



# Methodological review of life cycle assessments of carbon capture and utilisation – Does modelling reflect purposes?

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## ABSTRACT

Carbon dioxide capture and utilisation (CCU) is considered a climate change mitigation strategy and life cycle assessment (LCA) is often used to assess its decarbonisation potential. The current study investigates the understandability of the LCA studies of CCU systems in this context by reviewing 106 LCA studies of CCU systems on their methodologies. The results show a diversity in LCA studies performed. They studied a range of CCU products created from varying sources of carbon dioxide and had different industrial scopes. The majority of studies compare the climate change impact of the investigated CCU process to the conventional production systems or products. Of the 106 articles, 47 report a reduced and 27 claim a negative impact regardless of the source of captured carbon or the storage time of the CO<sub>2</sub> in the product. Half of the reviewed studies did not report the goal with the LCA, and those who stated a goal seldom explained the purpose of the assessment. This made the methodological choices and results of the studies difficult to understand. For more understandable LCA studies of CCU systems, the modelling needs to reflect the purposes of the assessments. This includes considering the time aspects of when and for how long carbon is retained by the studied CCU systems and products. Furthermore, there is a need for improvement in both the reporting of LCA studies and the guidelines, especially regarding the reporting of the goal and how the goal definition phase is connected to the methodological decisions in the LCA study.

## 1. Introduction

To reach the Paris Agreement of keeping the global average temperature to “well below 2 °C above pre-industrial levels”, and limit the increase to 1.5 °C, carbon-reducing and even carbon sink technologies are said to be needed (UNFCCC, 2016). One climate change mitigation strategy that industry can apply is carbon dioxide capture and utilisation (CCU) (IPCC, 2023), i.e., technologies where carbon dioxide (CO<sub>2</sub>) is captured and used in the production of a new product (IPCC, 2018).

CCU is debated as there is conflicting evidence of its usefulness and carbon abatement potential. While a handful of reviews and meta-analyses have concluded that some CCU technologies have lower global warming impacts than conventional technologies, e.g., mineral carbonation (Baena-Moreno et al., 2019; Thonemann et al., 2022), there are others that point to the contrary. For example de Kleijne et al. (2022), concluded that not many of the existing technologies would be mature and compatible in time for fulfilling the Paris Agreement (emissions halved by 2030 and net zero by 2050). In another review, Thonemann (2020) found that some CCU technologies for chemical production lead to higher environmental impacts than conventional alternatives. In

their reviews, both Cuéllar-Franca and Azapagic (2015) and Takht Ravanchi and Sahebdehfar (2021) concluded that CCU technologies delay emissions rather than eliminate them since avoided emissions will eventually be released during the life cycle of chemicals and fuels.

Although most reviews focus on the carbon reduction results some also mention methodological concerns. These include considerations such as the choice of impact categories, the lack of specification on handling multifunctionality, and the failure to explicitly define system boundaries (e.g. Thonemann, 2020; Thonemann et al., 2022). When Terlouw et al. (2021) evaluated life cycle assessment (LCA) method choices regarding carbon dioxide removal (CDR) technologies (but not for CCU), they deemed that LCA results are unreliable and unsuitable for decision support.

Despite the critique, many new carbon capture projects are planned or starting up. The number of projects “in the pipeline” has increased, from fewer than 100 in 2020 to around 400 by mid-2023 (IEA, 2023). The environmental assessment of carbon capture projects can play a crucial role in guiding ongoing developments. Considering the conflicting evidence and expectations towards CCU projects (Hepburn et al.,

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2019; Palm and Nikoleris, 2020) and the urgency of climate goals, it is vital that assessments are transparent and easy to understand.

To better understand the reasons for the conflicting evidence from the environmental assessments of CCU, it is necessary to look more closely at the employed LCA methods in such studies. When doing this, the versatility of LCA methodology must be considered as well as the urgency of the climate goals. This work aims to investigate the understandability of the LCA studies in the context of the climate urgency. This is achieved by reviewing the types of LCA studies relative their methodological choices. More specifically, we aim to find out:

- What types of LCA studies have been conducted on CCU technologies?
- Are results of LCA studies understandable and congruent with the aim of decarbonisation?

With understandability, we mean comprehending the credibility, i.e., “alignment between theory, research question, data collection, analysis and results” (Stenfors et al., 2020, p. 598). This translates to alignment between the purpose of an LCA (its goal) and methodological choices for the life cycle inventory analysis and life cycle impact assessment (its scope). With congruity, we mean appropriateness and consistency, which in the context of decarbonisation refers to relevancy of methodologies in LCA studies in relation to the urgency of carbon reduction.

## 2. Background

Several reviews and method guidelines cover the topic of LCA and CCU. Here, we review existing knowledge, especially regarding chosen, recommended and lacking methodological approaches.

### 2.1. Reviews of LCAs of CCU

Different types of reviews have been made in the CCU field. There are reviews of CCU that focus on technology or products and include their environmental impacts (Artz et al., 2018; Baena-Moreno et al., 2019; Zhu, 2019). This shows the importance of LCA studies in this field.

Earlier reviews of LCA studies of CCU focused predominantly on environmental impacts (Cuéllar-Franca and Azapagic, 2015, 2017; Müller et al., 2020b; Thonemann, 2020; Garcia-Garcia et al., 2021; de Kleijne et al., 2022; Thonemann et al., 2022), but did not look into the methodology of the reviewed LCA studies. When performing their meta-analyses and harmonising LCA studies, the reviews took for granted that the methods of reviewed LCA studies were appropriate to the respective study.

There are other types of reviews, such as Cruz et al. (2021) who studied the application of LCA of CCS and CCU through bibliometric analysis and Ren et al. (2021) who investigated the CO<sub>2</sub> reduction potentials of carbon-reducing technologies in Chinese industry. This points towards a general interest in the field. Recently, Pinto et al. (2024) reviewed different LCA guidelines for carbon capture and circular product systems.

Some of the previous reviews raised methodological issues of LCA of CCU systems and recommended harmonisation to solve the problems. Harmonised calculation rules were suggested by, among others, Thonemann et al. (2022, p. 11), who concluded: “From an LCA perspective, harmonized calculation rules in the form of recommendations regarding handling multifunctionality, the burden of captured CO<sub>2</sub>, and the LCI modeling approach, as well as a higher degree of transparency in LCA studies, are needed.”. Harmonisation is also the suggested solution for handling diverging results according to Garcia-Garcia et al. (2021, p. 1013), who concluded: “Also, different LCA studies of the same or similar CCU processes often give divergent results, which highlights the need to harmonize the LCA methodology in CCU studies.”.

While previous reviews have focused on quantifying environmental impacts or on the technology or product itself, the need for a review of employed methodologies remains. The versatility of the LCA method allows for diverse studies, which is not taken into account in harmonisation or standardisation recommendations.

### 2.2. Reviews of LCA methodology

Reviews of LCA methods, in general, are found in methodological and critical reviews. A review in the context of CCUS with a methodological focus has been done by Wang et al. (2024), however, with a focus on prospective techno-economic assessment (TEA) and LCA and hence not a review of how LCA has been applied in the field. They provided some guidance on how to conduct prospective LCA of CCS or CCU systems and identified challenges of doing this with integrated assessment models (IAMs). Methodological reviews focusing on methodological choices in LCA studies within a field of application have provided inspiration on how to conduct a method review instead of a review on environmental impacts. Such reviews have been done on aquaculture systems (Henriksson et al., 2012; Bohnes and Laurent, 2018), building industry (Abd Rashid and Yusoff, 2015), hydrogen energy systems (Valente et al., 2016), plastics (Bishop et al., 2021), flow batteries (Dieterle et al., 2022), thermal insulation materials (Füchsl et al., 2022), solid waste management (Mulya et al., 2022), bio-based platform molecules (Blanco-Cejas et al., 2023) and fertilisers (Miao et al., 2024), but not any on CCU. Some gave practical recommendations regarding method choices (Henriksson et al., 2012; Bohnes and Laurent, 2018; Bishop et al., 2021; Dieterle et al., 2022; Mulya et al., 2022). A few reviews recommended standardisation or harmonisation of LCA for future work (e.g., Abd Rashid and Yusoff, 2015; Valente et al., 2016; Mulya et al., 2022; Blanco-Cejas et al., 2023).

More general advice on conducting a methodological review has been found in the literature on critical review of LCA, especially the review of credibility and reliability. A critical review can, for example, evaluate alignment of methods with standards, methodological relevance to the goal definition, validity of methods, data and calculations appropriateness and correctness, validity of conclusions and/or transparency (Baumann and Tillman, 2004). Critical reviews can be either mandatory or optional and done by either internal or external parties, depending on the use of the study (ISO, 2006). The guidelines distinguish between credibility and reliability for external reviews in contrast to quality assurance from internal reviews (Garvens, 2023). One important criteria is if the method choices, not all but the most indicative in relation to goal and scope, align with the goal definition.

For this work, a review focusing on the fit of methodological choices is most appropriate.

### 2.3. Variants of carbon capture

When reviewing the LCAs of CCU, a good understanding of CCU is useful. It is key to understand the extent to which the LCAs manage to capture complexities related to multifunctional industrial systems, decarbonisation approaches and carbon accounting.

There are several types of carbon capture approaches and CCU holds a particular position among these since the captured carbon is utilised for making products. This means that captured carbon dioxide, to some extent, replaces other raw materials. IPCC (2018) defines CCU as “A process in which CO<sub>2</sub> is captured and then used to produce a new product.”. In this review, this is the definition used for CCU.

Another type of carbon capture approach is carbon dioxide capture and storage (CCS), defined by the IPCC (2018) as “A process in which a relatively pure stream of carbon dioxide (CO<sub>2</sub>) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere.”. This highlights the importance of time in terms

of how long the carbon dioxide is removed from the atmosphere, permanently or only temporarily. When the product from a CCU process stores the carbon for a “climate-relevant time” (IPCC, 2018), this allows CCU to be called carbon capture, utilisation and storage (CCUS). Thus, the lifetime of CCU products is of importance for the climate change abatement potential of CCU. And a question arises if this is addressed in some way in the LCAs of CCU.

Another variable that influences the carbon abatement potential of CCU is the source of carbon. IPCC (2018) defines negative emissions as “Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural carbon cycle processes”, which in the case of CCU means carbon captured via direct air capture (DAC) or through biogenic sources. Technologies that result in negative emissions are also called negative emissions technologies (NETs) and when the removed carbon is also durably stored, this is called carbon dioxide removal (CDR). This aspect of CCU relates to the scope of the modelled system in LCAs, particularly to what extent the carbon flow is considered.

Based on these definitions, not all CCU systems are capable of achieving negative emissions. This depends both on the storage time for the captured carbon and the source of carbon. When examining the LCA studies of CCU in relation to decarbonisation and the climate urgency, it is necessary to determine the sources of carbon, where in the industrial system this carbon is captured, and the duration for which the carbon is stored in the product. These aspects should be identifiable in the goals and scopes of the LCA studies.

#### 2.4. LCA guidelines specific to CCU

Given the complexities of CCU systems, application of LCA to CCU is not straightforward. Several recommendations and guidelines have specifically been developed to aid LCA of CCU, either published in academic journals or as technical reports (see Table 1). There are also CCU-specific guidelines for methods assessing life cycle environmental impacts in combination with other aspects, for example, social and economic (e.g., Bennett et al., 2014; Engebø et al., 2014; McCord et al., 2021), which will not be discussed here.

The guidelines considered in this work cover advice on all steps of the LCA. Of particular interest are the recommendations regarding goal and scope, where the guidelines exhibit some differences (see Table 1). Some recommend specific method choices (e.g., von der Assen et al., 2013; Müller et al., 2020a; Langhorst et al., 2022; Skone et al., 2022; Raadal and Modahl, 2022), while others give more general advice (e.g., von der Assen et al., 2014; Ramirez et al., 2020). The multitude of guidelines raises a question of if and how the guidelines have been followed by LCA practitioners.

#### 2.5. Goal and scope definition in LCA

In addition to the CCU-specific guidelines, general guidelines for goal and scope in LCA need to be considered. According to ISO 14040:2006 (ISO, 2006), the first step of an LCA is the definition of the goal and scope. Before the introduction of the standard, there were other descriptions of the methodology. In 1993, the first step was still called *goal definition*, followed by a step of inventory (Guinée et al., 1993), but two years later, in 1995, it was called *goal definition and scoping* (Lindfors et al., 1995). Regardless of the different method descriptions, there is a consensus that goal definition is the most critical part of LCA (e.g., Lindfors et al., 1995; Klöpffer, 1997; Baumann and Tillman, 2004).

The methodological decisions made by the practitioner for an LCA study are made in the phase of goal and scope (Lindfors et al., 1995; Baumann and Tillman, 2004). In all the following phases, the methodological decisions need to be consistent with the defined goal of the LCA study (Bjørn et al., 2018). In The Hitch Hiker’s Guide to LCA, it is described how “The commissioner’s role is to state the goal of

the study and the practitioner’s role is to know and describe the implications of different methodological approaches” (Baumann and Tillman, 2004, p. 73). Essentially, the scope is the analyst’s translation of the commissioner’s goal for the study. This enables a distinction between defined goals and defined scopes.

##### 2.5.1. Goal definition

The goal definition is important because it outlines the purpose of the study, its intended application and the method choices (Lindfors et al., 1995; Baumann and Tillman, 2004; Bjørn et al., 2018). The goal can be vague at the beginning of the LCA study, but for the practitioner to be able to make the relevant methodological choices, the study needs to have a specific purpose (Baumann and Tillman, 2004). This is made clear by the following statement in the Nordic Guidelines on Life-Cycle Assessment:

“It is of utmost importance to define clearly the purpose of the study and the intended use and users of the results. It is obvious that this needs to be clearly stated in the final report. The reader will otherwise not be able to understand why different assumptions are made in the study. The practitioner needs to understand the *detailed purpose of the study*, i.e. *the reason why the study is made, in order to make proper decisions*. It is not sufficient just to define the purpose in terms of what will be done, e.g., ‘to compare the environmental impacts associated with paints used for wall decoration.’” [emphasis added] (Lindfors et al., 1995, p. 29)

In Life Cycle Assessment: Theory and Practice (Bjørn et al., 2018, p. 67), a chapter is dedicated to the goal definition, providing guidance on “(1) Intended applications of the results, (2) Limitations due to methodological choices, (3) Decision context and reasons for carrying out the study, (4) Target audience, (5) Comparative studies to be disclosed to the public and (6) Commissioner of the study and other influential actors.”

Directions on how to define the goal are also presented in The Hitch Hiker’s Guide to LCA: “Formulate the *question* of the commissioner as precisely as possible” [emphasis in original] (Baumann and Tillman, 2004, p. 377). This highlights the importance of the LCA analyst’s understanding of the needs of the commissioner, to be able to formulate the purpose of the LCA study.

In summary, the defined goal of an LCA study should present the specific purpose of the study. For this review that means, that the defined goal should present the purpose of the study and should also be possible to be identified and understood in the published LCA studies.

##### 2.5.2. Scope definition

According to the ISO standard (ISO, 2006), the scope of an LCA study is determined in the same phase as the goal definition. A scope definition should, according to Baumann and Tillman (2004), contain specifications of the modelling, which should be consistent with the goal of the study. These specifications include the choice of impact categories, time horizon, system boundaries and functional unit. In the context of CCU, the choice of impact categories answers what results the study communicates. Time horizon is of importance for both the urgency of the climate crisis and also for the potential carbon storage which depends on storage time. System boundaries describe what parts of the real system are included in the modelled system in the LCA. The basis of the chosen functional unit is telling of the purpose and use of the LCA study, as well as its comparability.

**Table 1**  
A table summarising the CCU-specific guidelines regarding goal and scope.

Guidelines	Goal guidance	Scope guidance
<a href="#">von der Assen et al. (2013)</a>	Gives no goal guidance as the focus is on a few pitfalls: treating utilised CO <sub>2</sub> as negative emissions, allocation between the multiple products (from capture and utilisation) and CO <sub>2</sub> storage duration.	Recommends to treat CO <sub>2</sub> as an economic flow. Gives guidance on how to handle multifunctionality (joint evaluation system expansion, otherwise separate functional units). Recommends use of time-dependent GWP when possible.
<a href="#">von der Assen et al. (2014)</a>	Defines the goal as “the question LCA is supposed to answer” and also discusses what LCA cannot answer (e.g., Is X environmentally sustainable?).	Recommends to compare equally (product function, system boundaries), consider all relevant flows, consider CO <sub>2</sub> source, and account for all products.
<a href="#">Langhorst et al. (2022)</a> , earlier versions	Provides a list of four possible research questions that should be used, for comparative assessments which “intend to support decision making”.	Provides a decision tree to choose a functional unit (based on energy, mass etc.), and another for life cycle coverage (system boundaries).
<a href="#">Zimmermann et al. (2020)</a> and <a href="#">Zimmermann et al. (2018)</a>	Recommends to state the class of CCU technology, limitations and identification of commissioner and actors.  The newer version (2022), also provides some more guidance for low TRL technologies.	Recommends that the source of CO <sub>2</sub> should be included within the system boundaries.  Recommends to use specific data when available and state which data is used and the level of data quality needed.
<a href="#">Skone et al. (2022)</a> , earlier version <a href="#">Cooney et al. (2019)</a>	Provides a specific goal (intended application, reasons for carrying out the study, intended audience, public disclosure) that the LCA should have, given that the specific purpose is performing an LCA for reporting in US DOE NETL projects.	Provides a proposed product system and examples of functional units for different products and different system boundaries. Also, proposes a comparison product system.  Provides a list of different LCA expectations for different TRL levels and data representativeness.  Requires GWP and recommends additional impacts and TRACI 2.1 for calculating.  Provides rules on how to display the results and recommends ways to determine completeness, perform sensitivity analysis and document data quality assessment.
<a href="#">Müller et al. (2020a)</a>	Since it is based on the same work as <a href="#">Langhorst et al. (2022)</a> , it provides a similar list of research questions to choose from.	Similar to <a href="#">Langhorst et al. (2022)</a> .
<a href="#">Ramirez et al. (2020)</a>	Presents different decision contexts and presses the importance of a clear goal definition for the decisiveness of the rest of the LCA.	Gives guidance on how to choose a functional unit for different processes (e.g., chemical/material for comparison to its conventional reference product, another unit for comparison of different CCU processes).  Recommends cradle-to-grave system boundary.
<a href="#">Raadal and Modahl (2022)</a>	Gives no goal guidance as the focus is on multifunctionality.	Focuses on solving multifunctionality. Recommends to use system expansion without substitution, treat CO <sub>2</sub> as an economic flow, include energy demand in the functional unit for chemicals and fuels, and analyse more impact categories than only climate change.

### 2.5.3. Types of LCA

Types of LCAs are usually categorised by method (e.g., attributional, consequential, prospective, dynamic) but not use or purpose. Related to understanding the goal of an LCA study, it is worth noting that there are different types and uses of LCA. Bjørn et al. (2018) distinguished between three types of decision contexts (micro-level decision support, meso/macro-level decision support and accounting) and recommend practitioners to state the context in their studies. Another categorisation is proposed by Baumann (1995), who distinguished uses or applications of LCA by type of decision-making context (e.g., strategic decisions, construction and design, procurement and sales) and actors involved (e.g., authorities, companies, individuals, NGOs). Baumann also expressed the need to further identify types of LCA application and improve context specific methodological advice. Due to the versatility of LCA, there are more types of LCAs than the specific decision contexts mentioned in these previous studies.

### 2.6. Synthesis of background

One knowledge need identified for this review is to understand the types of LCA studies on CCU technologies, which relates to both different LCA goals and different studies of CCU systems. Distinguishing features of various CCU systems, such as the source of carbon and the product produced, make key aspects to determine the potential for carbon reduction and carbon storage duration. Given the urgency of decarbonisation, how the time aspect of the technology's reliability and its potential to meet the Paris Agreement is handled in the study needs to be better understood in the performed LCA studies.

To summarise, when reviewing LCA studies of CCU systems it is necessary to both look at types of LCA studies (i.e., goals and scopes) and types of CCU systems. When reviewing the understandability and credibility of the assessments, in particular the definition of the goal, a decisive factor for an LCA study's credibility, becomes a key criterion in the review.

## 3. Method

To evaluate the LCAs of CCU, a systematic search and review of scientific articles was conducted. The review looks specifically at the method choices in the LCAs, with a focus on the matching of goal and scope. Given the context of the climate urgency, the studies were also reviewed with regard to their analysis towards decarbonisation, for example, the consideration of time aspects.

The articles were first reviewed to describe the object of study in the LCA studies conducted and their methodological features. Next, an evaluation of clarity and credibility was made by focusing on the coherence between the stated objectives and the scopes of the LCA studies, the reported results, and the handling of time aspects. Also, a more detailed analysis was conducted on a smaller group of articles. This more detailed analysis aimed to better understand the goal of the studies in their context and to further evaluate how scope is matched to the goal. Lastly, the use of guidelines was analysed to understand what could have affected the method choices in the LCA studies.

### 3.1. Literature search

The relevant articles were found by searching the databases Scopus, Web of Science and Google Scholar. Fig. 1 illustrates the search and selection process. Different variations of the concepts of life cycle assessment and carbon capture and utilisation were used for the search for relevant articles. For LCA: "life cycle", "lifecycle" and "life-cycle" in combination with both "assessment" and "analysis" as both terms were used interchangeably. For carbon: "carbon dioxide", "CO<sub>2</sub>" and "carbon capture". To cover utilisation: utili\*, upgrad\*, reus\*, recycl\*, upcycl\*, conversion or valori\*. Operators NEAR/ and W/ were used to find CCU articles, where the words for carbon capture are within two

words of the words for utilisation. The search string was specified for title, abstract or keywords in Scopus and Web of Science, and modified to be shorter in Google Scholar (to fit the limitations). The search covered everything published by 2022.

For the screening, the tool Rayyan (rayyan.ai) was used to detect duplicates and evaluate the relevance of articles. The abstracts were read to determine if the article would fit in the review. Articles that did not focus on LCA and CCU (e.g., CCS only, catalysts or other materials used in carbon capture etc.) were excluded. Studies related to enhanced oil recovery (EOR) and other studies where the captured carbon was not converted and used in a product (e.g., algae for biomass) were also excluded. The final set of LCA studies on CCU comprised 106 articles that were reviewed.

### 3.2. Review

The following aspects were evaluated in the articles: (1) objects of study: source of carbon, products created, (2) goal definition, (3) scope: system boundaries, (4) reported results and (5) the time aspect.

*Source of carbon.* The source of carbon for the CCU conversion process in the reviewed articles was identified. The source was categorised as either fossil, biogenic or atmospheric, or a mix of them. With this categorisation, it is possible to determine the possibility for net carbon reductions in line with the current IPCC definitions.

*Product(s) created.* The type of products created in the CCU system were categorised by the number of carbon atoms in the molecules: C1, C2, C3 etc. This aspect is of interest from the carbon capture perspective, as it reveals the ratio of CO<sub>2</sub> molecules required for the production of each molecule of the product. This categorisation also provides information on the kind of product produced.

*Goal definition.* To understand the types of LCA studies made and their communicated results, their purpose and methods were analysed. To identify the purpose of an LCA study, the stated goal definition was evaluated. Here, the goal was identified by looking for the words "goal", "aim", "objective" or "purpose" firstly in the method/LCA section of the article and secondly in the introduction of the article.

*Scope.* The scope of each LCA study was examined to see how it was connected to the goal of the study. Many choices are made during the scoping of an LCA, but here, we concentrated on aspects that are telling of the use of each study, in particular the system boundaries and the modelling choices.

*System boundaries.* The technical system boundary was considered, more specifically what parts of the industrial system were represented in the LCA model of the studies, see Fig. 2. This was done by both identifying the stated system boundaries (e.g., cradle-to-gate, cradle-to-grave) and further by examining what was included in the analysis, in terms of the technical system boundaries. In this case, the industrial system was divided into five parts: (1) the source producing emissions captured, (2) the capture process, (3) the CO<sub>2</sub> conversion process, (4) the use of the product and (5) the end of life (see Fig. 2).

To investigate the scopes of the LCA studies in more depth, the modelled parts of the industrial system were mapped in relation to the industrial system framework illustrated in Fig. 2. To simplify the mapping, different starting points in the life cycle were named and the reviewed studies were categorised into groups starting at three different places: the source (the process the flue gases are captured from), the capture (the capture process itself) or feedstock (the input to the conversion process, from CO<sub>2</sub> to CCU product).

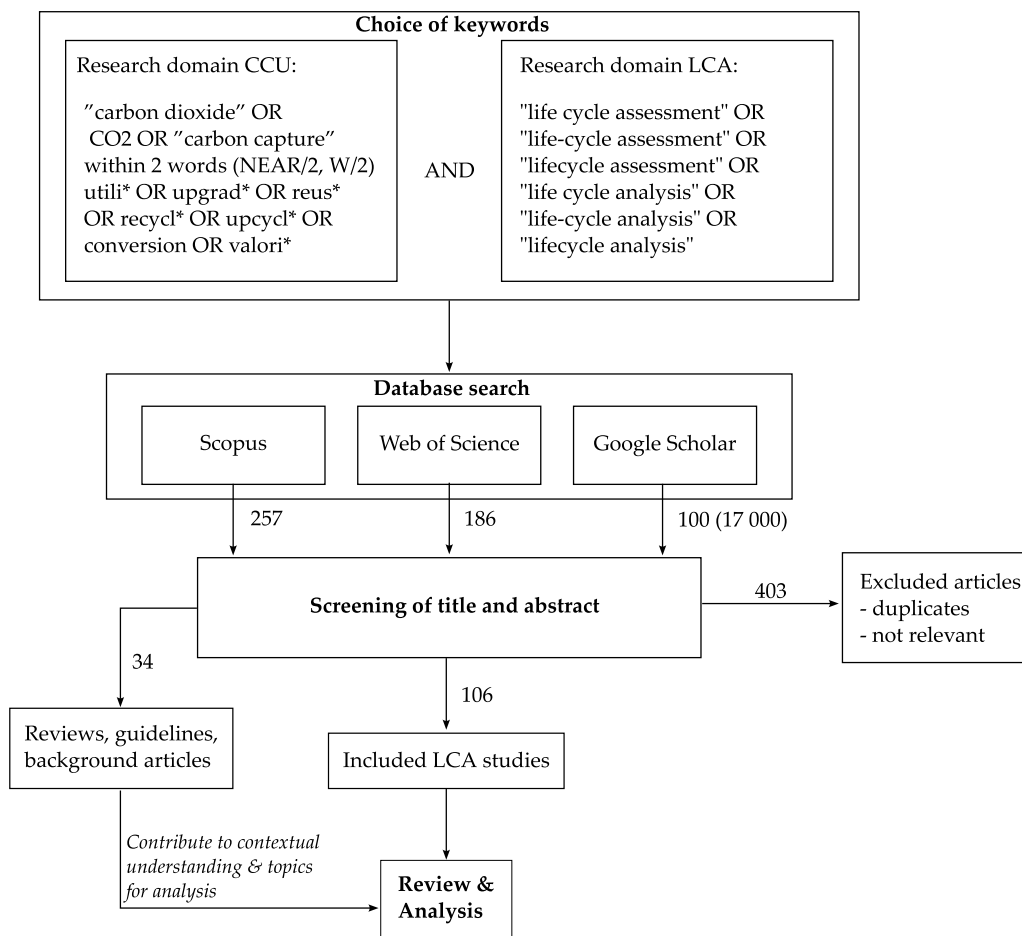


Fig. 1. Method of the literature review.

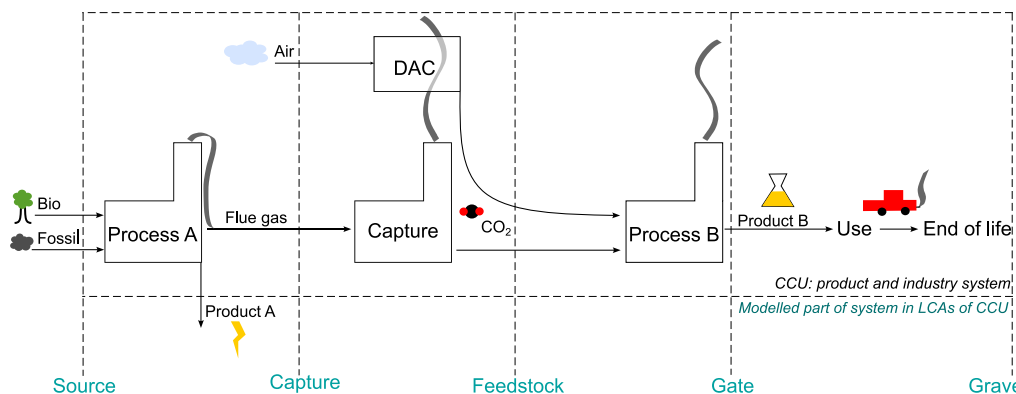


Fig. 2. Industrial system framework and different scopes of LCA models. The vertical lines represent a few different starting and ending points in an industrial system, for modelling the CCU system in LCA studies.

**Reported results.** The reported results of the LCA studies were sorted based on whether they reported a decrease or increase in climate change impact in their comparisons with a reference product or system (e.g., a conventional alternative). For this, the articles were sorted into five categories: (1) negative (reduction below zero), (2) reduced, (3) dependent on scenarios (both increased and reduced impacts), (4) increased impact and (5) a category for studies where no comparison (to a conventional alternative) was made.

The studies reporting negative impacts were reviewed further regarding how this was achieved, for example if specific method choices such as system expansion were used. This was done to understand how negative emissions are accounted for and communicated within

assessments of CCU technologies, and ultimately examine the congruity with decarbonisation.

**The time aspect.** Analysing CCU systems in relation to the climate crisis and the Paris Agreement brings up the importance of time, especially when CO<sub>2</sub> is captured and for how long. *When* is relevant particularly for the emerging technologies of CCU, where the technology is not yet implemented but might be in the future. *For how long* is relevant for the products created, the use of them and for how long they are in use before reaching their end of life. The examined time aspects were:

- the time of the construction of the CCU plant

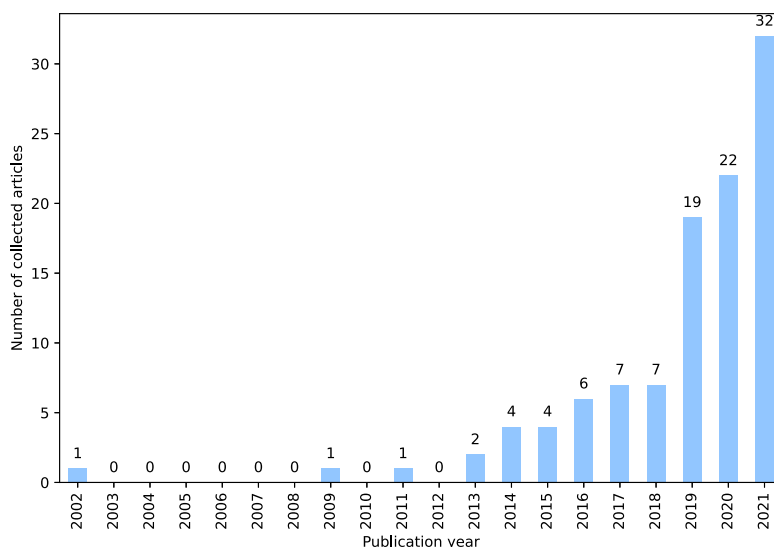


Fig. 3. Number of reviewed LCA articles published each year.

- the carbon payback time, defined as the time it takes to capture the amount of CO<sub>2</sub> through the CCU process to compensate for the impacts of constructing the CCU plant itself
- the lifetime of the product created in the CCU process
- the future developments of the background system, e.g., the future electricity system

Just stating the lifetime of the plant or its components in a study was not considered as handling of the time perspective in relation to urgent climate goals.

### 3.3. Detailed reviews

Two more detailed reviews were conducted: first on a subgroup regarding the match of goal and scope, and second the studies' use of guidelines.

*Analysis of one category of articles.* To better understand the different system boundaries found in the reviewed LCA studies and their connection to the stated goal and the scope aspects of the study, one group representing a category of studies with similar system boundaries was investigated in more detail. This group was analysed on the stated goal, the product studied, the functional unit and the reference case for comparison.

This analysis could in principle be performed for all groups of studies with similar system boundaries but was only done for one group due to time constraints. The group chosen was the one covering the largest part of the industrial system, “source-to-grave” in the industrial system framework (see Fig. 2).

*Use of guidelines.* The adherence to established guidelines was analysed to see if and how the LCA practitioners have followed the existing CCU-specific guidelines. The use of guidelines was deduced by searching for references to the guidelines (identified in Section 2.4). The sentences containing citations conveyed the purpose for which the guidelines were used, specifying exactly which aspects of the guidelines were referenced.

## 4. Results

The systematic literature search and selection process resulted in a set of 106 LCA studies for the review (see Appendix A). The reviewed articles were published between the years 2002 and 2021, with an increasing amount of articles published in recent years (Fig. 3).

### 4.1. Description of the LCA studies

The results of the review showed a diversity of systems under study and types of LCA studies conducted. The goals and the scopes were often hard to determine, so these became a matter for a following more detailed review (see Section 4.2). This section describes the reviewed LCA studies with regard to: (1) objects of study (source of carbon, products created from CCU), (2) goal definition, (3) scope (system boundaries), (4) reported results and (5) the time aspect. For all results, the number of articles is given in parentheses.

#### 4.1.1. Studied objects

The initial categorisation of studies showed that there was a diversity of industrial, production and consumption systems within the CCU systems studied. The studied technical systems varied, featuring different sources of CO<sub>2</sub> feedstock and producers, as well as various types of products generated by the CCU process.

*Source of CO<sub>2</sub> feedstock.* The most common source of CO<sub>2</sub> feedstock was fossil (56), but also other types such as biogenic (14) and atmospheric (4) origin were found in the CCU cases. Some studies were found to study scenarios of either source or a mix of several origins (21). In eleven (11) studies the source of carbon dioxide was not possible to identify.

*Product(s) created in the CCU system.* Many of the CCU products studied in the reviewed articles were C1-chemicals (65) (e.g., methanol, methane, formic acid, formates etc.). Twelve (12) studies considered the production of C2-chemicals, five (5) articles studied C3 products and one (1) of the works evaluated C4 products. Several (22) studies analysed the conversion of CO<sub>2</sub> into materials with many carbon atoms, such as polymers or Fischer–Tropsch fuels. In one (1) of the articles, the carbon content in the CCU product was not specified, as the products created were unspecified products for pharmaceutical applications.

#### 4.1.2. Defined goals

For half of the articles (54), it was not possible to find the *goal of the life cycle assessment* identifiably stated. If the goal of the study was simply to conduct an LCA, this counted as having an unclear goal with the LCA since no identifiable purpose was given (cf. Section 2.5.1). For the remaining articles, four main types of goals were found: (1) determine the environmental impacts, (2) compare the impacts to conventional alternatives, (3) compare different design choices, and (4) find hotspots. Other goals were grouped under the category “other”.

When the goal of the LCA was stated, it was often to determine the environmental impacts of CCU and compare it to some conventional process(es) (20), or just to determine the environmental impact (16). A few (7) studies also aimed to find hotspots, either to compare to a conventional process and find hotspots, or just find hotspots for technology development. In some cases (5) the goal was to compare, not to any conventional process or system, but between different technologies or pathways investigated in the study. Only four (4) studies had more elaborated goal statements:

- determine the environmental impact and “investigate the use of LCA and life cycle thinking early in the green design process”. (Ghavam et al., 2021, p. 5)
- find hotspots, inform policy and technology development and fill a data gap in literature (He et al., 2021)
- project the environmental impacts and find the difference between small- and large-scale cases (Khoo et al., 2020)
- compare to conventional products, and investigate specific research questions: “The goal and scope of the analysis are addressed by the following three research questions: (1) What is the change in product climate and material footprint for the substitution of fossil-based fuels and materials with products based on methanol from recycled CO<sub>2</sub>? (2) Are there trade-offs when the relative change in the product climate and material footprint is normalized against German reference values? (3) How does the defossilization of the electricity grid mix in Germany affect the product climate and material footprint of polypropylene (PP) and fuels from CO<sub>2</sub> recycling in 2020, 2030 and 2050 considering material recycling and waste incineration in the EoL phase of PP?” (Turnau et al., 2020, p. 8424)

Surprisingly, the majority of studies did not clearly report the purpose of the LCA. Just stating the goal as to determine environmental impacts, is in itself not a purpose but rather stating what will be done (cf. Section 2.5.1). In short, while most were unclear about the purpose of the LCA study, those who stated a goal aimed for comparisons and finding “hotspots” as if this would fully explain the scope or the purpose for those studies. Because of the difficulties to understand the goals for the LCAs, we conducted a more detailed analysis of one group of the LCA studies — see 4.2.

#### 4.1.3. Defined system boundaries

The defined system boundaries in the reviewed LCA studies varied, many (53) articles reported using cradle-to-gate boundaries in their assessment and fewer (15) studies stated that it was a cradle-to-gate study. Only one (1) article used the phrasing “gate-to-gate” (Meunier et al., 2020).

Some studies were more specific, e.g., cradle-to-gate for electricity and well-to-wheel for transportation (Al-Qahtani et al., 2020), cradle-to-cradle (Batuecas et al., 2021), cradle-to-factory gate plus end-of-life (Fernández-Dacosta et al., 2019). A large part of the reviewed articles (31) did not describe nor explain the system boundaries in the text, the boundaries were only presented in figures.

When comparing the modelled systems to the real industrial system (visualised in Fig. 4), it was found that there is a spread between the different “cradles” in the articles. Cradle-to-gate was found to be source-to-gate (29), capture-to-gate (39) or feedstock-to-gate (19), while cradle-to-grave was found to be source-to-grave (9), capture-to-grave (8) or feedstock-to-grave (2). The one (1) gate-to-gate study was one of the 39 capture-to-gate studies in this framework. Arguably, more than one of the reviewed studies could be called gate-to-gate since the “cradles” capture and feedstock can also be seen as “gates” of the preceding processes.

#### 4.1.4. Results reported in the reviewed LCA studies

Half (53) of the 106 reviewed articles reported results solely related to climate change, with many (34) focusing exclusively on CO<sub>2</sub>-equivalent emissions. Some (19) included one more impact category in their results, often fossil resource depletion or energy demand. The remaining half (53) covered a range of impact categories, from three to eighteen. Since all studies had one impact category in common (climate change), only this impact was investigated when reviewing the reported decarbonisation results.

A common comparison (88 of 106) was to some conventional product or production system. The remaining (18) studies involved other kinds of comparisons, such as comparing different process routes or technologies, or performing stand-alone studies mapping the impacts of the studied CCU product or system.

About half of the studies (47) reported a reduced impact, even negative in some cases (7) (see Fig. 5). Some studies (34) reported scenarios with both higher and lower impact, with some (12) reporting negative results in at least one analysed scenario. In contrast, only seven (7) studies reported a higher impact. In the studies where no comparison to conventional alternatives was made (18), a few (8) still arrived at negative results. In total, a quarter of the studies (27 of 106) reported negative results.

Two main ways to arrive at negative results were identified: accounting for the uptake of CO<sub>2</sub> as a negative impact and the avoided burden of production or by offsetting conventional alternatives. For instance, in the LCA study by Yue et al. (2021), the negative LCA results were due to accounting for CO<sub>2</sub> consumption as a negative emission, even though the source of CO<sub>2</sub> was fossil (coal-fired power plants). González-Garay et al. (2019) accounted for negative contributions from heat recovery and the captured (fossil) CO<sub>2</sub>. Ravikumar et al. (2020) arrived at negative results by offsetting conventional methanol with CCU-methanol. In these cases, avoided impacts are communicated as negative emissions. In other cases, it is clear that the negative results that come from avoided impacts are not negative emissions. For instance, in the consequential LCA by Christensen and Bisinella (2021), credit is given for the avoided burden of heat and electricity, CO<sub>2</sub> production or industrial capture and avoided production of conventional products.

#### 4.1.5. Handling of the time aspect

Most (80) of the articles did not handle the time aspect at all. Of those that handled or discussed time in some way, they either modelled future background scenarios, simulated scale-up or discussed temporary carbon storage, but without reference to the urgency of decarbonisation.

Fifteen (15) of the studies had future background scenarios in their analysis, mostly changes in the electricity mix or energy system. A few also modelled other changes in the background system, e.g., electricity and transportation fuels (Al-Qahtani et al., 2020), production chain projections (Quéheille et al., 2021), base material supply (Rosental et al., 2020), supply market prices (Rumayor et al., 2020). A few studies combined background scenarios with changes in the foreground system: Marbaix et al. (2020) combined background scenarios with scenarios for technical parameters and Quéheille et al. (2021) included scenarios of implementation, production time horizons and electricity demand at industrial scale.

Six (6) of the studies handled scale-up of the technology in some way, e.g., simulated data at a later stage in the development cycle (Cuéllar-Franca et al., 2019; Rumayor et al., 2019; Thonemann and Pizzol, 2019; Thonemann and Schulte, 2019; Guzmán et al., 2021; Paulillo et al., 2021). Paulillo et al. (2021) also modelled future background scenarios for electricity mixes of 2030 and 2050, but otherwise, when the technology is to be implemented was not mentioned in these studies.

Only five (5) studies handled time aspects in some way, and then in relation to temporary or permanent carbon storage, i.e., for how

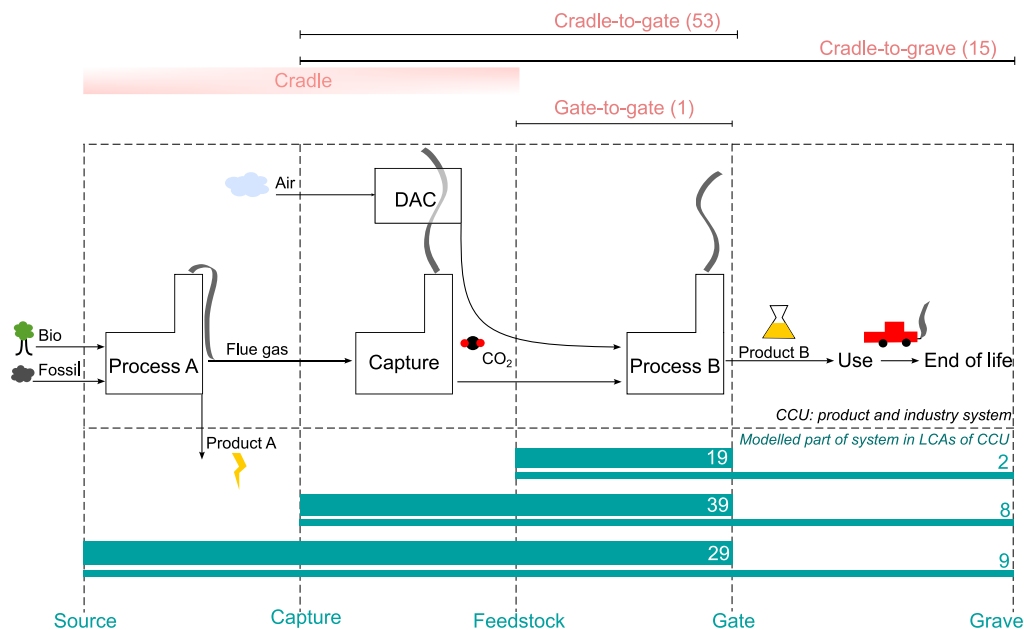


Fig. 4. A representation of the modelled part of the system in the reviewed LCA studies, in relation to the industrial system. Above: system boundaries stated in the reviewed LCA study. Below: identified boundaries with new terminology.

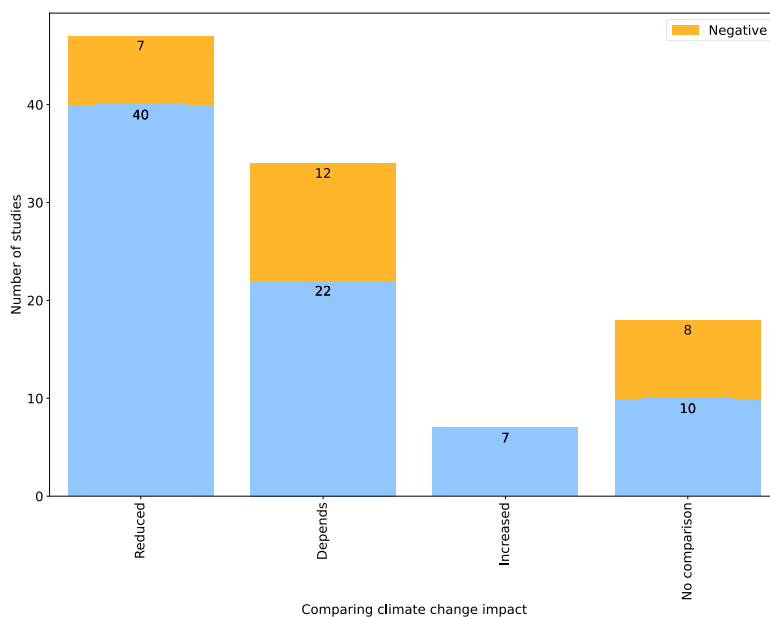


Fig. 5. Number of reviewed LCA articles reporting different climate change impact results. “Reduced” and “Increased” refer to the results compared to conventional alternatives. “Depends” stands for the studies which report both increased and reduced impacts depending on scenarios. “No comparison” stands for standalone studies where the product or system was not compared to a conventional alternative.

long the product holds the carbon captured by the CCU process and possible delayed emissions in the case of temporary storage. Only two (2) studies, with carbonates as the studied product, addressed permanent storage (Kashefi et al., 2020; Ostovari et al., 2020). A few (3) studies discussed temporary storage, but considered it to have no benefit since the same amount of carbon is stored in the conventional alternative (von der Assen et al., 2015; Kästelhön et al., 2019), or the same amount is emitted at the end of life (Fernández-Dacosta et al., 2019).

None of the other decarbonisation-relevant time aspects (the time of the construction of the CCU plant and the carbon payback time) were brought up in the reviewed studies.

#### 4.2. Detailed analysis of one category of articles

The conducted LCA studies appear diverse in terms of study objects and chosen system boundaries but unclear in terms of type of LCA study from their stated goals. A more detailed analysis reveals that, even within a group of studies that seem to examine the same system, there are several types of LCAs. The chosen group for this more detailed review is the group modelling the largest part of the industrial system, from the source of CO<sub>2</sub> to the end of life of the CCU product (see Fig. 4). With the terminology explained in both the method and results of this work, these are source-to-grave studies, comprising in total nine (9) of the 106 reviewed LCA studies. These are listed and summarised in Table 2.

**Table 2**

A table summarising the goals and scopes of the studied subgroup source-to-grave.

Article	Stated goal	CCU product(s)	Functional unit	Reference/comparison
<a href="#">Christensen and Bisinella (2021)</a>	No goal and scope. In the intro: "The purpose of this study is therefore to provide an early and stringent quantification of the climate change impacts of CCU applied to MSWI."	Methane, methanol, dimethyl ether, formic acid	"incineration of one tonne (1000 kg) of wet municipal solid waste (MSW), with the aim of capturing and utilising CO <sub>2</sub> from the flue gas."	Comparison of two different MSWI technologies
<a href="#">Collet et al. (2017)</a>	No goal and scope	Methane	"one MJ produced by combustion of CH <sub>4</sub> in a boiler, based on the lower heating value of CH <sub>4</sub> (50.0 MJ kg <sup>-1</sup> )"	Comparison of five different production scenarios to a fossil reference scenario
<a href="#">Cuéllar-Franca et al. (2015)</a>	No goal and scope, but they describe that "LCA is carried out to estimate environmental impacts and identify hotspots which can then be targeted for improvements in the next design iteration."	Synthetic diesel	"the production and consumption of 1 MJ of synthetic diesel"	Comparison to different types of diesel
<a href="#">Matzen and Demirel (2016)</a>	Goal not found. In the intro: "The purpose of this study is to conduct a life-cycle assessment for novel methanol and DME production for use as alternative fuels."	Methanol and dimethyl ether	Mentioned in different parts of the article: "MWh based on the turbines total life", "1 mt of H <sub>2</sub> ", "1 mt of methanol or 1 mt of DME as the functional unit for the methanol and DME plants, respectively." and "1 MJ of energy, based on the lower heating value of the fuel"	Comparison to natural gas and biomass gasification-based methanol and DME, gasoline, ultra-low sulphur diesel and liquefied natural gas
<a href="#">Meys et al. (2019)</a>	Goal to compare CO <sub>2</sub> -based products to conventional products	Rubbers	1 kg rubber, 0.185 kg of ammonia co-produced and the incineration of 1 kg of rubber as a component of a final elastomer	Comparison to conventional rubbers
<a href="#">Tomatis et al. (2019)</a>	Goal to compare products and find contributors to impacts	Dimethyl ether	For production systems, "one hour operation" and for the impact assessment "a driving distance of 100 km, equivalent to around 1.05 GJ of fuel consumed by a urban bus utilizing diesel engine"	Comparison to the conventional route
<a href="#">van der Giesen et al. (2014)</a>	No goal and scope. Intro: "Here we question if the production of liquid hydrocarbon fuels from CO <sub>2</sub> using existing technologies leads to lower life cycle greenhouse gas emissions and cumulative energy demands than existing liquid fuel routes and aim to answer this question by performing a life cycle assessment (LCA)."	Synthetic hydrocarbon fuels	1 MJ of liquid fuel	Comparison to "relevant existing liquid fuel routes"
<a href="#">Zang et al. (2021)</a>	No goal and scope	Methanol	1 MJ of synthetic methanol	Comparison to conventional methanol produced from natural gas cradle-to-gate and to different fuels cradle-to-grave
<a href="#">Zhang et al. (2020)</a>	No goal and scope	Methane	"1 vkm of distance travelled by an average mid-size CNG passenger vehicle."	Comparison to conventional natural gas

**Note** CNG: compressed natural gas, DME: dimethyl ether, MSWI: municipal solid waste incineration, mt: metric ton.

Even if the goal is not stated, the systematic comparison of the different LCA studies identifies that the studies have been done with different goals. Both functional unit and reference cases differ, even for the same CCU products. For example, for three studies with methanol, Zang et al. (2021) and Matzen and Demirel (2016) compare the impacts of CCU methanol to the impacts of other fuels, while Christensen and Bisinella (2021) compare two different technologies for municipal waste incineration as a source of carbon for methanol production. Collet et al. (2017) and Zhang et al. (2020) both compare CCU methane to the natural gas derived alternative as a reference, but one has a functional unit based on energy and another based on distance, which implies that they had different goals for their LCA studies.

The perspective of the study by Christensen and Bisinella (2021) seems to be from the decision maker at the incineration plant, as the CCU is applied to the incineration plant and the effects of this are investigated. In contrast, Tomatis et al. (2019) seem to have both a production and a consumption perspective, visible in the goal to find contributors to the environmental impacts of the production of the new product and compare the production route to the conventional one. Furthermore, the functional unit is based on both one hour operation of the production system (production) and driving distance (consumption). Additional perspectives can be identified in this small group of studies, for example, the product-focused assessments by Collet et al. (2017) and Meys et al. (2019) who compare the CCU product to conventional alternatives, or the industrial process design of Cuéllar-Franca et al. (2015) who also look for improvements in the design.

This analysis is not exhaustive for finding all the types of assessments that could possibly be found in the full sample of 106 articles, but it still shows the variety in this subgroup of nine studies with the same extent of scope of life cycle system modelling. Among these nine studies, the following types of LCAs were identified:

- Process design improvement
- Production route alternatives
- Product use comparison
- Cradle-to-gate for comparison, focused on the product
- Investment decision for the emitter

These types are not explicitly stated in the goals of these studies but were inferred from analysing their methodologies and units of analysis. It can be concluded, that there is a diversity of studies conducted with varying purposes on the same study objects, CCU systems.

#### 4.3. Use of CCU guidelines in LCA studies

Over half of the reviewed articles (60) did not cite any of the identified CCU-specific guidelines. The number of citations to each guideline report or article is found in Table 3. As can be seen in the table, most cited the works of von der Assen et al. (2013, 2014), then comes the works of Langhorst, McCord, Zimmermann, Müller et al. (2018, 2020, 2022). Typically, both guideline articles by von der Assen et al. (2013, 2014) were cited together and the total number of articles referencing von der Assen and colleagues' guidelines was 41 out of the 46 that reference the CCU-specific guidelines.

Of the articles citing the guidelines (46 in total), many LCA studies (19) did not apply any methodological guidance but used the guideline texts as a source for background facts. Some examples of this are: "A suitable method to benchmark fossil depletion and global warming impacts of CO<sub>2</sub>-based processes to fossil-based processes is life cycle assessment (LCA)" (Sternberg et al., 2017, p. 2244), "LCA is a widely used tool that is used to evaluate the net contribution of the use of carbon dioxide" (Rumayor et al., 2018, p. 2), "Existing studies have provided methodological guidance for LCA of CCU" (Christensen and Bisinella, 2021, p. 755).

In the LCA studies that cite the guidelines for their LCA method guidance (27), the guidelines are used for justifying one or a few

**Table 3**  
Number of studies citing CCU specific guidelines.

Guideline	Studies
von der Assen et al. (2013)	28
von der Assen et al. (2014)	29
Langhorst et al. (2022), including Zimmermann et al. (2020, 2018)	10
Skone et al. (2022), including Cooney et al. (2019)	1
Müller et al. (2020a)	6
Ramírez et al. (2020)	0
No citation of any of the above	60

choices in each study, e.g: to define negative emissions, treating CO<sub>2</sub> as an elementary flow, selection of functional unit, selection of allocation methods, selection of impact categories or justifying taking a consequential approach.

Worth noting is that the articles of von der Assen have been published some years before the other guideline documents. Some of the more recent guidelines might be cited more in future articles on LCA of CCU.

## 5. Analysis

The reviewed studies exhibit a greater diversity in modelled scopes and methods than expected, especially when viewing this relative to the similarly non-specifically stated goals. To better understand what the reviewed studies represent and convey, we analyse the results to answer the research questions.

### 5.1. What types of LCA studies have been conducted on CCU technologies?

The reviewed LCA studies all investigated CCU processes that captured carbon of different origins and produced different products, most common were CCU systems capturing carbon from fossil sources to produce C1-chemicals. Even within this group of studies, there is a diversity of CCU systems. In studies of similar CCU systems there is also a diversity of types of LCA studies conducted, due to different purposes of analysis. Nevertheless, a majority of the studies reports results that indicate that the CCUs lead to some extent of decarbonisation.

The location of carbon capture in the industrial system varies, influencing the modelling in the LCA study and the handling of captured CO<sub>2</sub>. The framework in Fig. 4 highlights the different scopes of these studies, distinguishing between source-to-gate, capture-to-gate and feedstock-to-gate studies. This framework helped distinguish between different scopes of the LCA modelling of CCU, and allowed for more accurate mapping in industrial systems represented in the LCA models. This lead to differences in analysis and interpretation of results.

With such a variation of scopes, one might presume these to represent several types of LCA studies. However, the examination of methodological features (stated goal, system boundaries, product, reported results) revealed no distinct pattern within each group of articles. Moreover, since the goal for the LCA was not clearly stated in most articles, it is not possible to know if the scope reflects the study's purpose. In those studies where the goal was defined, the goal was described but not explained. Despite this, the purpose of a study can often be inferred from its scope and results. Even when inferring the purpose in the detailed review (in Section 4.2), it was found that still within a group of similar system boundaries the purpose of analysis differed. There seems to be different purposes for the studies, e.g., comparing production routes or supporting an investment decision, but such purposes were not reflected in the reported goals.

Furthermore, CCU-specific guidelines seemed to not be used to support scoping of the LCA studies. While many LCA studies refer to the guidelines, few apply the methods suggested in the guideline. The reviewed LCA studies used the guidelines for justifying one or a few method choices that are independent of each other, and not in

a coherent method that connects to the goal definition. As there are some decisions specific to CCU that could need guidance, e.g., multi-functionality, allocation and accounting for negative emissions, there is a demand for some advice. But as all choices depend on the goal definition, the guidelines need to address the connection to the goal of the study to provide proper guidance.

### 5.2. Are results of LCA studies understandable and congruent with the aim of decarbonisation?

Because the goal of the reviewed LCA studies was often not defined, the results become hard to interpret. One of the first steps of a critical review is to determine if the methods used are “relevant with respect to the goal definition” (Baumann and Tillman, 2004). When the goal and context were not stated in the reviewed articles, the relevance of the chosen methods was not possible to understand.

Half of the reviewed articles solely report impact assessment results related to emissions of CO<sub>2</sub>-eq, while a comparable number cover numerous impact categories. Some studies may exhibit a narrow environmental view, focusing excessively on carbon-related impacts. Conversely, studies reporting on multiple impact categories risk diluting key findings and confusing readers with an abundance of results. However, potential trade-offs between lowering climate change impact and increasing other environmental impacts are only found when several impact categories are assessed. Since CCU projects often aim to mitigate climate change impacts, it is logical that this aspect is the most studied, but what other impacts to include depend on the goal of the commissioner and the purpose of the analysis, which are typically not explained in the studies.

The lifetime of the products is important for assessing the carbon abatement potential, as it determines the duration of the storage of carbon in the created products — the carbon retention time. Unfortunately, the lifetime of products was seldom included in the studies since most studies only studied the life cycle up to the factory gate. Since absolute carbon reduction is only achieved when CO<sub>2</sub> is stored durably, it is not possible to determine this in most of these studies since the use of the product was outside the modelled system boundaries.

Many of the reviewed studies arrived at reduced (40) or negative (27) emissions or climate change impact. By definition, net-negative emissions are not possible when capturing fossil carbon (IPCC, 2018; von der Assen et al., 2013; Müller et al., 2020a), yet this was the case in half (14) of the studies reporting negative impacts. In some cases, it was clear that net-negative emissions just were the impact avoided and not negative emissions, but in others, it was not. Furthermore, accounting for avoided impacts does not necessarily result in negative results, sometimes it can also lead to showing a reduced impact of the CCU product compared to a conventional alternative. There is in principle nothing wrong with using substitution in an LCA, but when the goal of the study is not clear there is a risk of misinterpreting such results as carbon removal.

Another issue that matters for the carbon reduction potential of CCU is the rate of decarbonisation or when in time decarbonisation happens in relation to climate goals. Since the majority of the articles under review failed to address time aspects, conducting a thorough analysis of this becomes challenging. Even though some studies considered futures of background scenarios and others scaled up the technology, no study provided any answers on when in time the systems will be constructed or the carbon payback time.

Consequently, the question whether the studied CCU systems will result in carbon reduction in time for the climate goals cannot be answered with the reviewed studies. To evaluate if decarbonisation can be achieved within a reasonable time frame, the LCA studies need to consider the time aspect of construction, production, use and end of life as well as product lifetimes of the studied CCU systems and products.

## 6. Discussion

The review only included articles published by 2022 and more have been published since then. This is a research limitation that can be expanded in future studies. However, including more articles in the sample would not likely change the main conclusions of the review. Possibly, some guidelines could be cited more, but for example, the guidelines by Ramirez et al. (2020) and Raadal and Modahl (2022) were still not found to be cited by any LCA of CCU study by the year 2024. Furthermore, analysing more groups of the sample in more detail (as was done in Section 4.2), would give more results, but not diverging conclusions. The analysis aimed to showcase differences and parallels within a defined group to explore the types of studies conducted. In other groups, there might be more types, which only strengthens the conclusion that there is a variety of types of LCAs.

### 6.1. Understandability

In the context of decarbonisation efforts in society and the Paris Agreement, we note that there are many different kinds of studies in the body of articles conducting LCA on CCU. We observe that there seems to be a large focus on only climate change in many of these, which has earlier been identified in reviews of CCU by for instance Thonemann (2020), Thonemann et al. (2022). We also found that there is a large amount of studies reporting reduced or even negative impacts for CCU compared to conventional alternatives and we note that some of these arrived at negative emissions through unconventionally accounting for avoided emissions. Similarly, the problem of not differentiating between avoided and removed emissions has been discussed by, for instance, Tanzer and Ramirez (2019) in a review of NETs and by Terlouw et al. (2021) in a review of CDR technologies. Carbon accounting and terminology in the reviewed LCAs and in the definitions by the IPCC do not match, and more decarbonisation is reported than what would have been the case if IPCC terminology would have been used.

In the context of the urgency of decarbonisation efforts, we note that the time aspect is absent in most of the studies except when it comes to modelling future background scenarios and, in a few cases, discussions about the storage time in products. In a discussion of time and temporal carbon storage, Ramirez (2022) gave an overview of the average lifetimes of products: the majority of probable CCU products, i.e., plastics or fuels and chemicals, have lifetimes of weeks to months and only several years for some long-lived products like textiles, electronics or construction materials. In our review, most studies focused on C1-chemicals, which typically have lifetimes in the weeks to months range but could also be used in applications that retain the carbon for a slightly longer period. Therefore, it is crucial to handle these time aspects in LCA studies of CCU products. Without this, it becomes impossible to determine if examined CCU systems are sensible in relation to the 1.5 °C goal.

### 6.2. About LCA methodological practice

We also found that CCU-specific guidelines were not much used for methodological guidance in the conducted LCA studies. Some of the guidelines have a strong focus on the harmonisation and standardisation of the LCA methods (e.g., Sick et al., 2020; Müller et al., 2020a; Langhorst et al., 2022). Standardisation of LCAs can be the solution for some specific purposes, such as environmental product declarations (EPDs) for different products. However, considering the multitude of CCU systems found in this review that could be assessed and the diverse purposes of analysis, there are various types of LCA studies employing different methods. One standardised way of assessment would likely be insufficient to cover all possible variations of unique studies that serve their purposes. Therefore, more goal-specific guidelines are needed. The guidelines also need to give better guidance on disclosure of purpose of the analysis (e.g., in the goal definition) and how to explain

methodological choices to help the LCA practitioners in the reporting of their work.

A similar lack of guidance on the connection between goal definition and method choices in LCA standards and guidelines has been identified by Ahlgren et al. (2015), in the context of LCA studies of biorefinery systems. The authors discussed this issue mainly in connection to the choice of attributional or consequential LCA, but in our review we consider the goal definition to be decisive for all methodological choices.

Diverging methods of LCA studies have been discovered in earlier reviews in both CCU and other fields, but the proposed solution has been standardisation or harmonisation (e.g., Thonemann et al., 2022; Garcia-Garcia et al., 2021; Abd Rashid and Yusoff, 2015; Valente et al., 2016; Mulya et al., 2022; Blanco-Cejas et al., 2023). In contrast to these approaches, we embrace diversity and acknowledge that LCA studies for different purposes should be different. However, we find the issue of not communicating the purpose and context of the analysis the main flaw in LCA publication practice.

The lack of clearly stated goals seems to not only be a problem for LCA of CCU systems but has also been found in other fields. The issue of not defining the goals of the LCA study has earlier been found by Laurent et al. (2014) in a review of LCA studies of solid waste management systems. The authors point out that the missing context and possible uses have implications for the conduction of the LCA. Roßmann et al. (2021) noted the similar flaw of not communicating the application purpose in LCA studies of biofuels, and concluded also that this makes the LCA studies not comparable and possibly unusable because the assumptions made are not justified. Instead of speculating on reasons for this lack, further studies are needed.

The issue of not communicating the goal, context and purpose of the LCA is also a lack of transparency. A lack of transparency has been found to be an issue also in previous reviews of LCA of CCU, e.g., by Thonemann et al. (2022). Although some of the reviewed studies were transparent on their goal (e.g., to determine the environmental impacts of a system or a product) the lack of explanation of why or for what purpose still made it difficult to understand method choices. Hence, only increased transparency without explanations does not make the studies more understandable.

## 7. Conclusions

This review investigated 106 LCA articles on CCU to identify the types of assessments made and to understand what they communicate, especially with regard to decarbonisation and the climate urgency as expressed by the Paris Agreement.

The review revealed that although many of the studies appear to similarly compare CCU products/systems with conventional ones, employing LCA models with seemingly identical system boundaries (for instance, “cradle-to-gate”), the studies are not as homogeneous as they might initially appear. Reasons for this are that the studies cover a variety of CCU products with different applications, model different extents of the industrial system (e.g., different “cradles” in “cradle-to-gate”), and seem to serve different purposes in different applications (e.g., design choices, production/product comparisons or investment decisions).

Determining if CCU systems will deliver relative to their aim of decarbonisation is difficult to say because of unclear definitions in the studies and their failure to consider time aspects. However, since the different purposes of the studies and the reasoning behind the method choices were not easily detectable in the reviewed articles, and goals not explained or even stated, the methodology and the results become difficult to understand. The reasons for why the goals were not stated could be investigated further in future studies.

One aspect for improvement in the community of LCA of CCU, identified in this review, is the reporting of the goal and explanation of methodological decisions relative to the goal. This link is currently

unidentifiable in the LCA studies, but also weak in the existing guidelines. In some cases, there might be a need to recognise standardised guidelines for different types of CCU products for specific goals. However, there is also a need for guidance for the LCA practitioner on how to translate different goal definitions to different scopes and method choices in LCA studies. Furthermore, the adherence to guidelines in the practice of LCA of CCU was found to be limited, which points to that practitioners could use the available guidance more or there is a need for different guidelines.

As it was found through this review, there are many different types of LCAs within the practice of LCA of CCU. The diversity of studies conducted with different purposes is something that needs to be supported in the community of LCA of CCU to allow LCA to be used in various applications, and not counteracted with standardisation efforts.

In LCA practice, there is also a need for improvement in reporting of LCA of CCU studies, especially regarding the purpose of the LCA and addressing its time relevance to the climate urgency. The purpose of the LCA is needed for the understandability of the LCA study, while the time aspect is required for congruity with the aim of decarbonisation. With both dimensions missing in the reviewed LCA articles, it is impossible to determine how the modelling in these studies reflects the purposes of the assessments.

## CRediT authorship contribution statement

**Evelina Nyqvist:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Henrikke Baumann:** Writing – review & editing, Supervision, Conceptualization. **Gulnara Shavaliyeva:** Writing – review & editing, Supervision. **Matty Janssen:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.cesys.2025.100291>.

## Data availability

Data will be made available on request.

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