A Meta-model for Comparing Carbon Capture Storage and Utilisation Technologies using Life Cycle Analysis

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Abstract. This research paper comprehensively reviews current carbon capture and storage (CCS) and carbon capture and utilization (CCU) technologies with the aim of developing a metamodel to make the different approaches comparable. Furthermore, the study examines the different pathways of the technologies in a life cycle analysis (LCA) concerning their efficiency in terms of carbon footprint. The analysis shows that some processes are highly energy-intensive, underlining the need for renewable electricity to minimize CO_2 emissions. However, the study also points out several challenges, including in-complete data and unknown variables that hinder the im-plementation and evaluation of these technologies. In addition, the criticisms and limitations associated with CCS and CCU stress the need for further research and development in this critical area.

Introduction

The Paris Agreement [UnitedNations, 2015] is a crucial milestone in global efforts to mitigate climate change and underlines the urgent need for nations to work together to tackle greenhouse gas emissions. Carbon Capture and Storage (CCS), the process of trapping and storing Carbondioxide (CO_2) emissions, and Carbon Capture and Utilization (CCU), the transformation of CO_2 into valuable products, are crucial technologies for meeting the agreement's ambitious targets. In CO_2-intensive industries like the cement industry, capturing and mineralizing 1t of Carbondioxide equivalents (CO_2-Eq) could avoid over 1t of CO_2-Eq emissions by substitution of conventional production Ostovari et al. [2020]. However, the pressing issue is how effectively these technologies can fulfill current commitments and drive progress.

Understanding the opportunities and limitations of these technologies is essential to assesstheir potential to achieve the goals set out in the Paris Agreement. While there is extensive research on the individual aspects of these technologies, there still is a notable gap in synthesizing this knowledge into a co-herent framework. Therefore, our aim is twofold: to consolidate the existing research into a comprehensive overview by developing an over-all meta-model and to assess the collective potential of CCS and CCU to meet global emission reduction targets in terms of their carbon footprint, evaluated by a Life Cycle Assessment (LCA). In addition, our analysis will highlight existing data gaps and areas that require further investigation, thereby contributing to the ongoing discourse on climate change mitigation strategies.

1 Meta-Model

A model is required to execute a LCA calculating the environmental impact of technologies and processes. LCAs of carbon mineralization face the challenge of modeling many different processes and materials simply and comparably. For this reason, we developed a simplified meta-model. The model should consider the complexity of the various processes and feedstocks involved in carbon mineralization.

Problems creating a meta-model

Carbon mineralization involves various processes depending on the technology and feedstock used. These processes include CO_2 capture, the reaction of CO_2 with mineral materials, the transport of materials and products, the pretreatment of feedstocks, the further processing of products, and the utilization of electric energy, heat, and water.

Modeling these processes in a single comprehensive LCA model can be highly complex and resource-intensive.

Some of the specific modeling issues we encountered during this study are:

Technology pathways: various technologies and approaches to carbon mineralization can differ greatly in their processes, materials, and environmental impacts. Modeling this diversity requires the development of a flexible model that can accommodate the different technologies without becoming too detailed.

Feedstock diversity: Feedstocks for carbon mineralization can vary widely and include natural minerals (like olivine or serpentine), waste products (like steel slag, ashes, etc.), and CO_2 from various sources. Each feedstock has different properties and requires different processes and conditions to optimally capture CO_2. The model must analyze the varying environmental impacts resulting from the different resources and energy amounts required by each feedstock.

Interactions between processes: The various carbon mineralization processes interact in complex ways that influence the system's overall performance and environmental impact. These interactions must be integrated and simplified into the model to enable a holistic assessment.

Requirements for the meta-model

We developed a simplified meta-model to analyze the complexity of different carbon mineralization technologies and ensured comparability between different technologies and feedstocks. This meta-model should be an abstract model that simplifies the structure and behavior of the complex system by identifying the most critical factors and relationships. We intended the meta-model to have the following characteristics:

Simplification: The developed meta-model should reduce the complexity of carbon mineralization by eliminating unnecessary details and boundary effects. The goal was to abstract the different processes of the various pathways at a superordinate level and to sum-marise sub-processes.

Comparability: The meta-model should enable the comparability between different technologies and feedstocks by using consistent processes and a common functional unit as an assessment reference to quantify the relevant environmental impacts.

Parameterization: It should be possible to parameterize the meta-model to enable the variation of relevant variables such as energy consumption, input quantities, and outputs. In this way, the user can execute various scenarios and sensitivity analyses to investigate the effetcs ects of changes to the input parameters.

Development of the simplified meta-model

A detailed literature review has been elaborated, but cannot be included in this paper for reasons of space. Based on this review we analyzed various existing LCAs of CCS/CCU processes concerning the technologies, feedstocks, and process steps described. The relevant processes were determined based on these LCAs and the described models. The goal was to identify the intersections between the different models and determine generally applicable processes for the various pathways. The identified processes for the meta-model are feedstock supply, CO_2 capture, pre-treatment, carbonation, and post- processing. With the help of these processes, we derived an initial model that serves as the basis for the LCA analysis which is shown in Figure 1. Carbonation itself and the necessary pretreatment are the main processes at the center, accompanied by feedstock supply and CO_2-supply-processes on the input side and the post-processing on the output side. A possible utilization of end-products is not covered by the proposed meta-model because no meaningful generalising model assumption can be made at this point due to the large number of usage options. The next step was to implement this model in the LCA-software Umberto [ifu, 2024] to carry out the LCA for various carbon mineralization pathways.

2 Life Cycle Assessment

LCA is a method used to comprehensively analyze a product's or technology's environmental impact over its life cycle. The ISO 14040 and ISO 14044 [ISO, 2020a,b] standardize and describe the procedure and structure of an LCA. Despite being standardized, LCAs in the field of carbon mineralization are challenging to compare, as critical factors such as the functional unit, system boundaries, and individual processes can be selected differently. For this reason, a guideline for implementing LCAs for carbon capture was used as a basis for this study [Müller et al., 2020].

Goal and scope The main objective of this LCA is to quantify and compare the environmental impact of different carbon mineralization processes with the developed meta-model. Therefore, testing the meta-model with actual data is another study objective. The assessment concentrates on the carbon foot-print caused by the different technologies.

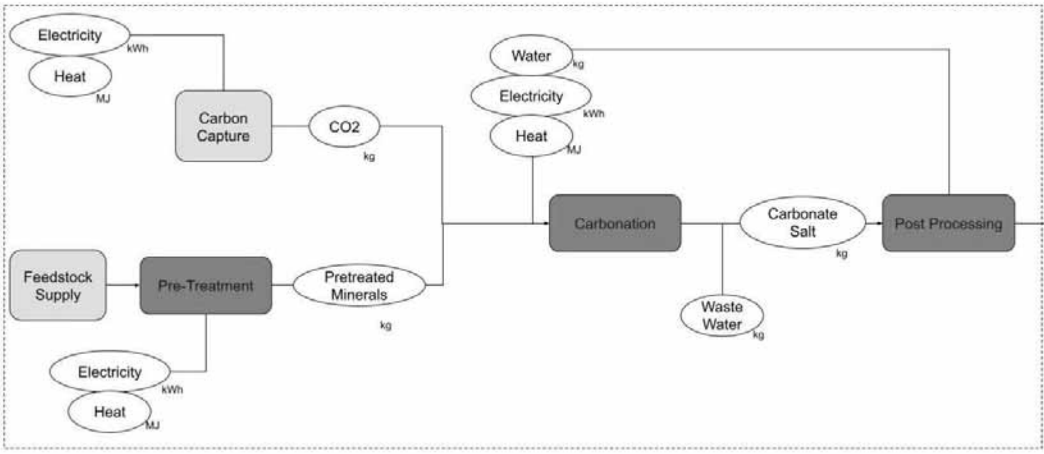

Figure 1: Developed meta-model for LCA.

Such a comparison helps drive the development and implementation of environmentally friendly carbon capture technologies and, thus, significantly contribute to reducing global CO_2 emission. Carbon mineralization is an approach for per-manently storing carbon by reacting and binding carbon dioxide in a stable mineral form [Stokreef et al., 2022]. For this reason, we defined the functional unit in this study as 1t of CO_2 bound by a carbonization process. This choice provides a direct and comparable bench-mark for assessing different carbon capture technolo-gies and processes. With this definition of the functional unit, we can cross-check the CO_2 emissions from all activities during the mineralization. If the emissions are less than 1t of CO_2 eq per tonne of bound CO_2, we can state that the emissions are net-negative, i.e., the process removes CO_2 from the atmosphere.

The system boundaries of this LCA were defined to consider the direct environmental impacts of the carboniza- tion processes. It was decided not to include the use of potential end products that could result from carbonization processes in this analysis. This focus allows a more accurate assessment of the carbonization technologies' environmental impacts without being distracted by variable application contexts, use scenarios and substitutions. The CO_2 supply was included in the system boundary, as the process of CO_2 supply can require a huge amount of energy and is, therefore, a decisive factor in determining the environmental impact of carbon mineralization.

The following two types of CO2 sources were considered in this study: direct air capture and point sources (such as industrial facilities like power plants and factories).

Umberto was used to implement the developed meta-model and calculate the environmental impact. In Umberto, the relevant process parameters and resource inputs were mapped in the model (see supplementary files). Figure 2 shows the implemented Umberto model. To simplify the modeling in Umberto, we made the following assumptions:

- Identical transport (60km by lorry) for the feedstocks was assumed in all pathways
- Electricity generation based on the German electricity mix
- For comparison, label certified electricity from Switzerland with renewable energies
- Heat from natural gas
- Non-existent extraction of olivine and serpentine in Umberto was replaced by a comparable process of limestone extraction

2.1 Life cycle inventory and data situation

We had to obtain reliable data for different carbon mineralization pathways for the analyses on the developed meta-model. Own measurements or actual data from a company were not available. For this reason, we analyzed the data from LCAs found in the literature review to identify relevant data.

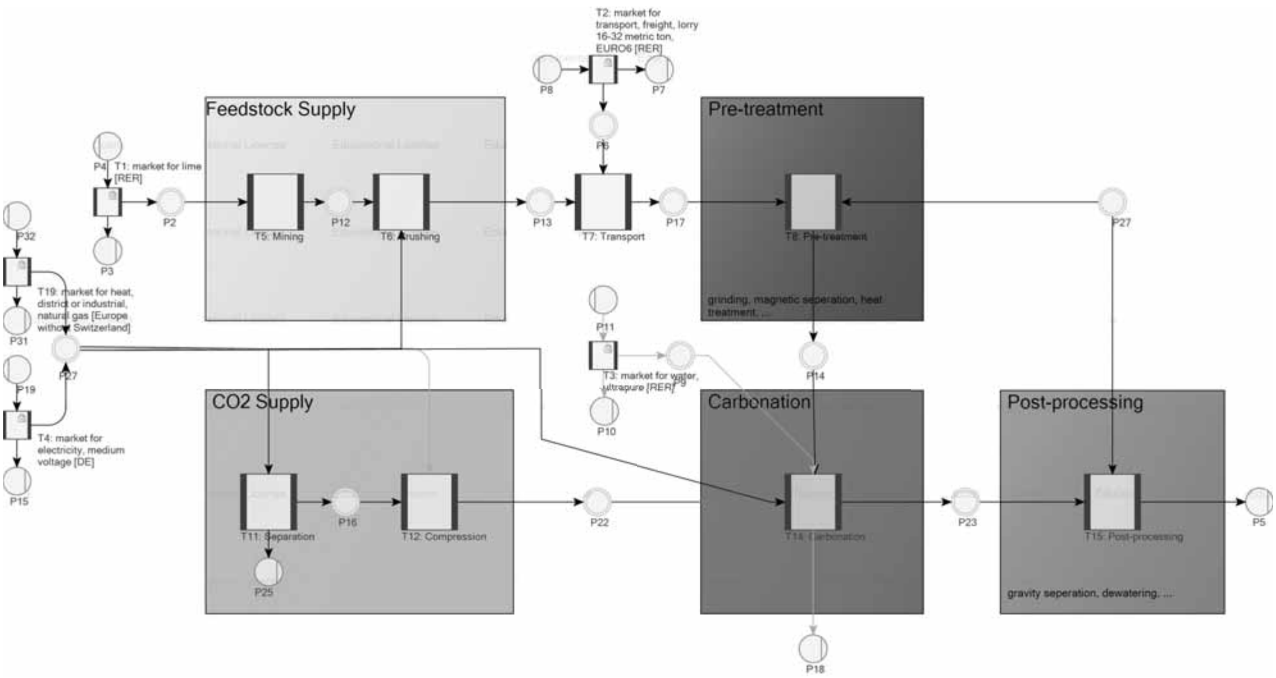

Figure 2: Developed model for LCA in Umberto.

This data research results in a collection of data presented in several tables, sorted according to the processes described in the meta-model (see supplementary files).

For further investigation, we found data on various technology pathways (direct and indirect). It was also important to consider data for dif-ferent feedstocks, as different feedstocks used to have a considerable influence on the mass balances of inputs and outputs. Data was found for olivine, serpentine, and various waste materials such as steel slack [Bargiacchi et al., 2020, Digulla and Bringezu, 2023, Müller et al., 2020, Naraharisetti et al., 2017, Ostovari et al., 2020, Sanna et al., 2012, 2014, William Oconnor et al., 2005]. In addition to the data collected, various libraries and markets were used in Umberto to enable realistic modeling of the energy requirements [ecoinvent, 2023]:

- market for transport, freight, lorry 16-32 metric ton, EURO6 [RER]
- market for lime [RER]
- market for electricity, medium voltage [DE]
- market for electricity, medium voltage, label-certified [CH]
- market for heat, district or industrial, natural gas [Europe without Switzerland]
- market for water, ultrapure [RER] (only for serpen-tine)
- market for blast furnace slag [GLO] (rotary packed bed pathway)

During the data research, we identified several issues and challenges:

Up-to-date data: Up-to-date data is essential to correctly map technological developments and trends to obtain meaningful results in the LCA. Our data re-search revealed that in some cases, only older data (for example William Oconnor et al. [2005]) is available for individual processes and that this data formed the ba-sis for various other LCAs found in the literature re-view [compare Ostovari et al., 2020, Naraharisetti et al., 2017, Kremer et al., 2022]. We must critically question whether this data is still meaningful today and reflects the current state of the art.

Accessibility of the data: In our data research, we have encountered problems with restricted access to specific datasets or data not being published in full. Reasons for this could be data protection, commer-cial interests, or other legal and administrative reasons. Due to the limited data available, we could not guaran-tee completeness across all carbon mineralization path-ways in our LCA. We could only map and analyze the processes and technologies for which data was available.

Accuracy: The accuracy of the data is crucial, as incorrect or inaccurate information can lead to false conclusions. That applies, in particular, to data on the inputs and outputs of the individual processes and on energy consumption. As we have not measured any data, we have to rely on third-party information for the data we use. Note that some of the data come from experiments under laboratory conditions [Wang and Maroto-Valer, 2011, Bodénan et al., 2014, Fabian et al., 2010, Romão et al., 2012]. For this reason, we can only make limited statements about our results for industrial and scaled applications where other conditions may exist.

Consistency: Data consistency is a critical factor in comparing different studies, technologies, and locations. As already described, there is the problem that sometimes only limited data can be retrieved, or data is only available for individual processes. For this reason, we combined our data from different sources. This results in a loss of consistency, as data generated under different conditions and for different purposes is correlated and summarized.

2.2 Life cycle impact assessment

The created meta-model enables the modeling of different CCS methods but builds on a limited data situation. In order to obtain meaningful results with the meta-model, we attempted to perform the impact analyses with data that was as coherent as possible. For this reason, this impact assessment focused on modeling the five pathways described in Ostovari et al. [2020]. We implemented the meta-model with the modeling software Umberto LCA+.

Carbonation occurs in the direct pathway with a continuously stirred tank reactor (CSTR) without any intermediate steps. The pre-treatment and carbonation conditions depend on the feedstock. Data for olivine and serpentine were available in the study. Olivine is mined and prepared by grinding and milling in the pre-treatment stage. In the subsequent carbonization, the pulverized olivine reacts with water and CO_2 from the CO_2 supply. After that, the results undergo further processing in the post-processing stage. The procedure with serpentine is the same except for the pre-treatment stage. Magnetic separation isolates the iron, and heat treatment is required. The pathway OlivineCSTR100 is based on the study by Eikeland et al. [2015]. The pathway SerpentineCSTR115 described in Ostovari et al. [2020] referenced results from William Oconnor et al. [2005].

These sources also investigate the direct process using a rotary-packed bed reactor (RPB). This RPB often uses steel slack as a feedstock. Steel slack is a waste product in various industries, requiring no additional extraction process. After grinding, it can react with CO_2. The RPB process offers several advantages, including using off-gas containing 15-20% CO_2 instead of pure CO_2. Furthermore, the waste product steel slack is utilized as feedstock, resulting in possible cost and energy savings [Ostovari et al., 2020, Pan et al., 2015].

In addition to these direct concepts, Ostovari et al. [2020] describe two indirect pathways examined in this study using the meta-model. These are the Nottingham pathway and the AA pathway. Serpentine is usually the feedstock for both of these pathways. Pre-treatment and post-processing in the AA pathway correspond to the direct concepts, while it takes intermediate steps in the carbonation. The serpentine reacts with ammonium sulfate in a solid-solid reaction, and the actual reaction with CO_2 follows afterward [Romão et al., 2012]. In the Nottingham pathway, the actual carbonation also takes place in two steps: first, an aqueous extraction and then an aqueous carbonation. In the Nottingham process, the feedstock supply and the pre-treatment stage are identical to the direct processes, as serpentine is also used as feedstock here. One exception is heat treatment during pre-treatment, which is unnecessary for the Nottingham Pathway. During the carbonation, the serpentine initially reacts with ammonium bisulfate in an aqueous reaction to generate a magnesium-rich solution that reacts with CO_2 in the second stage and binds the CO_2. The described Nottingham Pathway in Ostovari et al. [2020] is based on Wang and Maroto-Valer [2011].

With the modeling, we aimed to analyze which process is responsible for how much of the CO_2 emissions. The model was calculated once with the German electricity mix and heat from natural gas and once with a green electricity mix. Due to the data availability, which usually only contains energy consumption for a single process, we analyzed only CO_2 equivalence. However, this does not mean that other influences are irrelevant; instead, there is insufficient data to provide further information on other aspects.

Figure 3 shows the results for the German electricity mix. The CO_2 equivalence is positive in two methods, implying that the process produces more CO_2 than is stored. In the Rotary packed bed pathway, the CO_2 equivalence for the feedstock supply is negative, as it uses a blast furnace slag here.

Umberto LCA+ rewards further use of this waste product with a negative CO_2 equivalence. For the Nottingham Pathway and Rotary packed bed pathway, no energy is required for the CO_2 supply, as emissions from point sources, such as indus-trial facilities, are used here.

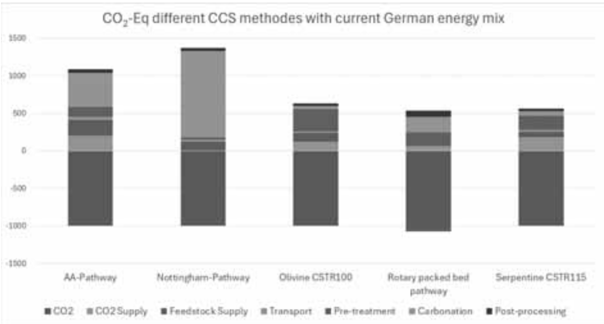

Figure 3: CO_2-eq for different mineralization pathways with German energy mix.

We then calculated all five models using green electricity. Due to the lack of a sustainable heat source in the Ecoinvent database, we also used green electricity as the heat source in these models. The results can be seen in Figure 4. All energy-intensive processes now have a significantly better CO_2 equivalence, and all methods store more CO_2 than they emit. On the other hand, the feedstock supply and transport processes still generate almost the same amount of CO_2 and are therefore responsible for a large proportion of CO_2 emissions.

The latter happens because we include the pre-chains in these steps using data from Ecoinvent. We assume current rock extraction and transport conditions, not future conditions, that could decarbonize these steps.

In all models, CO_2 is permanently bound in rock, i.e., long-term storage. We did not investigate other methods like producing e-fuels, which are burnt later in their lifecycle, emitting CO_2 again.

2.3 Life cycle interpretation

The results from diagrams 3 and 4 show that the energy-intensive processes are responsible for the CO_2-eq in particular. Using renewable electricity can avoid a large proportion of the CO_2 emissions caused by the storage of CO_2. Until this is the case, CCS only makes limited sense. The Nottingham pathway is particularly striking, as this process emits significantly more CO_2 than is stored under the current German electricity mix.

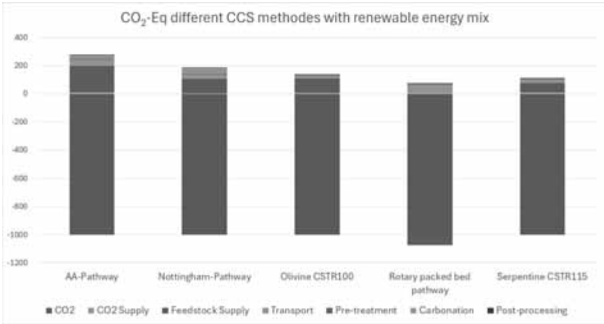

Figure 4: CO_2-eq for different mineralization pathways with renewable energy mix.

That leads to the conclusion that CCS only makes sense if the electricity mix is entirely renewable.

It is worth noting that there is an issue with the data situation. For various process steps, data from different sources, including data obtained in laboratory situations, were used in the analyzed studies. There needs to be empirical data on how energy use in large commercial systems will scale and develop.

3 Discussion

The LCA conducted in this study offers critical insights into the environmental impacts of CCS and CCU technologies. It underpins the urgent need for sustainable energy sources to power these technologies. Our findings highlight the challenges we must address to maximize the potential of CCS and CCU in effectively mitigating CO_2 emissions.

3.1 Energy Intensity and the Need for Renewable Energy

One of the most significant challenges highlighted by our analysis in Chapter 2.3 is the energy intensity of current CCS and CCU processes. The dependency on non-renewable energy sources not only undermines the overall carbon footprint reduction but also raises concerns about these technologies' sustainability and net environmental benefits. The transition to renewable energy sources is imperative to ensure that CCS and CCU technologies contribute positively to climate change mitigation efforts. This shift would align with the global push towards decarbonization and enhance the technologies' appeal from an environmental perspective.

3.2 Data Gaps and the Importance of Comprehensive Data Collection

As elaborated in Chapter 2.1, our study also reveals sub-stantial gaps in the available data, particularly regard-ing up-to-date information on the energy consumption and environmental impacts of CCS and CCU processes. These gaps hinder the ability to make informed deci-sions and assess the technologies' viability and effec-tiveness. Therefore, there is a pressing need for stan-dardized data collection methods and increased trans-parency in reporting to facilitate more robust and com-prehensive LCAs. Our findings align with a consensus; most papers examined in the literature review share that collaboration among academia, industry, and regulatory bodies is essential to establish uniform data collection frameworks and databases.

3.3 Technological Innovation and Scalability

The tone of the examined papers in the detailed literature review also highlights the importance of technological innovation in improving the efficiency and scalability of CCS and CCU technologies. Advances in process optimization, material sciences, and system integration are critical to overcome current limitations and reducing costs. Furthermore, exploring novel CO_2 capture and conversion pathways could open up new avenues for carbon utilization, thereby expanding the potential applications and markets for CCU products. Continued investment in research and development is crucial to accelerating these innovations.

3.4 Policy Implications and the Role of Incentives

The findings from our study show a need for supportive regulatory frameworks and incentives to promote the adoption and development of CCS and CCU technologies. Policies aimed at internalizing the cost of carbon emissions, such as carbon pricing mechanisms, can enhance the economic viability of CCS and CCU. Additionally, targeted subsidies, tax incentives, and funding for research and development can accelerate further development.

4 Summary

This research report examines various studies on CCU and CCS. In addition to reviewing already completed literature analyses, we conducted a literature search for the years 2022-2024. Based on this, we created an overview of the prevailing technology landscape. This foundation enabled us to develop a meta-model and conduct life cycle assessments on various technologies. The LCA results show that the type of electricity used significantly affects the overall efficiency of the technologies, especially in reducing the carbon footprint.

We identified numerous challenges and points of criticism. These include incomplete or outdated data, methodological weaknesses, and a lack of research in certain areas. Nevertheless, the analysis shows that CCS and CCU could contribute to achieving the 1.5-degree target of the Paris Agreement. The paper underlines the importance of further research and development in this area to fully exploit the potential of CCS and CCU and achieve the goals of the Paris Agreement.

5 Outlook

Looking to the future of these technologies, it is clear that despite the progress made in developing CCS and CCU, there still needs to be more research. In particular, existing data gaps need to be closed to make informed decisions about implementing and scaling these technologies.

A key focus of future research should be on improving the accuracy and completeness of available data. Achieving this demands increased collaboration between government agencies, research institutions, and industry partners to establish uniform standards for data collection and provide comprehensive data sets.

In addition, we need methodological improvements to enhance the robustness of life cycle assessments and better understand potential environmental, economic, and social impacts. New modeling and simulation approaches could help capture the systems' complexity and provide more accurate results.

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