas composition and quantity depend on the geological conditions encountered in the different fields. Depending on technology, most of the mineral content of the fluid and some of the gases are re-injected back into the reservoir. The gases are often extracted from a steam turbine condenser or two-phase heat exchanger and released through a cooling tower. CO_2, on average, constitutes 90% of these non-condensable gases. A field survey of geothermal power plants operating in 2001 found a range in direct CO_2 emissions from 4 to 740 g CO_2/kWh with a weighted average of 122 g CO_2 /kWh. In closed-loop binary-cycle power plants, where the extracted geothermal fluid is passed through a heat exchanger and then completely injected, the operational CO_2 emission is near zero (op.cit). The country-wide weighted average emission estimate for Iceland is 34 g CO_2/kWh (Fridriksson, Mateos, Audinet, & Orucu, 2016)

According to Fridriksson et al. (2016), the national regulatory frameworks for carbon emissions from geothermal power production varies from country to country, reflecting the limited understanding of the effects of power production on natural surface emissions, the minuscule size of the geothermal sector compared to other segments of the electricity generation sector, and its proportionately small (potential) GHG emissions contribution. In some countries, GHG emissions from geothermal power are not considered anthropogenic, in accordance with the understanding that emissions from power plants are counterbalanced by reduction in surface emissions as described above. In other countries, geothermal power producers that emit more than a given volume of GHG per annum are now required by policies to monitor and report their emissions.

This is in line with Paulillo, Striolo, and Lettieri (2019) who raises the discussion of whether geo-fluid dissolved CO2 should be considered an anthropogenic or natural source. In effect, the release of greenhouse gases from geothermal/volcanic systems is a natural process that would also occur in the absence of geothermal operations. But it is still unclear whether geothermal operations can accelerate this process. Whilst some studies showed that geothermal operations increases the natural CO2 emissions; other studies (Bravi & Basosi, 2014) maintain that these emissions cannot be considered "carbon free".

In Europe today there is an ongoing discussion on whether emissions from geothermal power production should be considered anthropogenic or not. Iceland includes these emissions in its national inventory while Italy does not (Ármannsson, Fridriksson, & Kristjánsson, 2005) (Fridriksson et al., 2016).

2.3 Industrial point sources

CO2 emissions from industrial point sources come from a large range of industrial processes. It is important to define whether the emissions are of fossil or biogenic origin, or a mix of these.

3 Main pathways for utilisation of captured CO2

According to (Patricio, Angelis-Dimakis, Castillo-Castillo, Kalmykova, & Rosado, 2017) the following three main categories of CCU applications are expected to play a role for future CCU development:

1) Biological conversion (e.g., algae for fuels and food)
2) Chemical conversion (e.g., methanol and methane for fuel and chemical production)
3) Mineralization (e.g., carbon-based products used in building materials)

Different CCU based products can be, more or less, long-lived according to their use and lifetime. This study has categorised the following two major categories of potential CO2-derived products:

- Long-lived products (assumed > 100 years)
  - e.g. building materials, carbon-based products
- Short-lived products (assumed < 1-2 years)
  - e.g. e-fuels, biomass products, industrial products

The first category can be assumed to store CO_2 for more than 100 years while the second one only stores CO_2 for 1-2 years before it is re-emitted.

An important question related to this is how the climate impact of potentially storing CO_2 is to be calculated for a CCU based product with a lifetime of 100 years vs. 1-2 years? According to Müller et al. (2020), CCU products offer temporary carbon storage. Due to temporary carbon storage, CO_2

emissions can be delayed and, thus, do not contribute to climate change during the time of storage. Therefore, temporary storage is not an independent or additional benefit. However, delayed emission shall not be discounted over time. Instead, emission time profiles, the amount and duration of carbon stored, may be reported as a separate item (op.cit).

Aines (2022b) suggests that a timeline of 100 years is the current accepted lifetime for a durable removal of CO_2 emissions. An argument for this limit is that if the carbon removal lasts longer than the peak in temperature, it will help reduce that peak (even if it raises temperatures after the peak). 100 years is likely later than any temperature peak if efforts are at all successful. However, it is a good practice to strive for storing as long as possible, but not necessarily dismiss solutions that may provide other benefits (Aines, 2022a).

As there is currently no clear criteria for which lifetime a CCU product should have to qualify for durable stored CO_2, this report recommends a lifetime > 100 years. This assumes that Global Warming is calculated over 100 years.

This means that for all CCU products with a lifetime shorter than 100 years, the re-emitted CO_2 from the use phase must be taken into account when assessing the environmental performance of the product.

In a transition to net zero emissions, the CO_2 used to produce synthetic fuels in a CCU pathway would increasingly need to be captured from sustainable bioenergy sources or from the atmosphere (DAC). If not, it would only lead to a delayed emissions of fossil-based CO_2 when the fuel is combusted (IEA, 2021).

4 Life Cycle Assessment (LCA) methodology

4.1 LCA in general

A LCA covers the whole life cycle of a product or service and is often associated with the term «cradle-to-cradle». By applying the LCA method, the potential environmental impacts along the life cycle of a product or a service can be analysed and assessed. LCA represents a structured, comprehensive and internationally standardised ISO 14040/14044 (ISO, 2006a, 2006b) method for quantifying environmental and health impacts, resources consumed, and resource depletion that are associated with any goods or services ("products"). It is applicable to products, processes, services and firms, in order to document their environmental performance, to identify potentials for environmental improvements, to compare alternative options as well as to substantiate eco-labelling criteria. In accordance with the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010), Life Cycle Thinking and LCA create the scientific approaches behind modern environmental policies and business decision support related to sustainable consumption and production. An LCA consists of four steps. It starts with deciding the goal and scope, which is the basis for the system boundaries and all the following steps of the assessment. The second step involves data collection for the system and establishing the life cycle inventory. The output from the analysis is categorised and characterised in the third step, according to the potential impact in different environmental impact categories. Interpretation of the results and the overall assessment is the last and final step of an LCA. In practice, these steps are part of an iterative process.

There are three central points in a life cycle assessment:

- One considers the entire technical system required to produce, use, and dispose the product (system analysis), also taking into account any relevant indirect processes.
- One considers the entire material and energy flow through the value chain of the product, NOT just an isolated process or activity.
- One considers several relevant environmental impact categories for the entire system, NOT just one single environmental indicator (e.g. emissions of solvents or dust).

Two main modelling approaches are in use for LCA (European Commission Joint Research Centre, 2010): the attributional approach and the consequential approach. These two approaches are described as "the account of the history of the product" (attributional) and "consequences of possible changes between two alternative products" (consequential). The main difference between the attributional and consequential approach is that while the attributional approach analyses an existing situation, the consequential approach analyses how a situation changes as a result of a decision. In other words: The attributional approach is modelled under ceteris paribus ("other things being equal") conditions while the consequential approach is modelled under the conditions of mutatis mutandis ("the necessary changes being made") (Frischknecht & Stucki, 2010). It should be emphasised that the consequential approach analyses the macro-economic consequences (e.g. changed production capacity) of a decision (European Commission, 2010).

4.2 Impact assessment

In the impact assessment step of a LCA, all the collected consumption and emission data is assessed in terms of potential environmental impacts. There are several existing methods for life cycle impact assessments that quantify potential impacts within certain environmental categories. The impact categories range from global warming, acidification, ozone depletion, radiation, human and environmental toxicity, to use of energy, scarce resources, water, and land areas.

A full scale LCA should cover a broad range of categories in order to avoid problem shifting (solving one problem while causing another), but it is common to select a few that can be considered most important for the system under study.

Table 1 shows typical environmental impact categories to be assessed in LCA. The climate change impact category is generally the most focused, and several climate change impact assessment methods are available. However, it is important to assess several impact categories to avoid problem shifting.

Table 1 Common environmental impact categories and methods

Environmental impact category	Unit	Impact assessment method *	Comment and potential effects
Climate change IOBC	kg CO_2-eqv.	IPCC 2021 GWP 100a uptake v1.00	Climate change assuming instant oxidation of biogenic CO_2 (IOBC). Sum of the two sub-indicators CC fossil and CC land transformation in addition to biogenic methane emissions. For more information about the IPCC 2021 method, see below.
Climate change (four sub-categories: CC uptake, CC fossil, CC biogenic and CC LU/LUC)	kg CO_2-eqv.	IPCC 2021 GWP 100a uptake v1.00	IPCC 2021 is the successor of the IPCC 2013 method, which was developed by the Intergovernmental Panel on Climate Change. This method lists the climate change factors with a timeframe of 100 years. The GWP 100 factors are recommended as default by UNEP-GLAM (2017), and the GWP20 and GTP100 factors for sensitivity analysis. Uptake and release of biogenic CO_2 is accounted for in two separate indicators. The characterisation factor for biogenic methane is therefore increased to correct for the included carbon dioxide uptake. Reference: Intergovernmental Panel on Climate Change (IPCC): http://www.ipcc.ch/
Climate change (three sub-categories: CC fossil, CC biogenic and CC LU/LUC)	kg CO_2-eqv.	EN 15804+A2 Method V1.02	Climate change leads to increased average global temperature, more extreme weather, increased sea level, impacts on human health, material resources, and ecosystems. This method is identical to the EF 3.0 method, except for a few characterization factors: - carbon dioxide (biogenic), emission, factor 1 (0 in EF) - carbon monoxide (biogenic), emission, factor 1.57 (0 in EF) - methane (biogenic), emission, factor 36.75 (34 in EF) - carbon dioxide, resource, factor -1 (0 in EF) Both uptake and release of biogenic CO_2 is accounted for in the sub-category “CC biogenic”. Reference: European Commission – Joint Research Centre (2021). EN 15804 reference package, https://eplca.jrc.ec.europa.eu/LCDN/EN15804.xhtm
Acidification potential	Mol H^+ eq.	EN 15804+A2 Method V1.02	Acid depositions lower pH in soil and water bodies and affect plants and animals, as well as buildings and other infrastructure. Accumulated Exceedance. Reference: Seppälä, Posch, Johansson, and Hettelingh (2006).
Eutrophication (EP), freshwater	kg P eq.	EN 15804+A2 Method V1.02	EUTREND model. Reference: Goedkoop et al. (2009)
Eutrophication (EP), marine	kg N eq.	EN 15804+A2 Method V1.02	EUTREND model. Reference: Goedkoop et al. (2009)

Eutrophication (EP), terrestrial	mol N eq.	EN 15804+A2 Method V1.02	Accumulated Exceedance. Reference: Seppälä et al. (2006).
Use of fossil resources: ADP_{fossil}	MJ LHV	EN 15804+A2 Method V1.02	ADP_{fossil} is short for Abiotic Depletion Potential for fossil fuels. This is a resource indicator showing use of primary fossil energy. It does not count the direct use of fossil energy, rather the fossil energy that is taken from the earth as a consequence of the activities in the value chain under scrutiny. Example: for a truck using diesel when transporting timber, the ADP_{fossil} will constitute the fossil feedstock energy in diesel (crude oil), in addition to the fossil energy needed for offshore operations, transport of crude oil onshore, refinery processes and transport of diesel for sale. ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016). Reference: van Oers, de Koning, Guinée, and Huppes (2002).
Use of primary energy: cumulative energy demand (CED)	MJ HHV	Cumulative Energy Demand v1.11 from ecoinvent (November 2018)	CED is short for Cumulative Energy Demand, and it is a resource indicator in the same way as ADP_{fossil}. However, the CED indicator includes not only fossil primary energy, but all forms of primary energy. As a consequence, the CED value is most often larger than the value for ADP_{fossil} when analysing the same system. In the diesel example above, renewable primary energy used for producing diesel will be included as well. This could, for example, be hydro power in electricity used by the offshore installations producing crude oil, which in turn is transformed into diesel in the refinery.

* Methods mainly from EN15804+A2 have been given as examples.

CCS and CCU focus generally on improving the results for climate change. It is, however, crucial to analyse more impact categories when comparing the environmental performance of CCS and CCU systems. It is also important to make sure that the chosen climate change assessment method fits with your modelling approach regarding biogenic CO_2. If an IOBC (instant oxidation of biogenic carbon) method is chosen, it is crucial that biogenic CO_2 which is stored is given a negative burden (benefit). In the modelling tool, this is done by multiplying this amount with -1. To avoid this issue, one can instead choose a climate change assessment method that includes uptake of biogenic CO2. These methods treat emissions of both fossil and biogenic CO2 equally and the risk of mistakes being made in CCUS systems is reduced.

4.3 LCA of CCU and multifunctionality

Müller et al. (2020) have developed specified guidelines for Life Cycle Assessment of CCU as a collaborative process involving over 40 experts building upon existing LCA standards and guidelines.

Most LCA studies on CCU (Müller et al., 2020) aim at quantifying the potential environmental impact reductions of CCU processes or products in comparison to existing processes, e.g., the aim of the study is to answer the question: What is the environmental impact reduction of a CCU-based product or service compared to the same product or service derived from fossil carbon sources?

Applying LCA to CCU technologies leads to specific methodological issues connected to multifunctionality, due to the double role of CO_2 representing both emission and feedstock. This is caused by the fact that CCU systems connects two (or more) product systems; the first being the source of the CO_2 and the second being the CO_2-based production system which uses CO_2 as feedstock. Together, these two systems produce a minimum of two products, and this is the overall multifunctionality of the CCU system. There is also a second layer: as CO_2 is used as a feedstock in the second system, it can be seen as a product of the first system. Hence, the first system has two product flows; the original product and CO_2.

According to ISO 14040/44, multi-functionality should be solved according to the following stepwise procedure:

1. Dividing the relevant process into sub-processes with related input and output data (sub-division)
2. Expanding the product system to include additional functions (system expansion)
3. Allocate according to physical or economic conditions (allocation)

Müller et al. (2020) describe the possibility of the above solutions for solving multifunctionality for CCU systems as follows.

4.3.1 Sub-division

Dividing the relevant process into sub-processes with related input and output data is not a solution for solving multifunctionality for CCU systems since CO_2 is always produced jointly with the main product. Hence, sub-division is not applicable for solving multifunctionality for CCU based products.

4.3.2 System expansion without substitution

System expansion expands the functional unit to include other functions of the product systems than those which were originally stated in the goal and scope definition. If this expanded function is still meaningful, the multi-functionality problem is resolved (European Commission Joint Research Centre, 2010).

As described in chapter 4.3, the goal of LCAs for CCU systems is often to compare the CO_2-based product to a conventional product (reference product). To compare these products, each product system needs to fulfil the same functional unit, which means that the system boundaries must be expanded for both product systems, see Figure 3 (Müller et al., 2020).

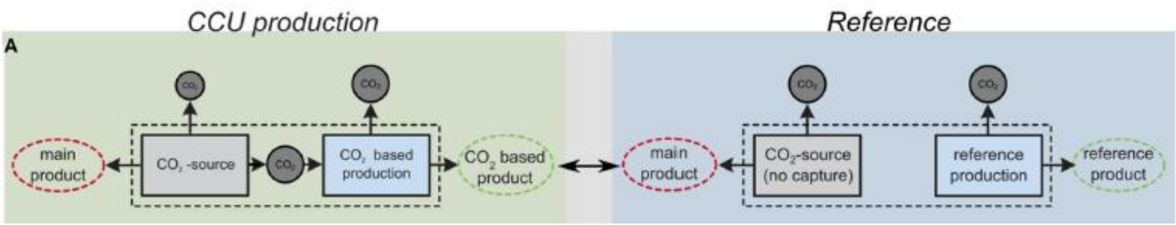

Figure 3 Production of equivalent products and functions with and without CCU using system expansion (Müller et al., 2020)

When comparing a CO_2-based product and a reference product (dashed green lines in Figure 3), the main product (dashed red line) must be added to both systems in order fulfil the same functional unit. Expanding the system with the conventional production of the main product without carbon capture in the reference system enables a fair comparison of the CCU production and the reference production.

The functional unit for an LCA with the aim of comparing the above described CCU system to a conventional system is suggested as follows: *Production of the main product with or without capture of x tonne CO_2, transport of CO_2 and production of the CO_2-based product/reference product corresponding to the captured amount of CO_2.*

4.3.3 System expansion with substitution

System expansion with substitution is another way of solving the multifunctionality problem in CCU systems. In this approach one of the co-products substitutes conventional production, and the avoided environmental burdens are credited to the remaining system. For CCU systems, the substituted process is usually the production of the main product without carbon capture. Hence, the CCU system is credited for the otherwise emitted CO_2, see Figure 4. The benefit of this solution is that it compares the CO_2-based product and the reference product "directly" as the result expresses the difference in emissions from the main product with and without capture.

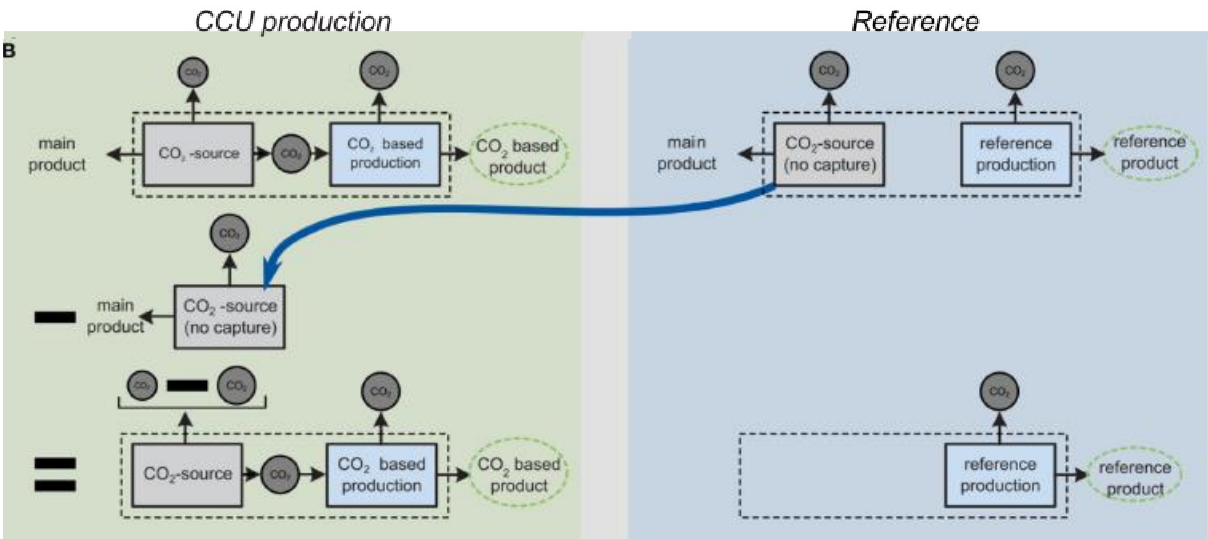

Figure 4 Production of equivalent products and functions with and without CCU using system expansion with substitution (Müller et al., 2020)

It should be emphasised that system expansion and system expansion with substitution are mathematically equivalent in comparative LCA. However, results, meaning and interpretation of results, are not because the system boundaries and functional unit are altered. System expansion via substitution can lead to "negative" environmental impacts (e.g., negative CO_2 emissions), because co-products are credited. These negative environmental impacts can be misunderstood in a way that producing more of the product could offer infinite benefits to the environment. However, these negative environmental impacts simply indicate that the CCU production system has lower environmental impacts than the conventional production of the reference product, and not that the absolute burdens are reduced.

4.3.4 Allocation

Allocation partitions the in- and outputs of the multifunctional process among the products or functions reflecting an underlying physical causal, economic, or other non-causal physical relationship in this priority, respectively (ISO, 2006b). This is shown in Figure 5.

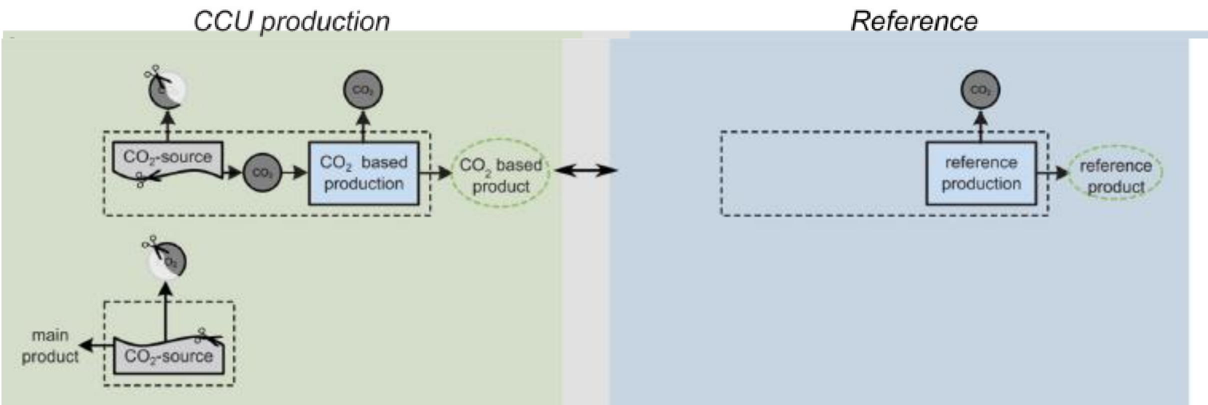

Figure 5 Production of equivalent products and functions with and without CCU using allocation (Müller et al., 2020)

A physical causality can be found by quantitatively changing the amount of main product and the CO_2-based product produced and observing how the inputs and outputs are affected. Setting the amount of the main product to zero, leads to a process without inputs or outputs, and therefore a non-CO_2-based product. Hence, this physical causality makes no sense for CCU systems.

Other physical causalities for allocating the emissions of the CO2-source among the main product and the CO_2-based product can be difficult. Mass can be applied to most processes, but not to power plants, since electricity has no mass and thus, all emissions would be distributed to CO_2. Energy is not a suitable attribute either, since CO_2 does not contain any energy (its lower heating value is zero), and no emissions would be distributed to CO_2 using energy allocation.

If a physical causality cannot be applied, economic allocation is most used. The economic value of CO_2 is uncertain: since the capture process is related to costs, the price of CO_2 might be positive and thus, economic allocation would attribute CO_2 with positive emissions. However, it can be argued that CO_2 has a negative economic value since it is a waste stream, which needs a waste treatment. In this case, the CO_2 source has only one function, i.e., producing the main product, and it has a technical waste flow, i.e., the concentrated CO_2 stream (which, per se, cannot carry any environmental burdens). The CO_2-utilizing step would then be multi-functional in the sense that a CCU product is produced, and the CO_2 waste stream is treated. The environmental impacts of the CCU utilizing step would be allocated between the CCU product and the waste treatment function (European Commission Joint Research Centre, 2010).

Since each of the above-described allocation approaches would give significantly different results and an objective selection of one allocation criterion is not possible, a sensitivity analysis using different allocation approaches will always be needed. According to Müller et al. (2020) an analysis using system expansion shall always be performed to assess the overall effect of introducing the CCU technology.

4.4 Recommended approach for solving multifunctionality

Guidelines provided by Müller et al. (2020), Zimmermann et al. (2018) and (Niklas von der Assen, Johannes Jung, & André Bardow, 2013) for CCU value chains focus on the importance of joint evaluation of all the functions in a CCU system through the use of system expansion. The application of system expansion ensures that the compared systems provide the same functions to society. We recommend solving multifunctionality using system expansion without substitution to ease interpretation of the results.

Furthermore, the feedstock CO_2 should be classified as an economic flow, rather than intuitively considering utilised CO_2 as a negative GHG emission.

For CCU based chemicals and fuel (e-fuel), which needs large amounts of (renewable) electricity, it is recommended to include this energy demand in the functional unit and the expanded system. This is to allow for analysing breakeven points. By varying the climate intensity of the substituted electricity in the reference product system, one can find the point where the reference product system and the CCU system is equal with regard to climate burdens. A higher climate intensity of the substituted electricity will give a reference product system which is beneficial over the CCU system with regard to climate burdens.

Finally, it should be emphasised that CCS and CCU generally focus on improving the results for climate change. It is, however, crucial to analyse more impact categories when comparing the environmental performance of CCS and CCU systems.

4.5 Fossil or non-fossil CO_2

It is important to distinguish between captured fossil and non-fossil (biogenic or released naturally) CO_2 emissions. In the modelling of CCS and CCU systems by Raadal and Modahl (2022), the biogenic emissions are assumed to have the same climate change effect as fossil CO_2 when emitted, and the emitted biogenic CO_2 is neutralised when biogenic CO_2 is removed from the atmosphere while the trees are growing. The EN15804+A2 method for climate change was used by Raadal and Modahl (2022) and the modelling was adapted accordingly. It is of vital importance that the LCA modelling of uptake and storage of CO_2 is handled in a way that harmonises with the chosen climate change impact assessment method (see also chapter 4.2).

For Iceland, the emissions from geothermal electricity generation are assumed anthropogenic and hence included in the national greenhouse gas inventory. Nevertheless, geothermal utilization is a geological source of CO_2 and geothermal electricity qualifies as fully renewable according to the EU directive 2018/2021 (European Commission, 2018). As described in chapter 2.2, there are ongoing discussions in Europe today on whether emissions from geothermal power production should be considered anthropogenic or not, and whether it can be proved that the CO_2 was previously released naturally. This study recommends that the emissions from geothermal power production, if they otherwise would have occurred naturally, to be treated like CO_2 from the air (DAC) and biogenic CO_2 regarding life cycle assessment of CCU systems. On the other hand, if the geothermal operations accelerate the natural CO_2 emissions, these extra emissions should be treated like anthropogenic/fossil. This issue should anyhow be described in detail and relate to the above-mentioned, ongoing discussions for the respective cases under study.

If the analysed systems include capture and use of biogenic CO_2, the system might lead to negative emissions if the CO_2-based product has a lifetime longer than 100 years. For CCU products with lifetime < 100 years, the CO_2 will be remitted during burning/use of the product.

4.6 CCU systems which need large amounts of energy/resources

Some CCU conversion systems, such as chemical conversion of CO_2 to CCU based chemicals and fuel (e-fuel[1]) products, need large amounts of electricity (preferably renewable). As this electricity can potentially have an important effect elsewhere in society, this can be included in the analysis. According to (Raadal & Modahl, 2022) these considerable quantities of electricity are provided to the reference product system in order to compare the two systems in a fair way. However, since the reference product system does not need this electricity, it can be used to replace electricity sources elsewhere. Ultimately, both systems still deliver the same functions (main product and CO_2-based product/reference product) and are provided with the same amount of (renewable) electricity. Not expanding the systems to also include this electricity is a common pitfall resulting in inconsistent system boundaries, according to (Niklas von der Assen, Johannes Jung, & Andrè Bardow, 2013) (Abanades, Rubin, Mazzotti, & Herzog, 2017). This choice can also be regarded as a modelling decision and opens the possibility of analysing breakeven points. By varying the climate intensity of the substituted electricity in the reference product system, one can find the point where the reference product system and the CCU system is equal with regard to climate burdens. A higher climate intensity of the substituted electricity will give a reference product system which is beneficial over the CCU system with regard to climate burdens. A Sensitivity analysis for this is provided in Raadal and Modahl (2022), and it shows that CCS is beneficial over CCU (fuel production) as long as fossil electricity is a part of the grid mix.

The functional unit for an LCA with the aim of comparing the above described CCU system to a conventional system is suggested as follows: *Production of the main product with or without capture of x tonne CO_2, transport of CO_2 and production of the CO_2-based product/reference product corresponding to the captured amount of CO_2;* ***and use of renewable electricity for internal purposes or for replacement****.*

[1] Electrofuels (e-fuels) are synthetic fuels made by storing electrical energy in the chemical bonds of liquid or gas fuels. E-fuels are produced with hydrogen that is obtained from the electrolysis of water by use of renewable electricity. The hydrogen is then combined with carbon dioxide to make hydrocarbons like diesel, methanol, etc. The term electrofuel is referring to the fuel production process rather than the fuel itself as the "final" fuels are similar/identical independent of whether they have been produced as e-fuels or by conventional processes. E-fuel processes are also called Power-to-X (PtX), Power-to-Gas (PtG) and Power-to-Liquid (PtL) as they need electricity to split water into hydrogen and oxygen.

5 Discussions and conclusions

CCS and CCU generally focus on improving the results for climate change. It is, however, important to analyse more impact categories when comparing the environmental performance of CCS and CCU systems, to avoid problem shifting.

CCU represents multifunctional systems. It is therefore crucial to establish relevant system boundaries when comparing the environmental performance of CCU systems and their reference product systems. The application of system expansion ensures that the compared systems provide the same functions to society. We recommend solving multifunctionality using system expansion without substitution to ease interpretation of the results.

When using system expansion with substitution, negative LCA results can occur. However, such negative LCA results only reflect that a comparison has been made. Negative LCA results do not imply that the CCU product has negative emissions over its life cycle. Therefore, negative climate change results obtained from substitution shall be clearly stated as an environmental benefit compared to another technology or scenarios and not as negative climate change results over the life cycle.

It is a good practice to elaborate a bit more on negative results. There are two types; real negative emissions and avoided burdens. The first category, real negative emissions, represents actual removal of CO_2 from the atmosphere, which of course relates only to the climate change impact category. The second category, avoided burdens, represents processes which contribute to avoided environmental burdens because they substitute more environmental burdensome processes/activities. Avoided environmental burdens might occur for all environmental impact categories (not only for climate change). The latter might lead to a lower environmental impact compared to a Reference case, a benchmark technology, etc. For climate change impact, the results of a CCU might show lower CO_2 emissions compared to a Reference case. However, as long as the CCU product has a lifetime less than 100 years, these emissions should never be called negative emissions in terms of removing CO_2 from the atmosphere, as they only reflect that a comparison has been made.

As the community is moving towards a circular economy, there will be an increased focus on the ranking of the environmental performance of use, reuse and recycling of our common goods and resources. It is to be expected that LCA methodology will be an important tool for this purpose, and that the expansion of the system boundaries will be crucial for the correct assessment of such systems. Sensitivity analyses will, however, be important for analysing future systems, e.g., with a grid mix consisting of a large degree of renewables.

It should be mentioned that since the system expansion perspective assesses the overall environmental impact from the expanded system (both the point source emissions and the CO_2-based product), it is difficult to create separate environmental footprints relating to the two specific products. This requires a further allocation of the overall benefits and burdens of the different functions being covered by the overall analysed system. As described in this report (chapter 6.3.4), an objective selection of one allocation criterion is not possible. Hence, a Phase II of the study is proposed for a more in-depth overview and further exploration of this issue.

Other approaches for calculating greenhouse gas emissions savings of recycled carbon fuels are presented in the draft delegated regulation under The Renewable Energy Directive which was published on May the 20th 2022 by the EU (European Commission, 2022). This draft proposes a methodology for determining greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels calculated as follows:

Total emissions (E) from the use of the fuel (gCO_2eq / MJ fuel) = $e_i + e_p + e_{td} + e_u - e_{ccs}$

Where:

- e_i = emissions from supply of inputs (including all emissions in the existing use or fate of the input that are avoided when the input is used for fuel production)
- e_p = emissions from processing + emissions from transport and distribution
- e_{td} = emissions from transport and distribution
- e_u = emissions from combusting the fuel when used
- e_{ccs} = emission savings from carbon capture and geological storage.

The greenhouse gas emission savings from renewable liquid and gaseous transport fuels of non-biological origin or from recycled carbon fuels are further calculated as $(E_F - E) / E_F$, where E_F represents the total emissions from the fossil fuel comparator.

This approach for calculating greenhouse gas emissions is a way of system expansion with substitution (ref chapter 4.3.3 However, it should be emphasised that this method does not represent a full LCA as it only assesses greenhouse gas emissions, in addition to attributing renewable electricity zero greenhouse gas emissions (as infrastructure is not included).

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Appendix 1: Practical LCA guidelines for CCU value chains

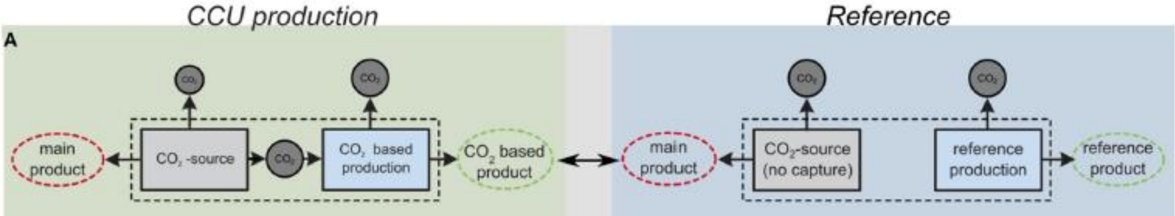
The following stepwise guidelines for performing an LCA for a specific CCU value chain are based on the literature described in this report.

1. Define the CO_2 source to be captured
    a. Describe whether the CO_2 to be captured comes from:
        i. The atmosphere (DAC)
        ii. Geothermal power production with naturally released CO_2
        iii. An industrial point source or geothermal power
    b. If the above point i. or ii. is chosen, the CO_2 emissions should be treated similar to biogenic emissions
    c. If the above point iii. is chosen, the CO_2 point source must be investigated (e.g. by describing the relevant energy source/carrier, process emissions responsible for the emissions) to define whether the CO_2 emissions should be treated as biogenic, anthropogenic, or a mixture.

2. Define the relevant CCU products to be analysed. The major categories of CCU applications are:
    i. Biological conversion (e.g., algae for fuels and food)
    ii. Chemical conversion (e.g., methanol and methane for fuel and chemical production)
    iii. Mineralization (e.g., carbon-based products used in building materials)

3. Define whether the CCU products to be analysed have a lifetime > 100 years.
    a. If the CCU product has a lifetime > 100 years, the CO_2 used in the CCU product can be assumed permanently stored, hence, it is not re-emitted.
    b. If the CCU product has a lifetime < 100 years, the CO_2 emitted when the product is degraded shall be considered as an emission.

4. Define the functional unit and system boundaries for the CCU production system and the reference product system using system expansion without substitution to solve the multifunctionality (see the figure below).



    a. Suggested functional unit for LCA of a CCU system:
        i. If the CO_2-based product does not require large amounts of renewable electricity: *Production of the main product with or without capture of x tonne CO_2, transport of*

CO_2 and production of the CO_2-based product/reference product corresponding to the captured amount of CO_2.

ii. If the CO_2-based product does require large amounts of renewable electricity: *Production of the main product with or without capture of x tonne CO_2, transport of CO2 and production of the CO2-based product/reference product corresponding to the captured amount of CO_2;* ***and use of renewable electricity for internal purposes or for replacement***.

b. If only the point source CO_2 emissions from producing the main product are of interest (not the main product process itself), the functional unit for the LCA can be simplified as follows by keeping the main product outside the system boundary: *Point source emissions from producing the main product, with or without capture of x tonne CO_2, transport of CO_2 and production of the CO_2-based product/reference product corresponding to the captured amount of CO_2 (and use of renewable electricity for internal purposes or for substitution).*

5. Perform the LCA of the defined systems and present the results for several environmental impact categories.

6. Provide uncertainty and sensitivity analyses of the main assumptions and modelling choices (for example the climate intensity of substituted electricity) to identify whether calculated differences of environmental impacts are significant or not.