Environmental and resource effects of CCU – a literature study

Delivery A2-1 in the 'CCUS Verdiskapingspotensialet' project

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Summary

The main goal of this study was to examine how different CCU routes perform environmentally and regarding resource efficiency. The report is a delivery in the 'CCUS Verdiskapingspotensialet - næringsutvikling og innovasjon' project for the Viken region (application no. 2022-0796).

The literature study has focused on finding reliable and quality assured LCA (Life Cycle Assessment)-based climate change results based on a common functional unit, or a unit which can be recalculated to a common functional unit based on information given in the paper. A common functional unit is needed to be able to make a fair comparison. To obtain this, NORSUS has searched for papers published in scientific journals. Quantitative results have only been included from papers which follow the recommended methodology for LCA of CCS and CCU systems; this being connected to system boundaries, the use of system expansion to solve multifunctionality, the inclusion of reference systems, and the definition of CCU. The functional unit for the quantitative results of this study is 1 tonne of CO_2 removed/captured.

NORSUS has focused on impacts on climate change in this study. For studies in which indicators beyond climate change have also been considered, results have been described in the text.

Four scenarios have been included to account for different electricity mixes in society. It should be emphasised that the CCU processes are assumed to be powered by renewable electricity in all scenarios.

The number of studies found for numerical comparison are not large enough to conclude based on statistical evidence. Other aspects of uncertainties are that the studies might have used different methods for calculating climate change and other environmental impacts, background databases might be different, and reference cases and time scenarios probably have been defined differently. The papers found are all desktop studies, as none describes physical facilities running today. It should be emphasised that this is a literature study, and the results and conclusions are based on the findings herein. However, since the results harmonise with the Gibbs free energy levels for chemicals/fuels, CO_2, and mineralised CO_2, NORSUS finds the following conclusions for the different CCU product categories justified for climate change:

- For chemicals and fuels:
    - Today and in the near future, CCS systems have a better performance than CCU systems. Not capturing CO_2 at all can also perform better than a CCU system.
    - In a fully decarbonised future for electricity grid mix and in 'electricity lock-in' situations, CCU systems are preferable.
    - The reason for the diverging conclusions depending on time horizon is the large consumption of renewable electricity in the process of converting CO_2 into chemicals/fuels. This electricity can, in the compared systems, be used to substitute other electricity sources.
- For direct use of CO_2:
    - Only today's situation is analysed, showing that direct use of CO_2 is beneficial.
- For mineralisation:
    - CCU systems where CO_2 is mineralised have a better performance than CCS systems. How much better depends largely on the climate burden of the product being substituted by mineralised CO_2.

An important aspect to consider when developing strategies on a political level, is whether suboptimisation can be tolerated as a means to develop technology and markets for a fossil free future. This is relevant, for example, for the aviation sector.

For environmental indicators other than climate change, information in literature is not consistent enough to make any numerical comparison. There is a large variation on which and how many indicators are included, and transparency on which method is used for each environmental impact indicator is sometimes lacking. Still, direct use of CO_2 seems to lead to environmental gains. For CCU producing chemicals/fuels and for CCU by mineralisation, literature reports both increased and decreased environmental burdens. NORSUS emphasises that for environmental indicators other than climate change, our considerations are preliminary, and that the literature basis used is not suitable for making any robust conclusions.

Contents

1 Introduction

This report documents the work performed during activity A2-1 in the ‘CCUS Verdiskapingspotensialet - næringsutvikling og innovasjon’ project for the Viken region (application no. 2022-0796). The main goal of activity 2 was to map the potential environmental and resource effects of use of CO_2 in Viken, and one of the activities to achieve this goal was to perform this literature study.

2 Methods

2.1 Goal and scope

The main goal of this study was to examine how different CCU routes perform environmentally and regarding resource efficiency. To obtain this, a literature study has been conducted. The literature study has focused on finding reliable and quality assured LCA (Life Cycle Assessment)-based climate change results based on a common functional unit, or a unit which can be recalculated to a common functional unit based on information given in the paper. A common functional unit is needed to be able to make a fair comparison. To obtain this, NORSUS has searched for papers published in scientific journals. Papers without quantitative results, which rather focused on methodology for CCS and CCU systems have been included as well. Quantitative results have only been included from papers which follow the recommended methodology for LCA of CCS and CCU systems; this being connected to system boundaries, the use of system expansion to solve multifunctionality, the inclusion of reference systems, and the definition of CCU (von der Assen et al., 2013, Abanades et al., 2017, Zimmermann et al., 2018). Studies in which CCS results are given have been included in our comparisons along with the CCU results. The term ‘CCUS’ has been used primarily for studies combining CCS and CCU.

The literature study has been guided by the following steps:

- Identification of relevant literature already known by NORSUS (scientific articles and technical reports)
- Identification and organisation of search strings
- Structured search in Scopus, including forward and backward ‘snowballing’
- Documentation of the search process
- Reading literature while narrowing down the amount of relevant documents
- Making summaries of the relevant documents
- Adding one NORSUS report to gain more data for direct use of CO_2
- Extraction and recalculation of data for comparison by a common functional unit

The study has used the definition of CCU as given by von der Assen (von der Assen et al., 2013): *‘CCU comprises both industrial capture to obtain concentrated CO_2, and separate functional utilization of this CO_2. Industrial capture includes scrubbing CO_2 directly from the atmosphere or from CO_2 point-sources such as fossil-fuelled power plants. A functional utilization of concentrated CO_2 means that the utilization process fulfils a function beyond storing CO_2. This function can be direct utilization of CO_2 as a product, e.g. as a solvent, or conversion of CO_2 into other products such as fuels. Processes that simply store CO_2 without further utilization are considered as carbon capture and storage (CCS). Biological processes that capture and utilize CO_2 simultaneously (bio-fixation) are excluded in our definition.’* (Underlining made by NORSUS.) Hence, activities, including use of biochar and recycling of carbon from plastics, have not been included. The same goes for naturally occurring growth of plants without human interruption. Growth of biomass based on industrial capture of CO_2, and cases in which the capture and utilisation processes are separated have, however, been included as CCU. Such processes have been defined as ‘direct use’.

2.2 Functional unit

The functional unit for the quantitative results of this study is 1 tonne of CO_2 removed/captured. For studies where results are given on another basis, the results have been recalculated (if possible) to the chosen functional unit, allowing for a comparative analysis with the other studies. For the reference scenarios, the quantitative results are related to the same amount of CO_2 as in the CCU (and CCS) scenarios, even though the CO_2 is not captured.

2.3 System boundaries

The system boundaries found in the literature are both from cradle to grave and from cradle to gate. Hence, the original, absolute results cannot be compared across studies. The differences in results between the CCU/CCS systems and the reference systems can, however, be compared across studies.

Only studies using system expansion to solve multifunctionality are included. Some studies use system expansion with substitution. This means that the reference system has been included in the CCU/CCS scenarios and these studies are also included.

To account for these differences, the original numerical results found in literature have been transformed so that the results can be compared.

In Figure 1 an illustration of the system expansion principle is shown for comparison of a CCU system with a reference system.

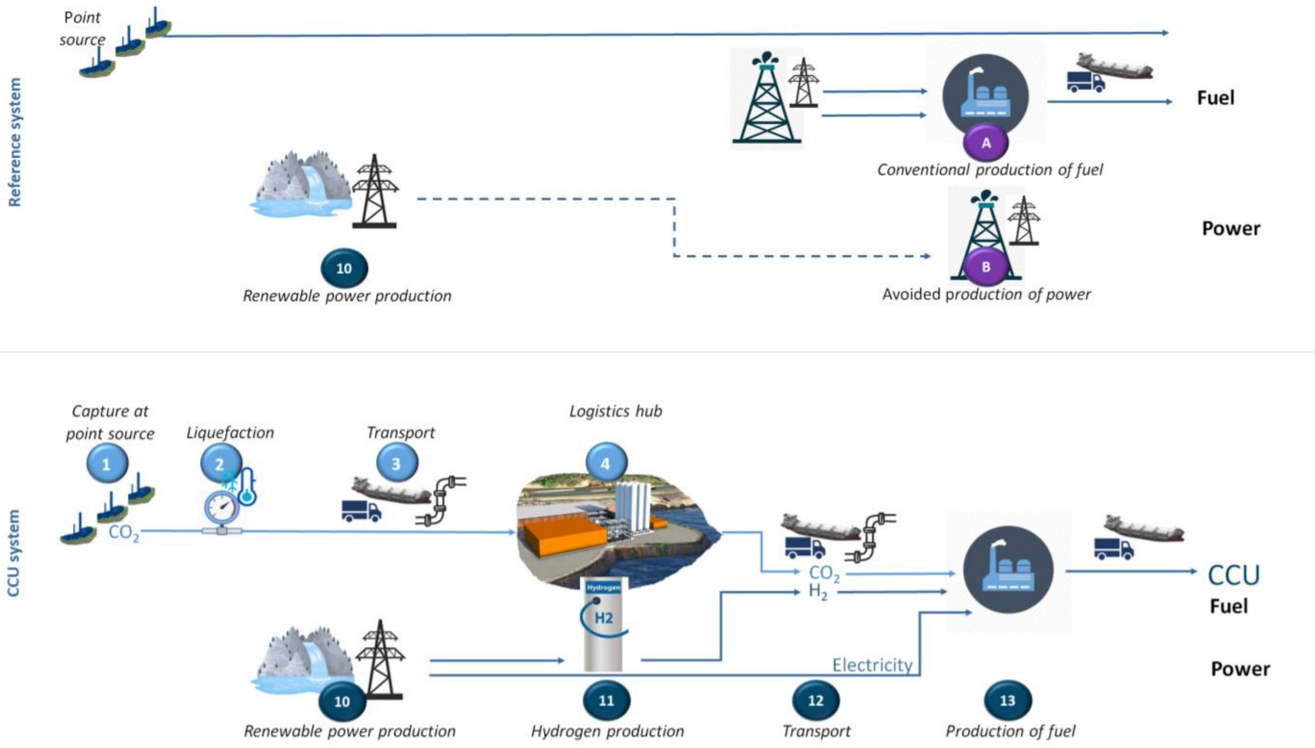

Figure 1 Example of systems using system expansion when comparing a CCU system with a reference system. The systems contain several functions (production at point source, production of fuel and use of large amounts of electricity). Both systems must contain the same functions, in the same amounts, to be comparable.

The application of system expansion ensures that the compared systems provide the same functions to society. As seen from the figure, the reference system must feed the social system with conventionally produced fuel in the same amount as the CCU system, as this fuel is not produced by the system itself. Accordingly, the reference system is provided with the same amount of renewable electricity as the CCU system, which can be used for other purposes because this electricity is not needed by the system itself. Hence, the renewable electricity can substitute other power production sources. Comparisons in this literature study are, hence, always based on burdens and gains for the full systems.

2.4 Allocation

No studies using allocation of burdens between the actors in the CCU chain are included, as this literature search was focused on studies using system expansion to solve multifunctionality (in accordance with recommendations given by von der Assen et al. (2013), Abanades et al. (2017) and Zimmermann et al. (2018)).

2.5 Impact categories

Since the main motivation of CCS/CCU is the reduction of greenhouse gas emissions, NORSUS has focused on impacts on climate change in this study. The goal has been to find numerical results which can be compared. For CCU, the motivation is also to reduce the use of fossil resources. Hence, for studies in which indicators beyond climate change have also been considered, results have been described in the text. Indicators focusing on use of fossil resources can have different names, for example 'fossil depletion' and 'depletion of fossil resources'. High values of these indicators represent high burdens, while negative numbers represent gains.

The studies have used different methods and versions of methods for calculating climate change impacts. Hence, different characterisation factors might have been used. This is a source of error which has not been possible to compensate for when comparing the results.

2.6 Scenarios

According to Müller et al. (2020), who developed guidelines for CCU in a process involving over 40 experts, scenarios for status-quo, a fully decarbonised (sic) future, and a transition scenario shall be included in LCA of CCU. This is recommended to account for the fact that CCU technologies are emerging technologies which require large amounts of renewable electricity. Therefore, assumptions regarding probable use of this electricity for other purposes is of high importance. This principle has been followed in the present literature review, by allowing the same amount of renewable electricity which is required in the CCU system to substitute electricity from the grid mix in the reference/CCS systems, according to the three above-mentioned scenarios. In addition, a fourth scenario has been included to account for a situation where the renewable electricity used for the CCU processes represent a lock-in situation, meaning that it is not available for other purposes. It should be emphasised that the CCU processes are assumed to be powered by renewable electricity in all scenarios. Hence, where results for several situations are presented in literature, the following assumptions represent the substituted electricity in the scenarios:

- Status-quo: a situation representing today's situation for the electricity grid mix, where natural gas is assumed the most probable electricity source to be substituted by renewable electricity in the reference/CCS systems. A climate burden of 650 g CO_2-eqv/kWh is assumed for the natural gas-based power.
- Transition phase: representing a situation in between the status-quo and the fully decarbonised future scenarios for the electricity grid mix, where the electricity being substituted by renewable electricity in the reference/CCS systems is assumed to have a climate burden of 350 g CO_2-eqv/kWh.
- Fully decarbonised[1] future: representing a situation in which the electricity mix is fully based on renewables, and where wind power is assumed the most probable electricity source to be substituted by renewable electricity. A climate burden of 10 g CO_2-eqv/kWh is assumed for wind power.
- 'Electricity lock-in' situation: a situation such that the renewable electricity used for the CCU process is not available for other purposes. Examples can be situations or regions with a surplus of renewable electricity production when, at the same time, the grid capacity is too low to export this excess electricity. This scenario assumes that no electricity is substituted in the reference/CCS systems.

In some studies, the time scenario has not been described (the carbon intensity of the most carbon-intensive component of the power system has not been revealed). In such cases, we have defined the scenarios to the best of our ability, and we have placed them in one of the four scenarios described above.

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[1] The term 'decarbonised future' is used to follow Müller et al. (2020). In this literature review the term is used to describe the electricity system only, and not the future of industrial organic chemistry.

3 Results

3.1 Documentation of the search process

The selection of papers is based on previous knowledge at NORSUS about literature on the CCS/CCU field, and by performing a structured search in Scopus. Forward and backward 'snowballing' was carried out by browsing the references of each paper (cited papers=backward snowballing) and by inspecting which papers are referring to each hit (citing papers=forward snowballing). In this process, the titles and abstracts were scanned for possible hits. After removing duplicates, the first selection consisted of 28 documents.

A second round was performed by reading the documents, by which 12 documents were discarded because they did not fit with the purpose of this project or because results were not possible to recalculate to a common functional unit. Lastly, one NORSUS report was added to gain more data for direct use of CO_2. We were then left with 17 publications for documentation in this report. Of these, ten include numerical climate change results and seven are more methodologically oriented. Eight include a discussion on environmental aspects other than climate change. The process of searching, 'snowballing', removing duplicates and discarding irrelevant and useless documents is described in Table 1 below.

Table 1 Documentation of the search process for finding useful CCS/CCU literature.

Search	Comments	Documents for reading	Documents found by 'snowballing' in Scopus		Duplicates	Comments	Additional documents for reading	
			Forward	Backward				
Documents known from previous work on CCS and CCU at NORSUS	Methodological studies focusing on system boundaries and functional unit (Zimmermann 2018/20, Abanades 2017, von der Assen 2013, and Raadal and Modahl 2022).	4	1 (of 17)	0 (of 74)	0	Connected to Zimmermann	1	8 (-5)
			2 (of 182), refined by 'CCS'	0 (of 44)	0	Connected to Abanades	2	
			6 (of 272), refined to 59 by 'life cycle'	0 (of 81)	2	Connected to Von der Assen 2 already in stock	4	
			0 (of 0)	4 (of 25)	3	Connected to Raadal and Modahl 3 already in stock	1	
	The 2019 NORSUS literature study on CCS/CCU	1		5 (of 64)	3	3 already in stock	2	2 (-2)
	The EDDiCCUt study (NTNU, Utrecht University, Tel-tek) 2017	3		1	1	1 in stock	0	0
				4	4	3 in stock, 1 with incorrect system boundaries	0	
				6	6	2 in stock 2 with incorrect system boundaries 2 without values	0	

Search in Scopus: (CCU OR carbon capture and (utilisation OR utilization)) AND (LCA OR life cycle assessment)	355 hits; refined to 12 hits by 'food'/'feed'.	3 (-2)	4 (of 39)		2	2 in stock	2	2 (-2)
	355 hits; refined to 63 hits by 'direct', of which 4 already in stock.	1	3 (of 47)		0		3	3 (-1)
	355 hits; refined to 19 by 'mineralisation', of which 3 already in stock.	1	0 (of 0)		0		0	
Sum		13						15
Not relevant after all		-2						-10
Addition of one NORSUS report		1						
Documents for documentation		12						5

The excluded papers are shown in Table 2, while the documentation of the 17 most relevant papers can be found in chapter 3.2.

Table 2 Excluded studies after reading of the full publications.

Study	Title	Reason for exclusion
Lardon et al. (2009)	Life-Cycle Assessment of Biodiesel Production from Microalgae	This study focuses on production of biodiesel from microalgae. Only relative numbers are provided and it is unclear whether the CO_2 used is captured. NORSUS assumes that the system under study is a classical bio-fixation case.
Borkowski et al. (2012)	Integrating LCA and thermodynamic Analysis for Sustainability Assessment of Algal Biofuels: Comparison of renewable Diesel vs. Biodiesel	This study compares renewable diesel to algal bodiesel produced from purified CO_2 captured by an amine process. LCA of CCU guidelines (by Zimmermann et al. (2018) and others) are not followed, and environmental burdens are allocated between systems instead of using system expansion.
Thonemann (2020)	Environmental impacts of CO_2-based chemical production: A systematic literature review and meta-analysis	Uses inventories to reproduce results, but capture burdens are not included (CO_2 input was modelled as a waste material) and studies are not excluded regardless of methodology. It is difficult to find a way to relate the FU to captured CO_2.
Turnau et al. (2020)	Material or fuel: comparative cradle-to-grave climate and material footprint analysis for the use of methanol from recycled CO_2	Compares use of methanol from both recycled CO_2 and the conventional route. Several products are compared, and both use and EoL are included in the comparisons. The FU is difficult to relate to.
Di Maria et al. (2020)	Environmental assessment of CO_2 mineralisation for sustainable construction materials	This study concerns LCA of carbonated construction blocks from mineral carbonation of stainless steel slags. These are compared to conventional blocks. System expansion is not used to solve multifunctionality, and the two systems do not deliver the same products to society.
Garcia et al. (2020)	A meta-analysis of the life cycle greenhouse gas balances of microalgae biodiesel	This is a meta-analysis of microalgal production studies. Only bio-fixation routes are considered, and none can be defined as CCU.
Kuo et al. (2021)	Cultivation and Biorefinery of Microalgae (Chlorella sp.) for Producing Biofuels and Other Byproducts: A Review	This is a review of the use of microalgae for fuels, and only bio-fixation studies are included. The maximum CO_2 content in gas is 30% and none include CO_2 capture.
Cruce et al. (2021)	Driving toward sustainable algal fuels: A harmonization of techno-economic and life cycle assessments (review article)	This is a study of biomass, but the system cannot be defined as CCU.
Leonzio et al. (2023)	Life cycle assessment of a carbon capture utilization and storage supply chain in Italy and Germany: Comparison between	Environmental impacts have been allocated between CO_2 and other products from the industry emitting flue gas. The study

	carbon dioxide storage and utilization systems	neither follows the guidelines for LCA of CCU nor does it refer to issues or such guidelines.
Newman and Styring (2023)	The pursuit of methodological harmonization within the holistic sustainability assessment of CCU projects: A history and critical review	This study concerns harmonisation of methods for LCA, TEA and social sustainability, for CCU projects, not focusing on LCA specifically.
Tu et al. (2017)	Meta-analysis and Harmonization of Life Cycle Assessment Studies for Algae Biofuels	This is a meta-analysis and reproduction of results using harmonised inventory data, concerning algae biodiesel. Only bio-fixation routes are considered, and none can be defined as CCU.
Chowdhury et al. (2023)	Life Cycle Based GHG Emissions from Algae Based Bioenergy with a Special Emphasis on Climate Change Indicators and Their Uses in Dynamic LCA: A Review	This paper provides a review of current biofuel production, primarily through alga-based routes. None can be regarded as CCU as only bio-fixation routes are included.

It should be noted that the European Commission's methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuel of non-biological origin and from recycled carbon fuels (EuropeanCommission, 2023) has not been part of this study. The reasoning being that this study focuses on LCA-based literature which can be used for assessing climate and resource effects of different CCU products compared to relevant reference systems. The above-mentioned EU method presents a method for assessing greenhouse gas emissions savings from fuel in order to calculate whether the minimum greenhouse gas emission saving threshold of 70% is reached (European Commission, 2018). (Underlining by NORSUS.) The EU method does not account for alternative use of the electricity needed for transforming CO_2 to a CCU fuel.

3.2 Summary of the most interesting papers

The summaries are presented by CCU product category and year; ordered chronologically from oldest to newest, in this chapter. The CCU products have been sorted into three main categories: chemicals/fuels, direct use of CO_2 and mineralisation. In the 'direct use' category, systems using CO_2 without further technological processing after capture/upgrading is placed. This means, for example, use of CO_2 for plants and algae production. In addition, a chapter containing papers focusing on CCS/CCU methodological issues is included. Papers focusing both on CCS/CCU methodology and on presenting numerical results have been placed under the methodology headline.

Information from the abstracts have been used, in addition to specific information in the main text, to sum up the most relevant information for this literature study. For each paper, the description starts with a table summarising the main information: the CCU product in focus, whether the CCS/CCU methodology is focused on, which numerical results are included (if any) and whether the results have been used directly or if they have been recalculated to fit with the common functional unit. The following symbols are used in these tables:

v	Means 'yes' or 'included'
-	Means 'not included'

Numerical results are found in chapter 3.3.

3.2.1 Papers focusing on CCS/CCU methodology

Abanades, Rubin, Mazzotti and Herzog (2017) in Energy and Environmental Science: On the climate change mitigation potential of CO_2 conversion to fuels

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Methanol	v	v	-	4 (more scenarios available)	v

In this paper, the goal is to propose and illustrate a framework for assessing CCU processes. A strong focus is on system boundaries and comparability. The CCU system is compared with a reference system producing the same product (methanol) without any CO_2 mitigation, and a CCS system that mitigates CO_2 while providing the same fuel product. CO_2 is captured from a hypothetical industrial source. The authors also generalise the discussion to other CO_2 conversion schemes by defining an idealised CCU system. The MeOH analysis shows that, as long as fossil fuel power plants remain on the grid, CCU is an inferior mitigation option compared to a system with CCS producing the same fuel without CO_2 utilisation. Not until the CO_2 emission rate of the most carbon-intensive components of the power system falls below 55 g CO_2-eqv/kWh does the CCU system begin to avoid more emissions than the CCU system.

The paper contains comparable results for the three systems for a range of carbon intensities of the power system. We have used results for four scenarios for each of these three systems; a status quo scenario, a transition phase, a fully decarbonised future, and an ‘electricity lock-in’ situation. The numbers have been recalculated to the chosen functional unit for this literature study, to be able to compare with results from other studies.

Zimmermann, Wunderlich, Buchner, Müller, Armstrong, Michailos, Marxen, Naims, Mason, Stokes, and Williams (2018) in publicly available report from Technische Universität Berlin, RWTH Aachen University, The University of Sheffield, Institute for Advanced Sustainability Studies e.V. Potsdam and CO_2 Sciences on behalf of The Global CO_2 Initiative/The World Economic Forum: Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization (Zimmermann et al., 2018)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
-	v	-	-	-	-

The authors claim that the methods applied to perform TEA and LCA are currently (as of 2018) lacking standardisation in academia and industry across most CO_2 utilisation fields. Hence, ‘apples-to-apples’ comparisons of different technologies are difficult. The aim of the project was to develop a standardised approach and guidelines for both TEA and LCA for CO_2 utilisation, intended to substantially reduce ambiguity in methodological choices and enhance the transparency and comparability of both TEA and LCA results. The guidelines were developed based on an extensive literature study and the input of two expert workshops, allowing for a close participation of the CCU community. Setting system boundaries for multifunctionality is highlighted as one of the main pitfalls for LCA of CCU, and system expansion is recommended for solving this issue.

For comparison with CCU systems, the reference process shall be modelled as the average market mix if further information is missing, and no large-scale structural changes occur. The current best available technology should be used as the reference technology. The difference between avoided and negative emissions are also discussed. Scenario analyses shall represent status-quo, a fully decarbonised future, and a transition phase.

Müller, Kätelhorn, Bachmann, Zimmermann, Sternberg and Bardow (2020) in Frontiers in Energy Research: A guideline for Life Cycle Assessment of Carbon Capture and Utilization (Müller et al., 2020)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
-	v	-	-	-	-

This paper builds on the study of Zimmermann et al. (2018). The authors describe how differing methodological choices in LCA can lead to large differences in results for CCU systems; and that one specific issue is the double role of CO_2 as an emission and a feedstock. As an example, the authors refer to studies of CO_2-based methanol, where cradle-to-gate carbon footprints range from -1,7 to +9,7 kg CO_2-eqv/kg methanol. The authors state that the current lack of a consistent basis for LCA of CCU hampers proper decision making and may also lead to sub-optimal decisions. In the paper, the authors present a comprehensive guideline for LCA of CCU technologies, tailored for a broad scientific audience. The paper contains several decision trees to aid in the choice of functional unit and system boundaries. How to solve multi-functionality and selection of reference processes are also thoroughly described. As CCU technologies are emerging technologies, and assumptions regarding energy use is of high importance, scenarios for status-quo, a fully decarbonised future and a transition scenario shall be included. The guideline has been developed in a collaborative process involving over 40 experts, and it builds upon existing standards and guidelines for LCA. The authors also state that reductions of environmental impacts for CCU products cannot be taken for granted, because high energetic co-reactants are needed to activate the chemically inert CO_2.

Raadal, Booto and Johnsen (2020) in technical report from NORSUS: Status for CCU og bruk av LCA innen CCS og CCU – Litteraturstudie (In Norwegian. Translated title: Status for CCU and use of LCA for CCS and CCU – a literature study) (Raadal et al., 2020)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
-	v	-	-	-	-

This report documents the status for use of CCU and the status for LCA methodology used on CCS and CCU. The authors conclude that the categories which stand out as most focused with regard to CCU are biological conversion (algae, chemicals), chemical conversion (chemicals, hydrocarbons), and mineralisation (for example for use in concrete). None of the studies considered turned out to follow the guidelines by von der Assen et al. (2013), Abanades et al. (2017), and Zimmermann et al. (2018) with regard to system boundaries. The few numerical results included in this report are given for different functional units and they are not compared with any references. The authors stress that for CCS in general, the literature shows that while the environmental burden decreases for climate change, the burdens increase for all other indicators.

Peres, Resende, Nunes and Morais (2022) in Clean Technologies (review paper): Advances in Carbon Capture and Use (CCU) Technologies: A Comprehensive Review and CO_2 Mitigation Potential Analysis (Peres et al., 2022)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
-	v	-	-	-	-

The authors describe CO_2 capture technologies and possible CCU applications. Sectors for use of CCU are ranged according to global capacity for use of CO_2, however the climate gains or burdens are not mentioned in this ranking. It is stated that both CCS and CCU technologies effectively can contribute to creating negative greenhouse gas emissions, but this is not followed by specific citations or numbers. It is also stated that these technologies (CCS and CCU) are energy intensive, requiring significant initial investments, and that renewable energy must be used to achieve environmental improvements. The authors do not distinguish between CCS and CCU with respect to energy intensity or environmental effects. They state that there is a lack of reviews on CCU technologies and that there is an urgent need for a comprehensive understanding of them. LCA is mentioned as a promising tool for the future.

D'Amore, Nava, Colbertaldo, Visconti and Romano (2023) in Energy Conversion and Management: Turning CO_2 from fuel combustion into e-fuel? Consider alternative pathways (d'Amore et al., 2023)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
E-fuels	v	-	-	-	-

This study challenges the exploitation of CO_2 from fuel combustion for the synthesis of e-fuels, as opposed to alternative pathways. The study shows that avoiding CO_2 emissions by turning CO_2 from fuel combustion into an e-fuel results in higher electricity demand, higher capital costs, and higher fuel costs than the electrification of heat supply and the direct conversion of the original fuel into a higher value synthetic fuel via electrified reforming. The authors conclude that when a fuel is available, generating process heat and syngas through direct electric heating is generally preferable to the combustion of the same fuel to supply the same heat, followed by electrochemical syngas production from the generated CO_2.

3.2.2 Papers focusing on chemicals/fuels as the CCU product

von der Assen, Jung and Bardow (2013) in Energy & Environmental Science: Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls (von der Assen et al., 2013)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Methanol	v	v	-	1	v

The authors write that CCU analyses based on ad hoc criteria such as the amount of CO_2 utilised, simplified CO_2 balances, or CO_2 storage duration might be useful criteria for very early stages of potential research pathways, still they are insufficient as a basis for decisions on implementations and they may lead to even a qualitatively incorrect environmental evaluation of CCU. Environmental benefits of CCU are therefore not given by default and require a reliable environmental evaluation.

The paper describes typical pitfalls for application of LCA to CCU. These are connected to (i) incorrectly considering utilised CO_2 as negative GHG emissions; (ii) multifunctionality and allocation of emissions between products, and (iii) CO_2 storage duration. To avoid these pitfalls, the authors describe a framework for LCA of CCU in which (i) utilised CO_2 is considered as regular feedstock with its own production emissions; (ii) recommendations for obtaining product-specific LCA results for CCU processes are given (system expansion is, however, recommended if the scope allows for a joint evaluation), and (iii) the CO_2 storage duration is incorporated into a time-resolved global warming metric. The developed framework is illustrated by simplified LCA of CO_2 capture from a power plant, and utilisation for methanol production. A system expansion approach is used so that all systems deliver the same products to society.

The study has not included alternative use of wind power used for the CCU process; hence we have defined the results to represent an 'electricity lock-in' situation. The results have been recalculated to the chosen functional unit for this literature study, to be able to compare with results from other studies. Furthermore, our literature study has not included results dealing with delayed emissions (< 100 years) and time-corrected characterisation factors for global warming allowing for a comparison of results between different studies.

Schakel, Oreggioni, Singh, Strømman and Ramírez (2016) in Journal of CO2 Utilization: Assessing the techno-environmental performance of CO2 utilization via dry reforming of methane for the production of dimethyl ether (Schakel et al., 2016)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Dimethyl ether	-	v	13	v	v

This study explores the techno-environmental performance of CO_2 utilisation through dry reforming of methane into syngas for the production of dimethyl ether (DME). The CO_2 source is a hydrogen production unit at a refinery, where solvent based CO_2 capture is applied. Electricity required for compression of syngas (in the CCU case) is assumed to be delivered by the grid. Hybrid life cycle assessment, using also economical (and not only process) data to develop life cycle inventories, is used to assess the environmental performance. The authors compare a utilisation option to a reference case without CO_2 capture and a case with CO_2 capture and storage, using systems expansion to ensure that all systems deliver equal amounts of products (H_2 and DME). The LCA results indicate that the climate burden for the CCU option is reduced by 8% compared to the reference, while it is 37% higher than the CCS case where CO_2 is stored and DME is produced conventionally. The study has considered several environmental impact categories in addition to climate. The CCS case increases the impact of all other indicators more than that of climate change, while the CCU case reduces the impact of some indicators and increases others. The authors state that the complex environmental trade-offs make it difficult to draw robust conclusions on the performance of CCU.

The electricity needed for production of DME in the CCU system is not included as avoided energy in the reference and CCS systems. Hence, we have classified this study to illustrate an 'electricity lock-in' scenario. The results have been recalculated to the chosen functional unit for this literature study, allowing for comparison among results from other studies. This recalculation was more cumbersome than for most of the other studies considered, as the needed information was not given explicitly in the paper. Heat values for DME and H_2 from Wikipedia were used by NORSUS for these calculations.

Fernández-Dacosta, van der Spek, Hung, Oregionni, Skagestad, Parihar, Gokak, Strømman and Ramirez (2017) in Journal of CO_2 Utilization: Prospective techno-economic and environmental assessment of carbon capture at a refinery and CO_2 utilisation in polyol synthesis (Fernández-Dacosta et al., 2017)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Polyol	-	v	6	1	v

This study presents a prospective assessment of carbon capture from a hydrogen unit at a refinery, where the CO_2 is either stored, or partly stored and partly utilised for polyols production. To ensure system equivalence, in the reference and CCS cases, the same amount of hydrogen (process from which the CO_2 is captured) is produced as in the CCUS case, and the same amount of polyol (CCU product) is produced as in the CCUS case. The combination of CO_2 capture and partial (10%) utilisation results in an interesting business case over capture and storage alone. A hybrid LCA was used, also using economic (and not only process) data to develop life cycle inventories. The environmental assessment shows that the climate change potential of this combined CO_2 storage and utilisation system is lower compared to a reference case in which no CO_2 is captured at the refinery. For the other environmental indicators, one shows poorer performance for the CCUS case than the reference. Still, the authors emphasise that the differences in results are small, and given the uncertainty assessment, the conclusion that CCUS is the environmentally superior option should be used with caution.

The same amount of steam from heat integration is assumed in all three of the analysed systems. In the CCS and CCUS systems, heat integration is produced in a natural gas boiler. The CCS and the CCU systems use large amount of electricity compared to the reference system. This is not included as avoided energy in the reference case. The difference in use of electricity between the CCS and the CCU system is, however, small. Hence, it is difficult to classify this study according to the four chosen scenarios. We have classified this study to be a status quo scenario. The results given in the original paper have been recalculated to the chosen functional unit for this literature study, allowing for comparison among results from other studies.

Fernández-Dacosta, Stojcheva, and Ramirez (2018) in Journal of CO_2 Utilization: Closing carbon cycles: Evaluating the performance of multi-product CO2 utilisation and storage configurations in a refinery (Fernández-Dacosta et al., 2018)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Dimethyl ether and polyol	-	v	1	1	v

This prospective study explores the techno-economic and environmental feasibility of novel systems that include more than one CO_2 utilisation product. The combination of multi-product CCU with CO_2 storage is also investigated. Two configurations have been designed, in which CO_2 is captured in a refinery and converted into dimethyl ether (DME) and polyols, simultaneously (parallel configuration), or in two consecutive cycles (cascade configuration). System expansion is used to ensure comparability between the systems. Hence, in the reference and the CCS systems, DME and polyol are still produced, but in the conventional manner. Compared to a reference system without capture, results show that the largest direct CO_2 emission reductions are achieved with CCS without utilisation (−70%) but at the expense of higher total costs (+7%). No significant differences were found between the cascade and the parallel configurations. However, when a second capture unit is installed, capturing also the CO_2 emitted during DME synthesis (for storage), this CCUS system achieves the lowest climate burden. This study considers two environmental impact categories; climate change and fossil depletion. For fossil depletion, the CCS case is slightly more burdensome than the reference, while the CCU with CCS system scores better.

Energy required in the CO_2-DME process (compression of syngas leaving the dry reformer for direct DME synthesis) significantly increases the electricity consumption in the CCU and CCUS systems. This is not included as avoided energy in the CCS and reference systems, hence NORSUS has defined this to be an 'electricity lock in' situation. The functional unit did not give the needed information for a recalculation. Instead, annual numbers for the assumed plant were used to find the relationship between the amount of captured CO_2 and produced DME.

Raadal and Modahl (2022) in Life Cycle Management/E3S Web of Conferences: LCA of CCS and CCU compared with no capture: How should multi-functional systems be analysed? (Raadal and Modahl, 2022)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit

Methanol	v	v	3	4 (more scenarios available)	v

In this study, the authors' aim was to assess the environmental performance of CCS and CCU value chains when compared with no capture for steam production at a Norwegian paper mill by employing LCA methodology on the basis of the relatively new guidelines provided by Zimmermann et al. (2018) and from von der Assen et al. (2013) for CCS and CCU value chains. This paper is based on the LCA work performed in the Øra Cluster Project in Fredrikstad, Norway (Raadal and Modahl, 2021), and additional information from the technical report have been used for the literature review. The authors focus on the importance of joint evaluation of all the functions in the CCU system through the use of system expansion, in addition to classifying feedstock CO_2 as an economic flow (sic), rather than intuitively considering utilised CO_2 as a negative GHG emission. The flue gas in the study is comprised of 99.3% biogenic CO_2 caused by the combustion of wood. These emissions are assumed to have the same climate change effect as fossil CO_2 when emitted and are neutralised when CO_2 is removed from the atmosphere while the trees are growing. The climate change impact category has been used, but the study has also included the use of primary energy in order to investigate possible trade-offs. The technical report also includes the indicators of acidification and depletion of fossil resources. The CCU scenario utilises the captured CO_2 as feedstock for methanol production. The study concludes that it is more climate friendly and energy efficient (measured as primary energy resources) to produce conventional fuel and to use the renewable electricity to substitute fossil power, today than it is to produce fuel from captured CO_2. The same goes for the indicators of acidification and depletion of fossil fuels. However, in cases such that substituting fossil electricity generation is less relevant, CCU is the best option for the indicators of climate change and depletion of fossil fuels. This can, for example, be the case in the future as production of fossil power decreases. For acidification and use of primary energy resources, CCU has the largest burdens regardless of time horizon.

The paper contains results for a range of carbon intensities of the power system. We have selected results for four scenarios for each of the three systems CCU, CCS, and a reference without CO_2 capture. The results have been recalculated to a common functional unit for comparisons with other studies.

3.2.3 Papers focusing on direct use of CO_2

Lyng (2020) in technical screening report from NORSUS, in Norwegian: Potensiell klimaeffekt ved bruk av CO_2 *fra oppgradering av biogass i veksthus (Potential climate effect by using* CO_2 *from upgrading biogas, in greenhouses) (Lyng, 2020)*

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Tomatoes	-	v	-	1	-

This report is a screening analysis of the direct use of captured CO_2 from anaerobic digestion, in contrast to use of conventional fossil CO_2, for production of tomatoes. Specific data have been given for a system located at 'The magical factory', an anaerobic digestion plant, in Southern Norway. The CO_2 is transported by pipeline to the greenhouse, which is located on the digestion plant's premises. The study has analysed two alternatives; one involving upgrading of the biogas is fully allocated to the biogas, and one in which CO_2 (the result from upgrading of the biogas) is considered as a technical flow, gaining 2% of the upstream burdens and 3% of the burdens from the upgrading. The last alternative is considered in this literature study, as this best follows the guidelines for LCA of CCS and CCU systems (and considers CO_2 as a technical flow). In the reference system, data from databases have been used. NORSUS emphasises that this is a screening study, and that it has not been verified by reviewers outside NORSUS. Hence, this can be a cause of error. The study was, nevertheless, included to gain more data for direct use of CO_2 in our comparisons.

Fernández-Ríos, Butnar, Margallo, Laso, Borrion, and Aldaco (2023) in Science in the total Environment: Carbon accounting of negative emissions technologies integrated in the life cycle of spirulina supplements (Fernández-Ríos et al., 2023)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Algae	-	v	8	1	v

This study investigates the role of two CCU technologies in decarbonising the production of spirulina algae, which is commonly consumed for its nutritional characteristics. The proposed scenarios consider substitution of synthetic food grade CO_2 in algae cultivation with CO_2 from beer fermentation and CO_2 from direct air carbon capture (only the reference and the CO_2 from beer fermentation have been included in this literature study). The functional unit is the annual production of algae in a small plant (400 kg dried algae). The authors have included eight other environmental indicators in addition to climate change. The results show a better environmental performance for the CCU scenario than the reference for all the investigated indicators, reaching a reduction of greenhouse gas emissions of 52%. For depletion of fossil resources, the reduction is 25% and for depletion of mineral elements a 3% reduction is given. The results are given for a 'realistic alternative in the short term'. Other energy scenarios are shown, however not for the reference. Hence, only the base cases have been included in our study.

Principally, recalculation from annual numbers to the common functional unit (captured CO_2) was uncomplicated. Still, we suspect that there is a typo affecting the transport emissions for the reference system. Hence, when recalculating the results, we have adjusted this emission value for transport[2].

3.2.4 Papers focusing on mineralisation of CO_2

Ostovari, Sternberg and Bardow (2020) in Sustainable Energy & Fuels: Rock 'n' use of CO2: carbon footprint of carbon capture and utilization by mineralization (Ostovari et al., 2020)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Mineralised products	-	v	-	1	For CCS (not necessary for CCU)

In this paper, the authors have analysed 7 mineralisation pathways proposed in the literature: 5 direct and 2 indirect, considering serpentine, olivine, and steel slag as feedstock. The mineralisation products are employed to partially substitute cement in blended cement. The paper describes how the mineralisation reaction is thermodynamically favourable and already occurs in nature. However, the mineralisation reaction is challenging due to its slow reaction kinetics. To overcome this, high reaction pressures and temperatures are often recommended as well as mechanical and thermal pretreatment of feedstock and a variety of reaction additives. The promising potential of mineralisation is, hence, challenged by the energy required to overcome the slow reaction kinetics.

The study uses a functional unit of 1 tonne of stored CO_2. The CO_2 for the mineralisation plant is provided by a steel plant. Conventional CO_2 capture using monoethanolamine is assumed for the capture activity. To overcome the multi-functionality issues, the authors employ system expansion via substitution (avoided

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[2] The climate burden for transport in the reference system is 0.64 tonne CO_2-eq/year, which is not the same as for transport in the other two scenarios (0.28 tonne CO_2-eq/year). These numbers should be the same. In addition, the assumed wrong number (0.64) is the same as uptake/release of biogenic CO_2 in the beer fermenter. Hence, we assume that a mismatch has been performed in the original paper.

burden), which means that the avoided impacts from additional functions is subtracted from the results. The substitution credit considered is 95% of the environmental impact due to production of ordinary Portland cement. Only climate change is used as an indicator for the results. To estimate an upper bound on the potential of CCU by mineralisation, the authors have considered an ideal-mineralisation scenario that neglects all process inefficiencies and utilises the entire product.

The results show that all considered CCU technologies for mineralisation could reduce climate impacts over the entire life cycle based on the current state-of-the-art and today's energy mix. For all mineralisation pathways, the carbon footprint is mainly reduced due to the permanent storage of CO_2 and the credit for substituting conventional products. The authors also claim that for all mineralisation pathways, the dependence on electricity supply is much smaller than observed for other CCU pathways depending on water electrolysis for hydrogen production. They, furthermore, conclude that the carbon footprint of CCU by mineralisation pathways is extremely sensitive to the substitution credit, and that a sound analysis of the substitution credit is essential.

No recalculation was needed for the main results. However, the CCS numbers were recalculated.

Ostovari, Müller, Skocek, and Bardow (2021) in Environmental Science & Technology: From Unavoidable CO_2 Source to CO_2 Sink? A Cement Industry Based on CO_2 Mineralization (Ostovari et al., 2021)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Mineralised products	-	v	17	1 (two more not used)	v

This study analyses the carbon footprint of the combined CO_2 mineralisation and cement production. Results for two configurations are given; i) one CCS configuration in which the CO_2 mineralisation plant captures the locally emitted CO_2 from the cement plant, and landfills the products of mineralisation (the main product of mineralisation, $Ca/MgCO_3$, is stable and can store CO_2 up to 10^5 years), and ii) one CCUS configuration in which the mineralisation plant captures and stores the locally emitted CO_2 but also utilises the byproduct (SiO_2) to substitute clinker and thus reduce the clinker usage in cement production. The main product of mineralisation ($Ca/MgCO_3$) is still landfilled. The byproduct (SiO_2) is either utilised or partly landfilled depending on the blended fraction in the cement.

The functional unit of our study is 1 ton of cement or 1 ton of blended cement with the same performance as that of conventional cement. The main results are shown for today's (2016) electricity supply, for the indicator climate change. Results are also shown for a future electricity mix, for the electricity mix of Norway, and for transition phases between these. These results have not been used by NORSUS, however, as they are given in a way that makes it more difficult to recalculate. Results for other environmental indicators are given in Appendix 1.

The results show that combined CO_2 mineralisation and cement production using today's energy mix could reduce the carbon footprint of the cement industry by 44% or even up to 85% considering the theoretical potential. For the current European electricity mix, all other environmental impacts except for climate change increase by up to a factor of 6.1 compared to ordinary Portland cement. The increase is mainly due to the increased energy demand and increased consumption of virgin feedstock. Shifting the energy supply to renewable energy (wind energy) decreases the environmental impacts related to fossil fuel consumption. Still, 6 out of 19 impacts increase significantly. This is caused by the required resources that are extracted from nature. Consequently, mineralisation increases the environmental impacts related to material consumption such as metal depletion, human toxicity, and freshwater consumption.

Excess CCU product (Ca/$MgCO_3$) is stored, hence the systems deliver the same products to society (despite not mentioning the system expansion approach). The results have been recalculated using information given in the results figures regarding captured amount of CO_2.

Thonemann, Zacharopoulos, Fromme, and Nühlen (2022) in Journal of Cleaner Production: Environmental impacts of carbon capture and utilization by mineral carbonation: A systematic literature review and meta life cycle assessment (Thonemann et al., 2022)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Mineralised products	-	Not used	15	1	-

This study is a literature review and a meta-analysis of mineral carbonation technologies in which harmonised methodological assumptions are applied to assess which of the proposed ex-situ carbonation routes in literature have the lowest environmental impacts. The use of 1 kg CO_2 is used as a functional unit, and 16 different impact categories are used. Multifunctionality is handled by substitution.

The main finding of the meta-analysis in terms of global warming and the impact category of minerals and metals is that direct aqueous carbonation, carbonation mixing, and carbonation curing show negative values (better than the reference). Hence, these three mineral carbonation technologies seem to be most promising. Still, the authors state that it is apparent that other impact categories show positive results (i.e. perform worse than the reference).

The 'realistic scenario' results for climate change vary from approximately -0.5 to -35 kg CO_2-eq/kg CO_2 used, relative to the reference. The highly negative global warming impact is explained by the avoided concrete production and depends on the concrete production process assumed to be avoided. Hence, results need to be interpreted with caution. The results have not been included in the NORSUS comparison, as this is a literature study and not original results. The study has been included as text because it documents a large span in climate change results.

Digulla and Bringezu (2023) in Energies: Comparative Life Cycle Assessment of Carbon Dioxide Mineralization Using Industrial Waste as Feedstock to Produce Cement Substitutes (Digulla and Bringezu, 2023)

CCU product	Methodology	Numerical results, climate	Numerical results, other indicators	Number of time scenarios	Recalculation of functional unit
Mineralised products	-	v	1	1	v

In this study, a systematic LCA analysis of mineralisation processes using industrial waste as feedstock is presented. Six mineralisation processes are modelled. Five of the processes use waste materials (steel slag, concrete waste, and municipal solid waste incineration ash) and one process uses olivine as feedstock. Two of the processes use exhaust gas from a cement plant as a CO_2 source, while the four others use captured, pure CO_2. Sequestration of CO_2 from the flue gas is assumed as burden free, and for the processes using pure CO_2 burdens from capture are included. System expansion with substitution is applied in order to enable direct comparisons between the processes and to resolve multifunctionality. All results are, hence, shown relative to each system's reference. For each of the processes, climate and material footprints are presented (two indicators). The results show that all processes generate significantly negative values for both indicators when cement substitute is considered as a product. This means that for both climate change and the resource indicator, the mineralisation CCU systems perform better than the reference systems. The sensitivity analysis shows that five out of the six processes also produce negative values for these factors when sand is considered as a product (reduced substitution; translates to a CCS system). The authors state that the study confirms that industrial mineralisation is a promising technology for reducing carbon dioxide emissions, and that future process development should focus on replacing carbon dioxide-intensive products while balancing energy and chemical demand with process efficiency.

One kg feedstock is used as a functional unit in this study, however the amount of CO_2 mineralised per kg feedstock is given, and recalculation to the common functional unit of this literature study was relatively straightforward.

3.3 Numerical results

In Appendix 1 the numerical results for climate change found in the reviewed literature are shown together with calculations to a common functional unit. These results use different system boundaries, and the absolute numbers cannot be compared across studies.

The figures in Appendix 1 show that the results are highly sensitive to the time horizon, especially for chemicals and fuels due to the large consumption of renewable electricity consumption in the CCU process which can be used to substitute other electricity sources in the compared scenarios. For the mineralisation cases, two references have provided several cases each, and these show, principally, quite similar results. Some cases are provided with separate reference scenarios while others have included the reference scenario results in the CCU/CCS results.

With regards to ensuring for a comparative analysis, some of the original numerical results for climate change have been recalculated. Hence, all the results are presented on a system expansion with substitution basis, allowing the results to be compared across studies. In addition, some of the results for mineralisation are presented as average values. All comparable figures are shown in Figure 2, were low values indicates better performance than large ones (hence, negative numbers are better than positive values).

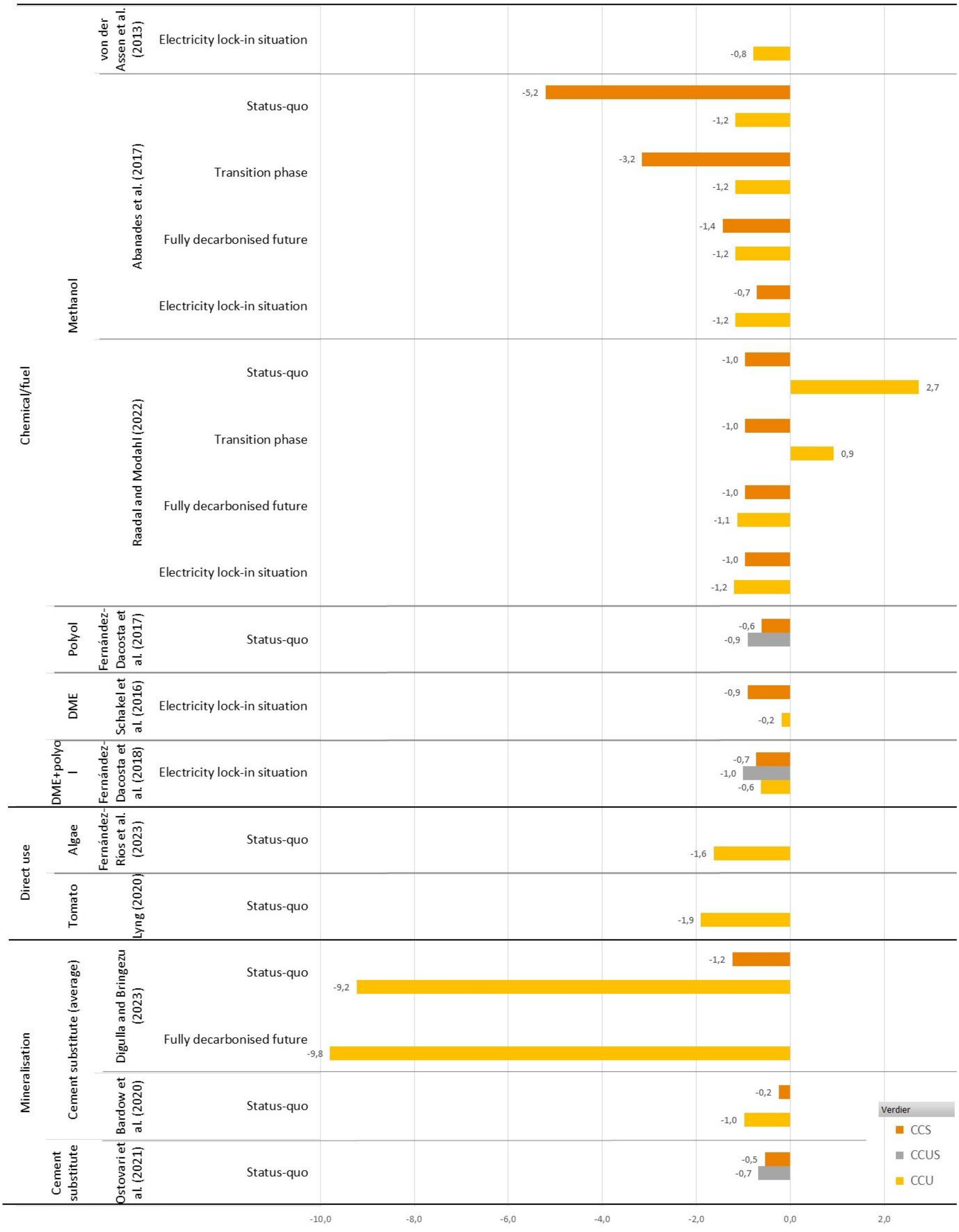

Figure 2 Climate change results (kg CO_2-eqv) for all the scrutinised case studies. Results are shown on a system expansion with substitution basis, meaning that all results are relative to each study's reference. This means that the bars show how each case performs compared to its own reference. Hence, all the bars can be compared, and they show the gains or burdens compared with systems without CCU/CCS. Negative

numbers = gains compared to systems without CCU/CCS, positive numbers = burdens compared to systems without CCU/CCS. The functional unit is 1 tonne of CO_2 removed/captured.

Figure 2 shows that all the CCS results are negative, meaning that they all lead to less climate burdens than the alternative (no capture). The CCS results vary from -0,2 to -5,2 tonne CO_2-eqv/tonne CO_2 captured, depending on time horizon and which product the corresponding CCU system is producing.

The CCU results are more diverse, ranging from +2,7 (worse than the alternative (no capture)) to -9,8 tonne CO_2-eqv/tonne CO_2 captured (better than the alternative). In the same way as for CCS, the CCU results are dependent on time horizon, however, they depend even more on which CCU product is produced. When comparing the different groups of CCU products (chemicals/fuels, direct use, and mineralisation), the mineralisation CCU cases have, by far, the best climate change results. These results are also better than the best CCS results.

For the systems having chemicals and fuels as their CCU product, CCS has a better climate performance than CCU for today's energy system (status-quo). In a fully decarbonised future, the climate performance for the CCS and CCU systems are more similar, and in 'electricity lock-in' situations the CCU systems can perform better than the CCS systems, with respect to climate change. For direct use of CO_2 we only found data representing status-quo. In contrast to the CCU results for chemicals and fuels for today's situation, however, the results for direct use of CO_2 are better than the alternative (no capture) for today's situation. For mineralisation, the time horizon does not significantly affect the CCU results. The reason for this is that it is the substituted mineralisation product (e.g clinker/cement substitute) that represents the major benefit (not the substituted electricity).

The few CCUS systems found show results close to their corresponding CCU and CCS systems.

4 Discussion and conclusions

The number of studies found for numerical comparison are not large enough to conclude based on statistical evidence. Other aspects of uncertainties are that the studies might have used different methods for calculating climate change and other environmental impacts, background databases might be different, and reference cases and time scenarios probably have been defined differently. The papers found are all desktop studies, as none describes physical facilities running today. It should be emphasised that this is a literature study, and the results and conclusions are based on the findings herein. However, since the results harmonise with the Gibbs free energy levels for chemicals/fuels, CO_2, and mineralised CO_2, NORSUS finds the following conclusions for the different CCU product categories justified for climate change:

- For chemicals and fuels:
    - Today and in the near future, CCS systems have a better performance than CCU systems. Not capturing CO_2 at all can also perform better than a CCU system.
    - In a fully decarbonised future for electricity grid mix and in 'electricity lock-in' situations, CCU systems are preferable.
    - The reason for the diverging conclusions depending on time horizon is the large consumption of renewable electricity in the process of converting CO_2 into chemicals/fuels. This electricity can, in the compared systems, be used to substitute other electricity sources.
- For direct use of CO_2:
    - Only today's situation is analysed, showing that direct use of CO_2 is beneficial.
- For mineralisation:
    - CCU systems where CO_2 is mineralised have a better performance than CCS systems. How much better depends largely on the climate burden of the product being substituted by mineralised CO_2.

An important aspect to consider when developing strategies on a political level, is whether suboptimisation can be tolerated as a means to develop technology and markets for a fossil free future. This is relevant, for example, for the aviation sector.

For environmental indicators other than climate change, information in literature is not consistent enough to make any numerical comparison. There is a large variation on which and how many indicators are included, and transparency on which method is used for each environmental impact indicator is sometimes lacking. Still, direct use of CO_2 seems to lead to environmental gains. For CCU producing chemicals/fuels and for CCU by mineralisation, literature reports both increased and decreased environmental burdens. NORSUS emphasises that for environmental indicators other than climate change, our considerations are preliminary, and that the literature basis used is not suitable for making any robust conclusions.

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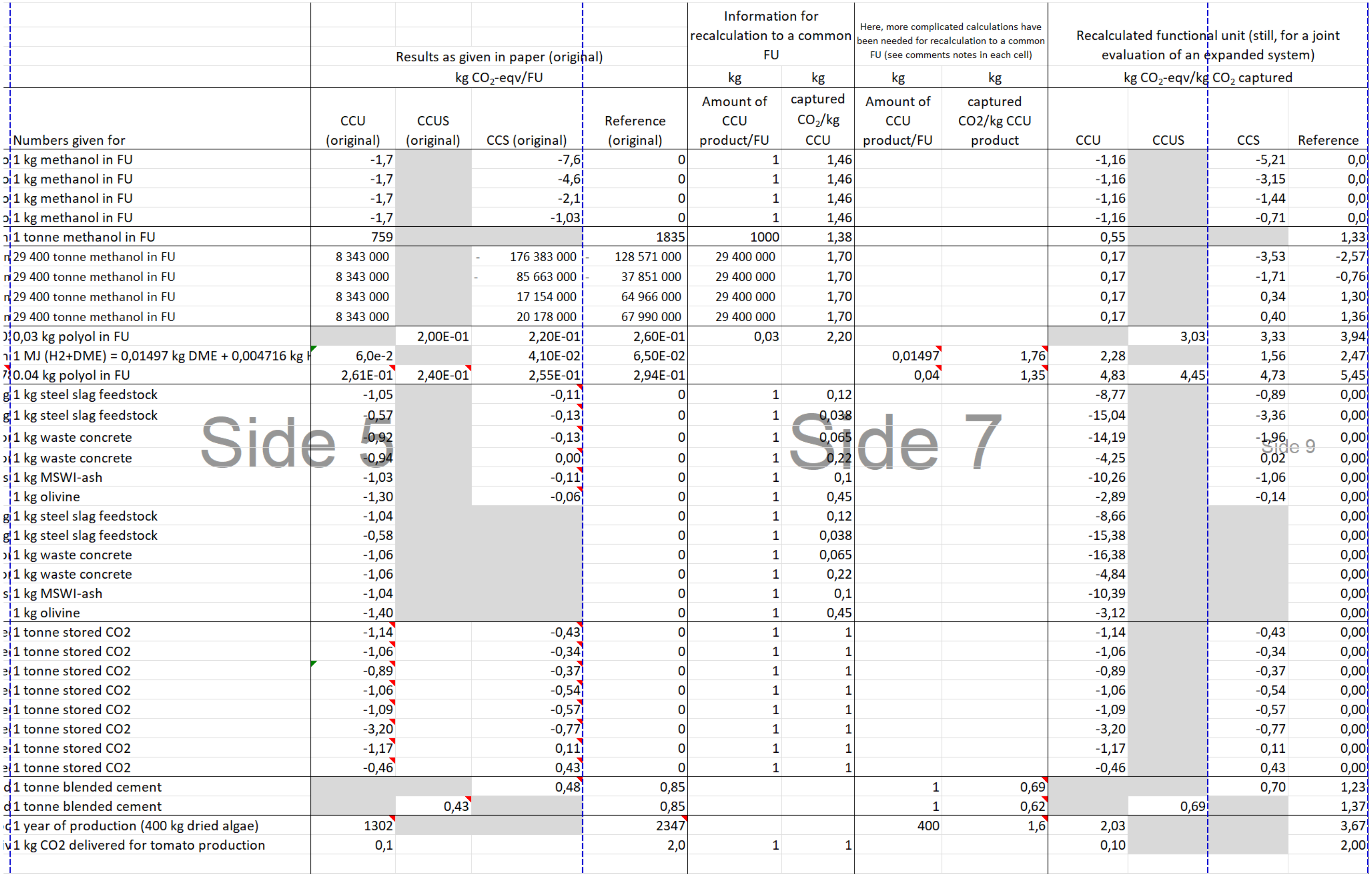
Appendix 1 Numerical results and calculations

In this table and in Figure A and Figure B, the numerical results for climate change are shown. Be aware that the absolute numbers cannot be compared across studies due to different system boundaries being used. The difference between CCU results and the reference case result in each study can, however, be compared with corresponding differences in other studies (for studies using system expansion with substitution, the reference system has been included in the CCU/CCS scenarios and the difference is, hence, given explicitly in the figure). For the climate, low values are better than large values (hence, negative numbers are better than positive values).

Recalculated results

Reference	Time period	CCU product	FU
Abanades et al. (2017)	Status-quo	Methanol	1 kg methanol + capture/non-capture of 1.46 kg CO2 + 9.82 kWh renewable power production
Abanades et al. (2017)	Transition phase	Methanol	1 kg methanol + capture/non-capture of 1.46 kg CO2 + 9.82 kWh renewable power production
Abanades et al. (2017)	Fully decarbonised future	Methanol	1 kg methanol + capture/non-capture of 1.46 kg CO2 + 9.82 kWh renewable power production
Abanades et al. (2017)	Electricity lock-in situation	Methanol	1 kg methanol + capture/non-capture of 1.46 kg CO2 + 9.82 kWh renewable power production
von der Assen et al. (2013)	Electricity lock-in situation	Methanol	1 tonne methanol + 1375 kg captured/non-captured CO2
Raadal and Modahl (2022)	Status-quo	Methanol	29 400 tonne methanol + capture/non-capture of 50 00 tonne CO$_2$ + 302 GWh renewable power production
Raadal and Modahl (2022)	Transition phase	Methanol	29 400 tonne methanol + capture/non-capture of 50 00 tonne CO$_2$ + 302 GWh renewable power production
Raadal and Modahl (2022)	Fully decarbonised future	Methanol	29 400 tonne methanol + capture/non-capture of 50 00 tonne CO$_2$ + 302 GWh renewable power production
Raadal and Modahl (2022)	Electricity lock-in situation	Methanol	29 400 tonne methanol + capture/non-capture of 50 00 tonne CO$_2$ + 302 GWh renewable power production
Fernández-Dacosta et al. (2017)	Status-quo	Polyol	1 MJ H2 + 0.03 kg polyol + 0.066 kg captured/non-captured CO2 + 0.187 kg LP steam
Schakel et al. (2016)	Electricity lock-in situation	DME	1 MJ LHV of net energy from H2 and DME produced
Fernández-Dacosta et al. (2018)	Electricity lock-in situation	DME+polyol	1 MJ H2 + 0.78 MJ DME + 0.04 kg polyol (and 0.0539 kg captured/non-captured CO2)
Digulla and Bringezu (2023)	Status-quo	Mineralisation 1 (cement substitute)	1 kg steel slag feedstock
Digulla and Bringezu (2023)	Status-quo	Mineralisation 2 (cement substitute and CaCO$_3$)	1 kg steel slag feedstock
Digulla and Bringezu (2023)	Status-quo	Mineralisation 3 (cement substitute and CaCO$_3$)	1 kg waste concrete
Digulla and Bringezu (2023)	Status-quo	Mineralisation 4 (cement substitute)	1 kg waste concrete
Digulla and Bringezu (2023)	Status-quo	Mineralisation 5 (cement substitute)	1 kg MSWI-ash
Digulla and Bringezu (2023)	Status-quo	Mineralisation 6 (cement substitute)	1 kg olivine
Digulla and Bringezu (2023)	Fully decarbonised future	Mineralisation 1 (cement substitute)	1 kg steel slag feedstock
Digulla and Bringezu (2023)	Fully decarbonised future	Mineralisation 2 (cement substitute and CaCO3)	1 kg steel slag feedstock
Digulla and Bringezu (2023)	Fully decarbonised future	Mineralisation 3 (cement substitute and CaCO3)	1 kg waste concrete
Digulla and Bringezu (2023)	Fully decarbonised future	Mineralisation 4 (cement substitute)	1 kg waste concrete
Digulla and Bringezu (2023)	Fully decarbonised future	Mineralisation 5 (cement substitute)	1 kg MSWI-ash
Digulla and Bringezu (2023)	Fully decarbonised future	Mineralisation 6 (cement substitute)	1 kg olivine
Bardow et al. (2020)	Status-quo	Mineralisation 1b (cement substitute)	1 tonne stored CO2
Bardow et al. (2020)	Status-quo	Mineralisation 2b (cement substitute)	1 tonne stored CO2
Bardow et al. (2020)	Status-quo	Mineralisation 3b (cement substitute)	1 tonne stored CO2
Bardow et al. (2020)	Status-quo	Mineralisation 4b (cement substitute)	1 tonne stored CO2
Bardow et al. (2020)	Status-quo	Mineralisation 5b (cement substitute)	1 tonne stored CO2
Bardow et al. (2020)	Status-quo	Mineralisation 5b ideal (cement substitute)	1 tonne stored CO2
Bardow et al. (2020)	Status-quo	Mineralisation 6b (cement substitute)	1 tonne stored CO2
Bardow et al. (2020)	Status-quo	Mineralisation 7b (cement substitute)	1 tonne stored CO2
Ostovari et al. (2021)	Status-quo	Mineralisation 1c (cement substitute and Ca/MgCO3)	1 tonne blended cement
Ostovari et al. (2021)	Status-quo	Mineralisation 2c (cement substitute and Ca/MgCO3)	1 tonne blended cement
Fernández-Ríos et al. (2023)	Status-quo	Algae	1 year of production (400 kg dried algae)
Lyng (2020)	Status-quo	Tomato	1 kg CO2 delivered for tomato production



	Results as given in paper (original) kg CO_2-eqv/FU				Information for recalculation to a common FU		Here, more complicated calculations have been needed for recalculation to a common FU (see comments notes in each cell)		Recalculated functional unit (still, for a joint evaluation of an expanded system) kg CO_2-eqv/kg CO_2 captured			
					kg	kg	kg	kg				
Numbers given for	CCU (original)	CCUS (original)	CCS (original)	Reference (original)	Amount of CCU product/FU	captured CO_2/kg CCU	Amount of CCU product/FU	captured CO2/kg CCU product	CCU	CCUS	CCS	Reference
1 kg methanol in FU	-1,7		-7,6	0	1	1,46			-1,16		-5,21	0,0
1 kg methanol in FU	-1,7		-4,6	0	1	1,46			-1,16		-3,15	0,0
1 kg methanol in FU	-1,7		-2,1	0	1	1,46			-1,16		-1,44	0,0
1 kg methanol in FU	-1,7		-1,03	0	1	1,46			-1,16		-0,71	0,0
1 tonne methanol in FU	759			1835	1000	1,38			0,55			1,33
29 400 tonne methanol in FU	8 343 000		- 176 383 000 -	128 571 000	29 400 000	1,70			0,17		-3,53	-2,57
29 400 tonne methanol in FU	8 343 000		- 85 663 000 -	37 851 000	29 400 000	1,70			0,17		-1,71	-0,76
29 400 tonne methanol in FU	8 343 000		17 154 000	64 966 000	29 400 000	1,70			0,17		0,34	1,30
29 400 tonne methanol in FU	8 343 000		20 178 000	67 990 000	29 400 000	1,70			0,17		0,40	1,36
0,03 kg polyol in FU		2,00E-01	2,20E-01	2,60E-01	0,03	2,20				3,03	3,33	3,94
1 MJ (H2+DME) = 0,01497 kg DME + 0,004716 kg H	6,0e-2		4,10E-02	6,50E-02			0,01497	1,76	2,28		1,56	2,47
0.04 kg polyol in FU	2,61E-01	2,40E-01	2,55E-01	2,94E-01			0,04	1,35	4,83	4,45	4,73	5,45
1 kg steel slag feedstock	-1,05		-0,11	0	1	0,12			-8,77		-0,89	0,00
1 kg steel slag feedstock	-0,57		-0,13	0	1	0,038			-15,04		-3,36	0,00
1 kg waste concrete	-0,92		-0,13	0	1	0,065			-14,19		-1,96	0,00
1 kg waste concrete	-0,94		0,00	0	1	0,22			-4,25		0,02	0,00
1 kg MSWI-ash	-1,03		-0,11	0	1	0,1			-10,26		-1,06	0,00
1 kg olivine	-1,30		-0,06	0	1	0,45			-2,89		-0,14	0,00
1 kg steel slag feedstock	-1,04			0	1	0,12			-8,66			0,00
1 kg steel slag feedstock	-0,58			0	1	0,038			-15,38			0,00
1 kg waste concrete	-1,06			0	1	0,065			-16,38			0,00
1 kg waste concrete	-1,06			0	1	0,22			-4,84			0,00
1 kg MSWI-ash	-1,04			0	1	0,1			-10,39			0,00
1 kg olivine	-1,40			0	1	0,45			-3,12			0,00
1 tonne stored CO2	-1,14		-0,43	0	1	1			-1,14		-0,43	0,00
1 tonne stored CO2	-1,06		-0,34	0	1	1			-1,06		-0,34	0,00
1 tonne stored CO2	-0,89		-0,37	0	1	1			-0,89		-0,37	0,00
1 tonne stored CO2	-1,06		-0,54	0	1	1			-1,06		-0,54	0,00
1 tonne stored CO2	-1,09		-0,57	0	1	1			-1,09		-0,57	0,00
1 tonne stored CO2	-3,20		-0,77	0	1	1			-3,20		-0,77	0,00
1 tonne stored CO2	-1,17		0,11	0	1	1			-1,17		0,11	0,00
1 tonne stored CO2	-0,46		0,43	0	1	1			-0,46		0,43	0,00
1 tonne blended cement			0,48	0,85			1	0,69			0,70	1,23
1 tonne blended cement		0,43		0,85			1	0,62		0,69		1,37
1 year of production (400 kg dried algae)	1302			2347			400	1,6	2,03			3,67
1 kg CO2 delivered for tomato production	0,1			2,0	1	1			0,10			2,00

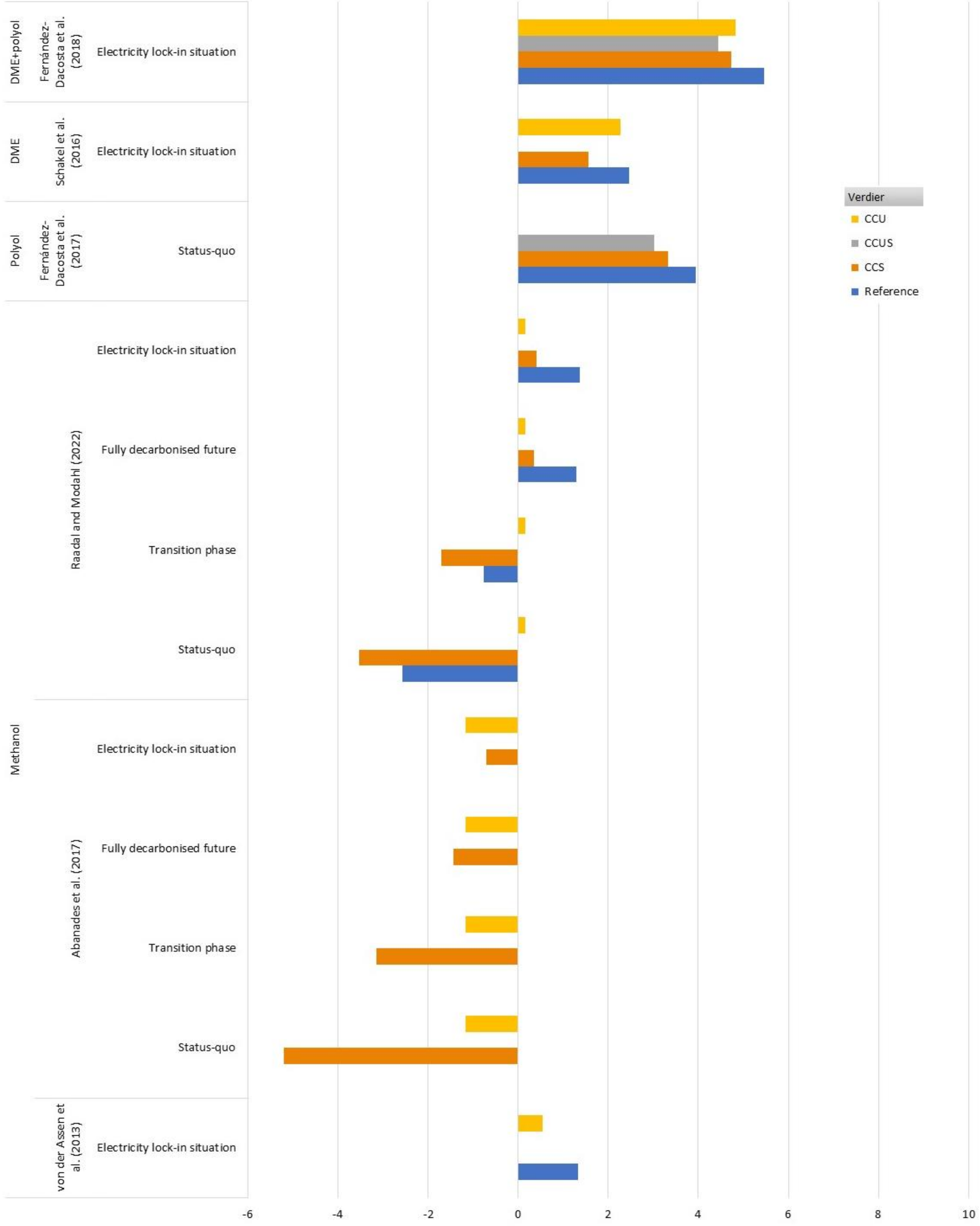


Figure A Climate change results (kg CO_2-eqv) for CCU case studies producing chemicals and fuels as the CCU product. The functional unit is 1 tonne of CO_2 removed/captured. Different system boundaries are used, hence absolute numbers cannot be compared across studies.

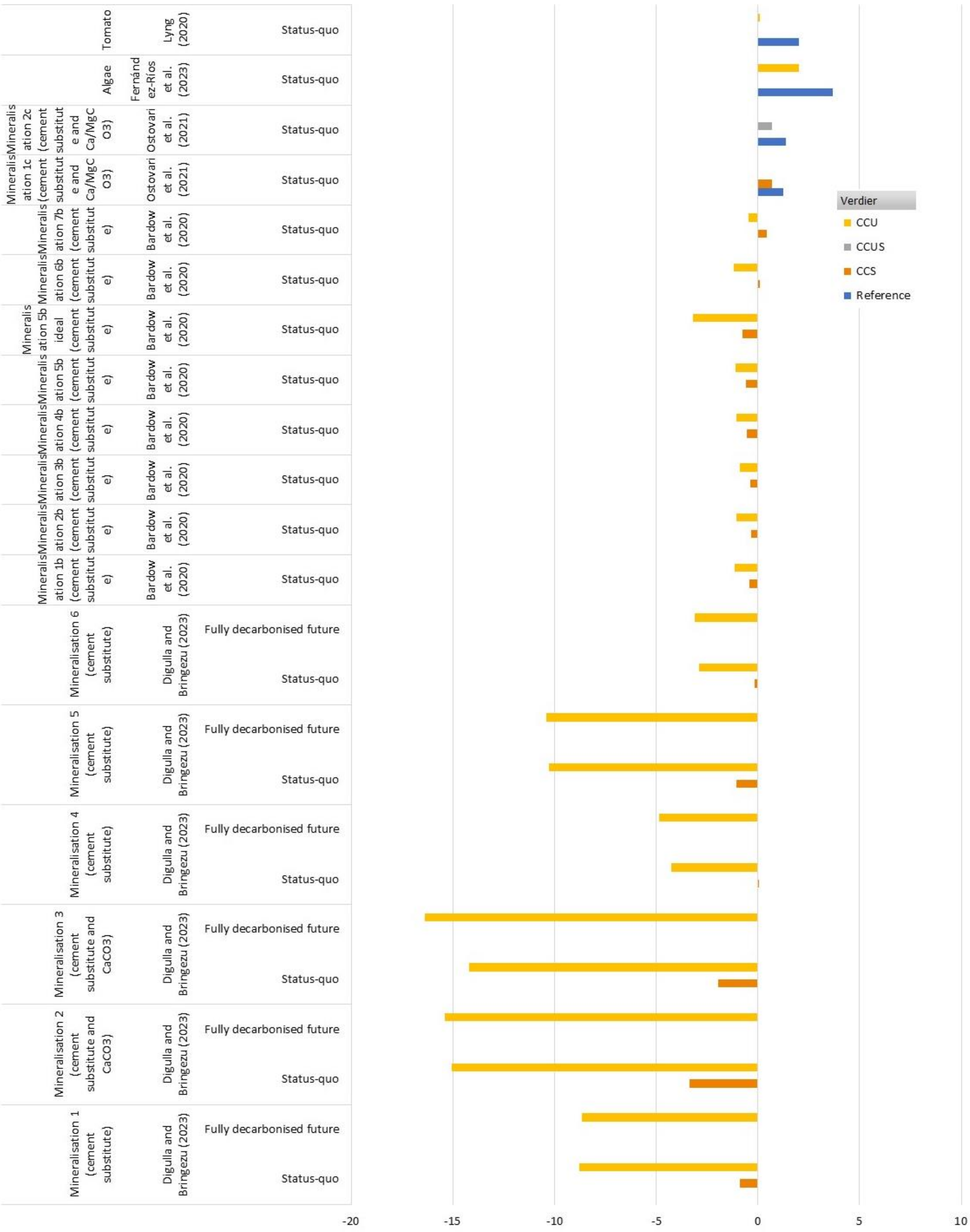


Figure B Climate change results (kg CO_2-eqv) for CCU case studies producing mineralised products as the CCU product, or which are using the captured CO_2 directly. The functional unit is 1 tonne of CO_2 removed/captured. Different system boundaries are used, hence absolute numbers cannot be compared across studies.

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