FINAL REPORT

Title:		Life Cycle Assessment of CCS (carbon capture and storage) and CCU (carbon capture and utilization).
Date:		July 7, 2021
Project number:		619092
Authors:		Hanne Lerche Raadal and Ingunn Saur Modahl, NORSUS
ISBN/ISNN/OR:		978-82-7520-858-1 / 2703-8610 / OR 28.21

Supported by:

CLIMIT

Title

Life Cycle Assessment of CCS (carbon capture and storage) and CCU (carbon capture and utilization).

Authors:	Hanne Lerche Raadal and Ingunn Saur Modahl, NORSUS
Internal Quality Control:	Fredrik Moltu Johnsen
Project number:	619092
Project name:	Industrial CCS cluster at Øra and regionally (Mulighetsstudie CCS-klynga på Øra og regionalt)
Supported by:	CLIMIT

ISBN/ISSN/OR:	978-82-7520-858-1 / 2703-8610 / OR 28.21

Keywords:
CCU
CCS
LCA
Øra industrial cluster

Availability
Open report

Number of pages:
50

Approved:
Date: July 7, 2021

Chair of Steering Committee
Pål Mikkelsen

Content

Summary 1
Norsk sammendrag 4
1 Introduction 7
1.1 Background 7
1.2 Geographical boundaries and boundaries to nature and society for CCUS systems 8
1.3 Management of the project and quality control 9
2 Goal and scope 10
2.1 Goal of the project 10
2.2 Scope 11
2.3 Functional unit (FU) 11
2.4 System boundaries 12
2.4.1 CCS systems: Geographical boundary and boundaries to nature and society 12
2.4.2 CCUS systems: Geographical boundary and boundaries to nature and society 13
2.4.3 Technology 14
2.4.4 Time 16
2.4.5 Cut-off criteria 16
2.5 Allocation procedures 16
2.6 Impact assessment 16
2.7 Modelling tool 17
3 Life cycle inventory 18
3.1 Use of generic and specific data 18
3.2 Data and data sources 18
4 Results and discussion for CCS systems: production of paper and WtE 21
4.1 Results for climate change 21
4.2 Results for acidification 25
4.3 Results for ADP_{fossil} (use of primary fossil energy) 27
4.4 Results for CED (cumulative energy demand) 29
5 Results and discussion for CCUS systems: production of paper and WtE, in addition to production of fuel (joint functional unit) 31
5.1 Results for climate change 32
5.2 Results for acidification 36

5.3 Results for ADP_{fossil} (use of primary fossil energy) 38
5.4 Results for CED (cumulative energy demand) 41
5.5 Sensitivity analyses 43
5.5.1 Climate change effect of substituted electricity 43
5.5.2 Climate change effect of compression loss 46
6 Conclusions 47
7 References 50

Summary

This report is a delivery of the project Industrial CCS cluster at Øra and regionally, supported by CLIMIT.

The emission of greenhouse gases (GHG) from human activities is one of the most important environmental issues of the twenty first century. The largest source of GHG is carbon dioxide, which has increased tremendously in the last decades, mainly due to fossil fuels combustion for power generation and automotive transportation. CCS (carbon capture and storage) is a way of reducing greenhouse gas emissions by capturing and subsequently storing the carbon dioxide (CO_2) permanently. CCU (carbon capture and utilization) represents a way of recycling the carbon in the captured CO_2 by converting it to fuels or other products. The acronym CCUS describes systems including both utilization and storage of captured CO_2.

This study has analysed systems for CCS (carbon capture and storage) and CCU (carbon capture and utilization) and compared these with their respective reference scenarios. The study has been carried out using Life Cycle Assessment (LCA) methodology according to the ISO-standards 14044/48 and guidelines provided for CCU value chains. The LCAs have been performed for two industrial cases: Norske Skog Saugbrugs, a paper production plant, and Sarpsborg Avfallsenergi (SAE), a waste to energy (WtE) plant.

Since a CCS and a CCU system provide different functions, the goal and functional unit for performing LCAs for CCS and CCU systems also differ. The goals for analysing the respective CCS and CCUS systems are given below:

CCS systems: to assess the environmental performance of CCS at Norske Skog Saugbrugs paper mill and the Waste to Energy plant SAE, respectively, compared to a Reference system without CCS.

CCUS systems: to assess the environmental performance of CCS and CCU at Norske Skog Saugbrugs paper mill and the Waste to Energy plant SAE, respectively, compared to a Reference system without CCUS. The CCU scenario uses the captured CO_2 as feedstock for methanol production (e-fuel). As methanol is one product from the CCU scenario, the comparable Reference and CCS scenarios must also provide this function. This is solved by extending the system to include conventional production of methanol in the compared scenarios. The CCU scenario additionally needs large amounts of renewable electricity to produce this fuel, and the CCS and Reference scenarios are therefore provided with renewable electricity which can be used to substitute other electricity sources. Hence, all the CCUS scenarios provide the same functions and are provided with the same large amount of renewable electricity:

1. Producing either paper or heat (WtE)
2. Producing fuel (methanol)
3. Using renewable electricity

The analysed systems and scenarios are summarised in the table below.

System	Case	Scenario	Functions
CCS	Norske Skog Saugbrugs	Reference	Paper production
		CCS	Paper production
	Sarpsborg Avfallsenergi (SAE)	Reference	Heat production
		CCS	Heat production
CCUS		Reference	Production of paper and fuel; use of renewable electricity

	Norske Skog Saugbrugs	CCS	Production of paper and fuel; use of renewable electricity
		CCU	Production of paper and fuel; use of renewable electricity
	Sarpsborg Avfallsenergi (SAE)	Reference	Production of heat and fuel; use of renewable electricity
		CCS	Production of heat and fuel; use of renewable electricity
		CCU	Production of heat and fuel; use of renewable electricity

Conclusions from the CCS systems

For climate change, the CCS scenarios perform considerably better than the Reference scenario (no CCS) and results in negative emissions. The results for all the other analysed impact categories are the opposite. This is logic and in line with other studies, as burdens from the capture plant and all related activities are added to the system, in order to reduce greenhouse gas emissions only.

CO_2 losses in the capture plant and during the value chain lead to a less advantageous result, however the losses have to be large (>90%) to outweigh the climate change effect of storing CO_2.

Still, CCS for biogenic CO_2 (BECCS[1]) is the only possibility for reaching negative emissions (removing CO_2 from the atmosphere); the larger share of biogenic CO_2 in the flue gas, the more negative emissions can be obtained. Therefore, the Norske Skog Saugbrugs case gives larger negative emissions than the SAE case.

Conclusions from the CCUS systems

For all the analysed impact categories, the CCU scenarios perform worse compared to the Reference and CCS scenarios. The main reason for this is that converting CO_2 to fuel is very energy intensive, and ultimately it leads to re-emitting the captured CO_2-emissions. For climate change, the most beneficial way to fulfil the goal for the CCUS system is to store the captured CO_2, use renewable power to substitute electricity from fossil sources, and to produce fuel by conventional technologies.

This study documents that as long as there is a possibility for renewable electricity to replace fossil electricity generation, this should be prioritised over CCU fuel production. If still fuel production based on CCU is chosen, an important criterion should be to document that the CCU fuel production process uses renewable excess electricity (not available for other purposes).

This study clearly shows that recycling of CO_2 into fuel is not a sustainable way to move forward as the captured CO_2 is re-emitted after going through energy intensive processes. When first being captured, the CO_2 should be permanently stored rather than be used for short-lived products with a high energy intensity production process.

CCU products can be more or less long-lived and more or less energy intensive during production. These two factors can affect the results for CCU products. Our study has analysed a short-lived product with an energy-intensive production process. An extreme example in the opposite direction is represented by a long-lived CCU product with an energy-efficient production process. This will represent permanent

[1] A commonly used acronym for CCS of biogenic CO_2 is BECCS; Bioenergy with Carbon Capture and Storage. This term is relevant for the biogenic share of the CO_2 from the two point sources used as cases in this study.

storage and lead to an environmental performance close to the result for the CCS scenario. Such a CCU scenario might perform better than the CCS scenario if the production phase for the product being substituted by the CCU product has a higher environmental impact compared to the CCU production. Other CCU products will result in environmental impacts in between the abovementioned extremes.

Potential of reaching negative greenhouse gas (GHG) emissions

A major message from the study is that a CCS system has the potential of resulting in negative CO_2-emissions (removing CO_2 from the atmosphere) when capturing and storing biogenic CO_2. CCU has not this potential, but it might lead to reduced emissions compared to alternative production routes.

Norsk sammendrag

Denne rapporten er en del av prosjektet Mulighetsstudie CCS-klynga på Øra og regionalt, støttet av CLIMIT.

Utslipp av klimagasser fra menneskelig aktivitet er en av de viktigste miljøutfordringene i dette århundret. Den største kilden til klimagassutslipp er karbondioksid, en klimagass som har økt dramatisk de siste tiår, hovedsaklig som følge av bruk av fossil energi til energi og transport. CCS (carbon capture and storage/karbonfangst og lagring) er en måte å redusere klimagassutslipp på ved å fange og permanent lagre karbondioksid (CO_2). CCU (carbon capture and utilization/karbonfangst og bruk) er en måte å resirkulere karbonet i fanget CO_2 på ved å konvertere det til brensel eller andre produkter. Forkortelsen CCUS beskriver systemer som inkluderer både bruk og lagring av fanget CO_2.

Denne studien har analysert verdikjeder med både CCS (carbon capture and storage) og CCU (carbon capture and utilization), og sammenlignet dem med deres respektive referansescenarier. Studien har benyttet metodikk for livsløpsvurderinger (LCA) i henhold til ISO-standardene 14044/48 og spesifikke retningslinjer for LCA av CCU-verdikjeder. Analysene er gjennomført for to industrielle aktører; anlegget for papirproduksjon ved Norske Skog Saugbrugs og energigjenvinningsanlegget Sarpsborg Avfallsenergi (SAE).

Siden CCS- og CCU-system gir forskjellige funksjoner, vil også mål og funksjonell enhet for gjennomføring av LCA bli ulike. Målet for gjennomføring av en livsløpsvurdering for de respektive CCS- og CCUS-systemene er beskrevet i det følgende:

CCS-systemet: å vurdere miljøpåvirkningene for CCS på Norske Skog Saugbrugs og for Sarpsborg Avfallsenergi, og sammenligne dette med referansescenarier uten CCS.

CCUS-systemet: å vurdere miljøpåvirkningene for CCS og CCU på Norske Skog Saugbrugs og for Sarpsborg Avfallsenergi, og sammenligne dette med referansescenarier uten CCUS. CCU-scenariet bruker fanget CO_2 som råvare for metanolproduksjon (til drivstoff: e-fuel). Siden metanol er et produkt fra CCU-scenariet, må referanse- og CCS-scenariene også gi denne funksjonen for å være sammenlignbare. Dette løses ved å utvide systemene til også å inkludere konvensjonell produksjon av metanol. I tillegg krever CCU-scenariet store mengder fornybar strøm, og referanse- og CCS-scenariene blir derfor tilegnet fornybar elektrisitet som kan benyttes til å substituere andre elektrisitetsteknologier. Dermed gir scenariene de samme funksjonene og blir tilført samme mengde fornybar elektrisitet:

1. Produksjon av enten papir eller varme
2. Produksjon av metanol
3. Bruk av fornybar elektrisitet

De analyserte systemene og scenariene er oppsummert i tabellen under.

System	Case	Scenario	Funksjon
CCS	Norske Skog Saugbrugs	Reference	Papirproduksjon
		CCS	Papirproduksjon
	Sarpsborg Avfallsenergi (SAE)	Reference	Produksjon av varme
		CCS	Produksjon av varme
CCUS	Norske Skog Saugbrugs	Reference	Produksjon av papir og metanol; bruk av fornybar strøm
		CCS	Produksjon av papir og metanol; bruk av fornybar strøm

		CCU	Produksjon av papir og metanol; bruk av fornybar strøm
	Sarpsborg Avfallsenergi (SAE)	Reference	Produksjon av varme og metanol; bruk av fornybar strøm
		CCS	Produksjon av varme og metanol; bruk av fornybar strøm
		CCU	Produksjon av varme og metanol; bruk av fornybar strøm

Konklusjoner for CCS-systemene

CCS-scenariene er klart best sammenlignet med referansescenariet (ingen CCS) for miljøpåvirkningskategorien klimaendring, og resulterer i negative klimagassutslipp. For alle de andre miljøpåvirkningskategoriene er resultatet motsatt og referansescenariet gir best resultat. Dette er logisk og i tråd med annen litteratur, siden de ekstra belastningene som oppstår ved fangstanlegget og relaterte aktiviteter legges til systemet med hensikt å redusere nettopp klimabelastninger (og kun dette).

CO_2-tap i fangstanlegget og videre gjennom verdikjeden medfører redusert klimanytte. Men klimaeffekten fra CCS sammenlignet med referansescenariet utjevnes først når tapene blir >90%.

Det er viktig å være klar over at det kun er CCS av biogent CO_2 (BECCS[2]) som har potensial for negative utslipp (altså å fjerne CO_2 fra atmosfæren). Jo høyere andel biogent CO_2 i røykgassen, jo større negative utslipp kan oppnås. Dette er årsaken til at Norske Skog Saugbrugs-caset resulterer i større negative utslipp enn SAE.

Konklusjoner for CCUS-systemene

For alle de analyserte miljøpåvirkningskategoriene presterer CCU-scenariet dårligst sammenlignet med referanse- og CCS-scenariene. Hovedgrunnen til dette er at konvertering av CO_2 til brensel er ekstremt energiintensivt, og i tillegg slippes fanget CO_2 ut til atmosfæren igjen. Den mest klimavennlige måten å oppfylle målet til CCUS-systemet på, er å fange og lagre CO_2 fra røykgassen, bruke den fornybare kraften til å erstatte fossil elektrisitet, og produsere drivstoff på konvensjonell måte.

Denne studien dokumenterer at så lenge det er mulig å erstatte fossil elektrisitet, så bør dette prioriteres fremfor produksjon av metanol basert på CCU. Hvis CCU-metanolruten likevel velges, bør det stilles krav til å dokumentere at produksjonen er basert på fornybar overskuddselektrisitet (som ikke er tilgjengelig for andre formål).

Studien viser tydelig at resirkulering av CO_2 til metanol/brensel ikke er en bærekraftig løsning, fordi utslippene slippes ut i atmosfæren igjen etter å ha vært gjennom en svært energiintensiv prosess. Når CO_2 først er fanget, bør det lagres permanent fremfor å bli brukt til produksjon av kortlevde produkter med høyt energibruk i produksjonsfasen. Denne studien har analysert drivstoff, som er et kortlevd produkt med en energiintensiv produksjonsprosess. Et eksempel i motsatt retning er et CCU-produkt med lang levetid og lav energibruk i produksjonsfasen, noe som vil tilsvare permanent lagring med en miljøpåvirkning relativt likt som for CCS. I dette eksemplet vil CCU kunne komme bedre ut enn CCS dersom produksjonsfasen for produktet som antas erstattet av CCU-produktet har høyere

[2] En vanlig forkortelse for CCS av biogent CO_2 er BECCS; Bioenergy with Carbon Capture and Storage (Bioenergi med karbonfangst og lagring). Dette begrepet er relevant for den biogene andelen av CO_2 fra de to punktkildene i denne studien.

miljøbelastning enn produksjonen av CCU-produktet. Andre CCU-produkter vil resultere i miljøpåvirkninger et sted mellom de ovennevnte eksemplene.

Potensial for å oppnå negative klimagassutslipp

CCS-systemer kan gi negative CO_2-utslipp (fjerning av CO_2 fra atmosfæren) kun dersom biogent CO_2 fanges og lagres permanent. CCU-verdikjeder har ikke denne muligheten, men kan likevel gi reduserte utslipp sammenlignet med alternative produksjonsruter.

1 Introduction

This report is a delivery of the project Industrial CCS cluster at Øra and regionally, supported by CLIMIT.

1.1 Background

The emission of greenhouse gases (GHG) from human activities is one of the most important environmental issues of the twenty first century. The largest source of GHG is the carbon dioxide, which has increased tremendously in the last decades, mainly due to fossil fuels combustion for power generation and automotive transportation. CCS (carbon capture and storage) is a way of reducing greenhouse gas emissions by capturing and subsequently storing the carbon dioxide (CO_2). CCU (carbon capture and utilization) represents a way of recycling the carbon in the captured CO_2 by converting it to fuels or other products. The acronym CCUS describes systems including both utilization and storage of captured CO_2.

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

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

It should be emphasised that, in order to be fully carbon neutral, all other GHG emissions must be zero over the life cycle.

It can be seen from Figure 1c that negative emissions will only occur for the cases when CO_2 is taken from the atmosphere (via biogenic point sources or direct air capture) and sequestered after the product life cycle. Furthermore, negative emissions occur only if the emissions over the entire lifecycle are less than 1 kg CO_2-eq. per kg CO_2 up taken.

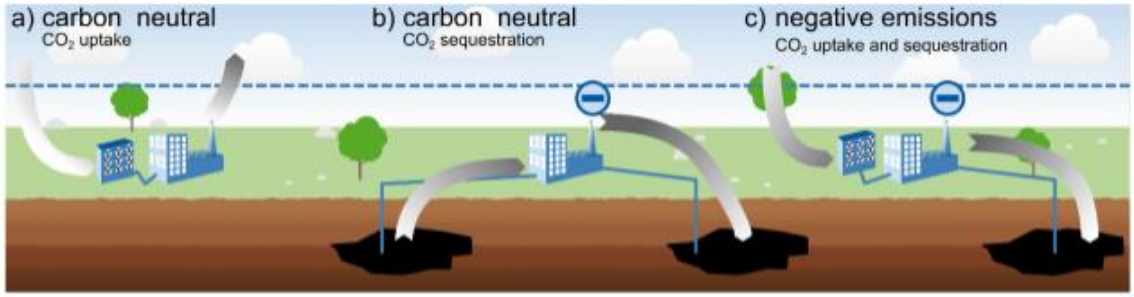


Figure 1 Principal flow diagrams for CO_2 neutrality and negative emissions (from Zimmermann, Müller et al. (2018)

Figure 2 shows corresponding flow diagrams for CCU cases. For all CCU cases, expect for a potential case when the captured CO_2 is permanently stored in a product, CCU technologies will have positive CO_2 emissions (burdens) over the life cycle, independent of whether or not the CO_2 source is fossil or

biogenic. This is shown in Figure 2. However, the emissions from the CCU case might be lower than for a competing Reference case based on conventional processes.

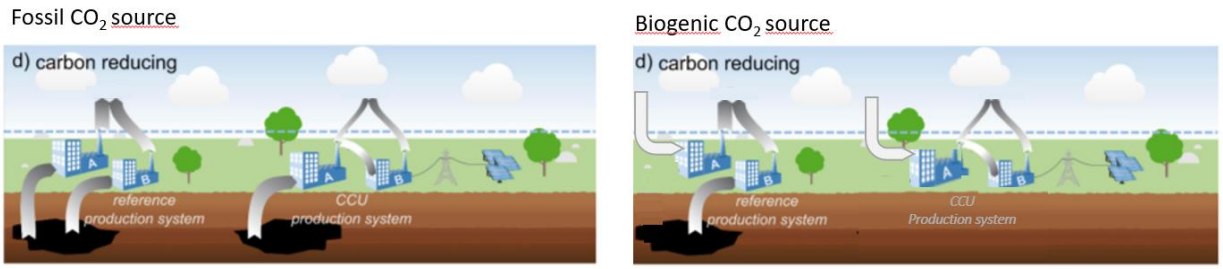


Figure 2 Principal flow diagrams for reduced CO_2 emissions, in CCU systems (from Zimmermann, Müller et al. (2018))

In this case, the CCU process might contribute to climate change mitigation through substitution and hence avoided emissions. Even though such processes lead to lower CO_2 emissions compared to the Reference case, they are not carbon negative. Through applying system expansion by substitution, negative LCA results can be computed. However, such negative LCA results only reflect a comparison. In particular, negative LCA results do not imply that the CCU product is carbon neutral or even has negative emissions over its life cycle. Therefore, negative CO_2 emissions obtained from substitution shall be clearly stated as an environmental benefit compared to the benchmark technology and not as negative CO_2 emissions over the life cycle.

1.2 Geographical boundaries and boundaries to nature and society for CCUS systems

Most CCU systems are multi-functional, because they provide two functions: 1) capture and removal of the CO_2 from a process, and 2) use the captured CO_2 as feedstock for a new product (e.g., fuel). This is show in Figure 3. Hence, the total emissions of the system are shared between these two functions/products.

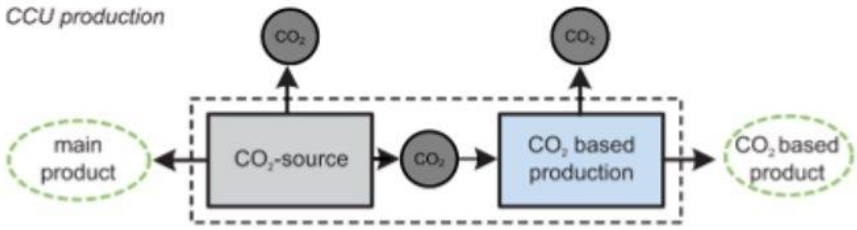


Figure 3 CO_2 capture with subsequently production of a CO_2 based product (from Zimmermann, Müller et al. (2018)).

This problem is called multi-functionality. Other co-products or functions may occur throughout the life cycle of CCU products. In general, the problem of multi-functionality is not a CCU-specific problem. The problem can be addressed using established LCA methodologies. However, a number of methodological choices have to be made, and system expansion is a recommended method for CCU systems. System expansion expands the functional unit to include other functions of the product systems than were

originally stated in the goal and scope definition. If this expanded function is still meaningful, the multifunctionality problem is resolved. As discussed above, CCU processes are often compared to conventional processes. To compare both product systems, each product system needs to fulfil the same functional unit and therefore, the system boundaries and the functional unit are changed for the product systems. For the comparison of the CCU process with two products (product of CO_2 source and product of CO_2-process) to a conventional system, the main product of the CO_2 source is added to the functional unit and the conventional system is expanded with the CO_2 source without capture (see Figure 4).

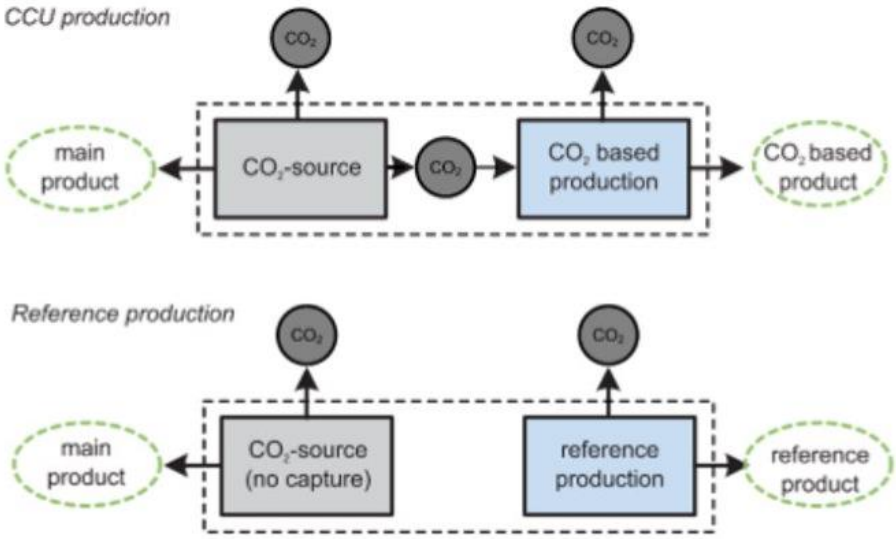


Figure 4 Production of equivalent products and functions with and without CCUS (from Zimmermann, Müller et al. (2018))

A functional unit for a system as described in Figure 4 might be: *Production of 1 MJ heat from waste incineration and 1 MJ fuel – with and without CCUS.*

1.3 Management of the project and quality control

The modelling and analyses behind this report has been performed in the period May 2020 to June 2021 and the methodology is based on guidelines found in the literature study (Zimmermann, Müller et al. 2018, Raadal, Booto et al. 2020). Discussions in the project's steering committee have been used to create a principal process flow diagram, which has been the foundation for defining the functional units of the analyses. This principal flow diagram, the functional units and the data gathered from cooperating partners and literature have in turn been transformed into an LCA model in the SimaPro software.

NORSUS has worked in close cooperation with CO_2 Capsol (Jan Kielland and Stellan Hamrin) and Baker Hughes (Kari Forthun and Torleif Kongsbakk Madsen) for data collection of the capture technologies. The same goes for Norske Skog Saugbrugs (Trond Mageli and Gudmund Jensen) and Sarpsborg Aavfallsenergi/SAE (Lise Haugesten and Frode Schjolden) for data collection for the point sources. CO_2 Capsol, Baker Hughes, Norske Skog Saugbrugs and SAE have all been presented the input data used in

the modelling and given feedback on possible errors. Errors have then been corrected before final analyses.

The steering committee has performed quality control on the principal process flow and given feedback on preliminary results and the draft report. Sensitivity analyses using extreme values has been used to stress test the model in search for errors.

2 Goal and scope

The study is carried out using life cycle assessment (LCA) methodology according to the ISO-standards 14044/48 (ISO 2006, ISO 2006) and the guidelines provided by Zimmermann, Müller et al. (2018) and von der Assen, Jung et al. (2013) for CCU value chains. These guidelines focus on the importance of joint evaluation of all functions in CCU system (using system expansion for solving the multi-functionality), in addition to classifying feedstock CO_2 as an economic flow (not intuitively considering utilized CO_2 as negative GHG emission). A literature study of LCA of CCUS systems (Raadal, Booto et al. 2020) was performed by NORSUS to set the premises for the systems analysed in this report. A summary of the guidelines found in this literature study has been included in the chapters 1.1 and 1.2.

Life cycle assessment of a product is defined as systematically mapping and evaluation of environmental and resource impacts throughout the entire life cycle of the product, from 'cradle to grave'. The analysis is based on a product system and considers environmental and resource impacts in relation to a defined functional unit, describing the performance of the product according to particular user needs.

2.1 Goal of the project

The goal of the project is two folded as the study looks at both CCS and CCUS systems. The examined CCU system represents production of a short-lived product (in this study: fuel). The intended audience of the study is all the partners in the project and interested parties in general.

CCS systems: To assess the environmental performance of CCS at Norske Skog Saugbrugs paper mill and the Waste to Energy plant Sarpsborg Avfallsenergi, respectively, compared to a Reference system without CCS.

CCUS systems: To assess the environmental performance of CCS and CCU at Norske Skog Saugbrugs paper mill and the Waste to Energy plant Sarpsborg Avfallsenergi, respectively, compared to a Reference system without CCUS. The CCU scenario in this study uses the captured CO_2 as feedstock for methanol production (e-fuel[3]). As methanol is one product from the CCU scenario, the comparable Reference and CCS scenarios must also provide this function. This is solved by extending the system to include

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

conventional production of methanol in the Reference and CCS scenarios. The CCU scenario additionally needs large amount of renewable electricity to produce this fuel, and the CCS and Reference scenarios are therefore provided with the same amount of renewable electricity, which can be used to substitute e.g., other electricity sources. Hence, by the use of system expansion (see chapter 1.2), all the CCUS scenarios provide the same functions and are provided with same large amount of renewable electricity:

1. Producing either paper or heat (WtE)
2. Producing fuel (methanol)
3. Using renewable electricity

2.2 Scope

It should be emphasised that the analyses are not designed in order to compare the two capture technologies because the capture systems have not been optimized when it comes to energy carriers and synergies with potential excess energy, etc. at the paper mill/WtE plant (see chapter 3.2). The difference between the two cases with regards to captured biogenic CO_2 is, on the contrary, an important aspect of the study. Hence, the CCS and CCUS results are compared with no capture (Reference) and not with other capture technologies.

This study has focused on the principal issues for CCS and CCUS systems; which life cycle phases are most important for the different indicators, and how does the share of biogenic CO_2 in captured CO_2 affect the results. As this study is principal and do not compare different technologies, external review has not been included.

It has been too early for the capture technologies involved to reveal detailed emission data for chemicals used in these processes for the actual cases. Hence, toxicity has not been included as an indicator due to lack of data.

Emissions of biogenic CO_2 are assumed causing the same climate change as fossil CO_2. These emissions are neutralized by assuming the same amount of CO_2 being removing from the atmosphere when the trees are growing.

2.3 Functional unit (FU)

The study presents the results for two different functional units related to the systems and the respective goals described in chapter 2.1:

1. CCS systems: industrial production with or without capture of 50 000 tonne CO_2, with corresponding transport and storage of CO_2.
2. CCUS systems: industrial production with or without capture of 50 000 tonne CO_2, with corresponding transport and storage or use of CO_2; production of fuel corresponding to the captured amount of CO_2; and use of renewable electricity for internal purposes or for substitution.

For the first functional unit, two scenarios have been analysed; with and without CCS. The second functional unit has been analysed using three scenarios; without CCS, with CCS, and with CCU. All scenarios have been analysed for two cases; Norske Skog Saugbrugs (paper production) and Sarpsborg Avfallsenergi/SAE (waste to energy), which in sum leaves us with 10 scenarios. This is summarised in Table 1 below.

Table 1 Scenarios analysed

System	Case	Scenario	Functions
CCS	Norske Skog Saugbrugs	Reference	Paper production
		CCS	Paper production
	Sarpsborg Avfallsenergi (SAE)	Reference	Heat production
		CCS	Heat production
CCUS	Norske Skog Saugbrugs	Reference	Production of paper and fuel; use of renewable electricity
		CCS	Production of paper and fuel; use of renewable electricity
		CCU	Production of paper and fuel; use of renewable electricity
	Sarpsborg Avfallsenergi (SAE)	Reference	Production of heat and fuel; use of renewable electricity
		CCS	Production of heat and fuel; use of renewable electricity
		CCU	Production of heat and fuel; use of renewable electricity

2.4 System boundaries

2.4.1 CCS systems: Geographical boundary and boundaries to nature and society

Figure 5 shows the process flow diagrams for the Reference scenario and CCS scenario, representing the CCS system.

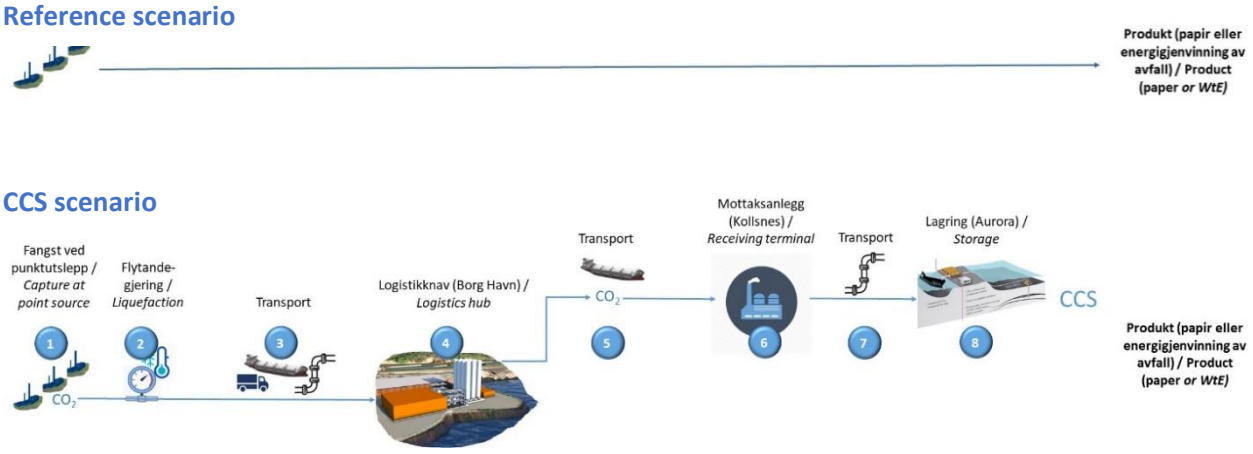
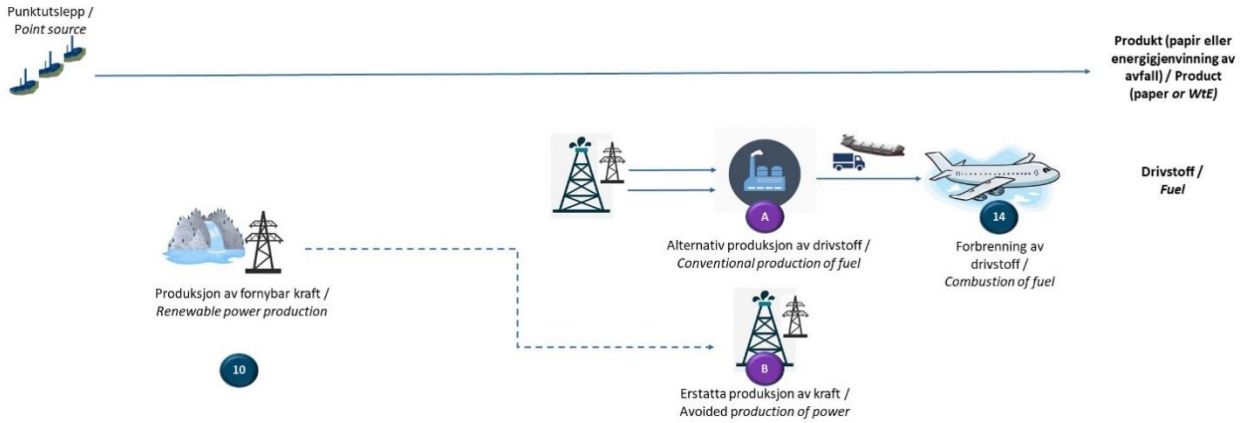


Figure 5 Process flow diagrams for the CCS systems

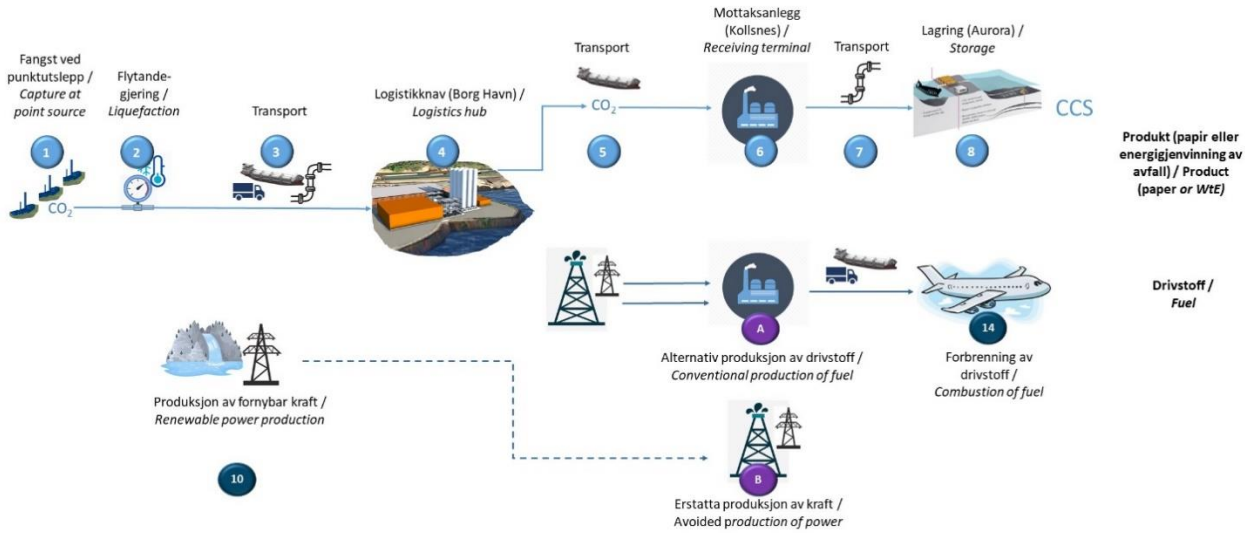
2.4.2 CCUS systems: Geographical boundary and boundaries to nature and society

Based on the system expansion method described in in chapter 1.2 for solving the multifunctionality problem, process flow diagrams for the Reference scenario, the CCS scenario and the CCU scenario are shown in Figure 6.

Reference scenario



CCS scenario



CCU scenario

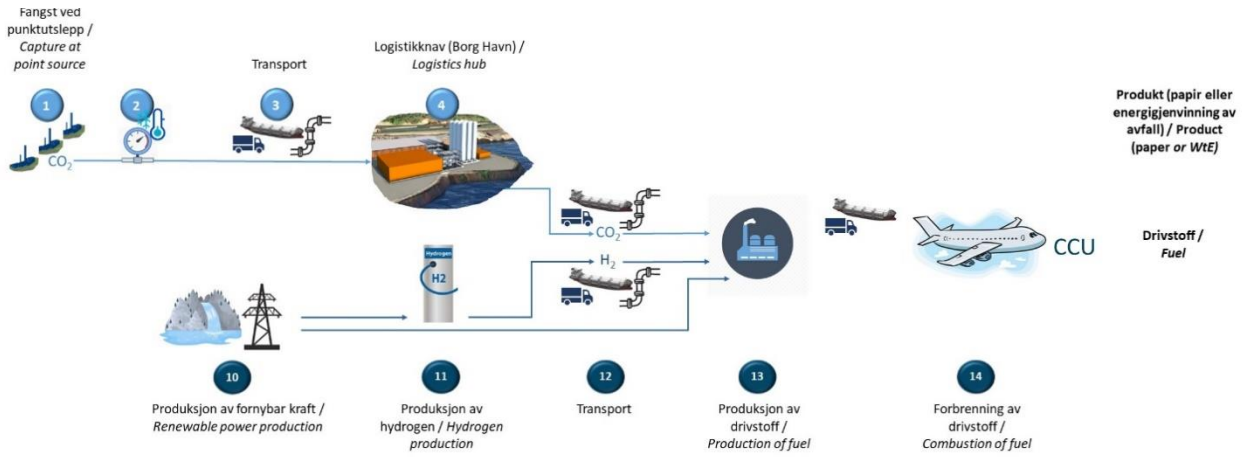


Figure 6 Process flow diagrams for the CCUS systems (joint functional unit)

Production of infrastructure has been added for pipeline transport of CO_2 offshore. For the other specific datasets (production og paper and heat, and for CO_2 capture), infrastructure is not included. Infrastructure is automatically included for all generic datasets.

The examined processes have been assumed to be located in Norway, except for production of conventional fuel and production of avoided power, which are assumed to be produced in Europe.

2.4.3 Technology

Modelling of the foreground systems of the industrial production, capture plant and the transport and storage value chain for captured CO_2 are based on specific data from Norske Skog Saugbrugs, Sarpsborg Avfallsenergi (SAE), CO_2 Capsol, Carbon Capture/Baker Hughes and Equinor and, thus, the exact technology. Data for the capture technologies (CO_2 Capsol and CarbonCapture/Baker Hughes) are, however, not representing any existing plants, rather they are more or less crude estimates given for future capture plants at Norske Skog Saugbrugs and SAE. Data for transport and storage for captured CO_2 is for a specific, planned CO_2 value chain; the Northern Lights project (Equinor 2020). Follow-up questions have been discussed with Equinor (Pinturier 2021).

Short descriptions of the capture technologies and the CO_2 point sources are given below.

CO_2 Capsol:

Capsol EoP (End of Pipe) is a patented post combustion carbon capture solution using pressure and Hot Potassium Carbonate (HPC). A pressurized system is used since chemical reactions are more efficient under high pressure. The Capsol EoP carbon capture solution is a stand-alone unit which does not interfere with the existing facility. Worldwide there are more than 1,000 plants where the HPC process is

used. Capsol EoP uses electric energy for running compressors and pumps. The energy needed for the desorber is internally recuperated by means of a combination of flash boxes and electrically driven compressors, hence there is no need for any heat integration between the point source and the Capsol EoP system. Hot potassium carbonate is a low-cost absorbent, and the Capsol EoP patented energy recuperation recovers most of the energy needed for capturing and pressurizing the CO_2 from the flue gas.

Baker Hughes:
Compact Carbon Capture is a Baker Hughes venture. Compact Carbon Capture was established in 2018 as an innovative start-up to commercialize a compact CO_2 capture technology (3C). In November 2020, the company was fully acquired by Baker Hughes. The Compact Carbon Capture rotating bed technology is a process intensification that utilizes rotation to intensify mass transfer. In principle, it can be applied to any solvent based post-combustion carbon capture technology. As a result of such process intensification, the size of the largest equipment items, namely the absorber and desorber/stripper columns, can be significantly reduced. By this, the capacity and hence the size of other auxiliary equipment can also be reduced.

Norske Skog Saugbrugs:
Norske Skog Saugbrugs in Halden was founded in 1859 and became part of Norske Skog Group in 1989. The company has a long tradition and high competence in making magazine paper for the international market. The main markets are Europe (UK, Germany, France and Italy) and North America. Norske Skog Saugbrugs produces paper on two paper machines with annual capacity 350.000 tonnes and have approximately 400 employees. A 70 MW bio boiler combusting bark, energy wood and other biomasses is used to produce steam for the paper production. The bio boiler at Norske Skog Saugbrugs is one of the largest point sources of CO_2 emission in Norway, and CCS can easily be implemented at the mill.

Sarpsborg Avfallsenergi/SAE:
SAE is a Waste to Energy (WtE) gasification plant for energy utilization of waste based fuels, using Energos gasification technology. The energy (steam) is delivered to Borregaard AS. The gross production capacity is 255 GWh and the net amount delivered is approximately 210 GWh. The total installed effect is 32.4 MW, by two lines of 16.2 MW each, and the steam production is 40 tonne per hour (22 bar). Approximately 80 000 tonne of waste is used as fuel annually and the CO_2 emissions are over 40 000 tonne/year. SAE is part of both the EU ETS and NOx fund.

Data for production of methanol from electricity and CO_2 have been found in literature (Agency) and Energinet 2017) and by personal communication (Korberg 2020). Several technologies have been considered, and a simple two-stage model for production of hydrogen followed by production of methanol from hydrogen and CO_2, both based on average data, have been used.

Data for chemicals, energy, waste treatment and conventional production of methanol have been found in the most updated ecoinvent database (version 3.6).

2.4.4 Time

Specific data for Norske Skog Saugbrugs and SAE represents 2015 - 2019. Data for the capture technologies were given autumn 2020 and winter 2021. Data for the CO_2 transport and storage value chain are from 2020.

Data for production of other raw materials, energy, transport and waste treatment options have been found in the most updated ecoinvent database (version 3.6). However, choosing the most correct technology has been prioritised over newer data.

2.4.5 Cut-off criteria

In order to reduce the extent and complexity of the study, the system boundaries were set to minimize the scale while still answering the research question properly. Hence, the production processes at the point source for CO_2 were not included, except for the flue gas itself. This choice has no consequences on the validity of the conclusions from the study, as the results for all scenarios (including the reference scenarios) would have been affected the same way. For the same reason, dismantling has neither been included.

2.5 Allocation procedures

For generic data, ecoinvent's 'cut off by classification' database have been used. The underlying philosophy of this approach is that primary (first) production of materials is always allocated to the primary user of a material. This is in line with the polluter pays principle. In this study, allocation has been avoided as far as possible by using a joint functional unit for the CCUS systems.

2.6 Impact assessment

In this report, the climate change impact category is in focus. However, in order to avoid problem shifting, some impact categories affected by the increased resource and energy use by CCS and CCUS have been included as well. Toxicity has not been included (see chapter 2.2).

Table 2 Impact assessment methods used in this study

Environmental impact category	Unit	Impact assessment method	Comment and potential effects
Climate change	kg CO_2-eqv.	EN 15804 +A2 Method V1.00 as implemented in SimaPro 9.1.0.11 multi user.	This method is identical to the EF 3.0 method, except for a few characterization factors: - carbon dioxide (biogenic), emission, factor 1 - carbon monoxide (biogenic), emission, factor 1.57 - methane (biogenic), emission, factor 36.75 - carbon dioxide, resource, factor -1

			Leads to increased average global temperature, more extreme weather, increased sea level, impacts on human health, material resources, and ecosystems.
Acidification potential	kg SO_2-eqv.	EN 15804 +A2 Method V1.00 as implemented in SimaPro 9.1.0.11 multi user.	Acid depositions lower pH in soil and water bodies and affect plants and animals, as well as buildings and other infrastructure.
Fossil resources: ADP_{fossil}	MJ LHV		ADP_{fossil} is short for Abiotic Depletion Potential for fossil fuels. This is a resource indicator showing use of primary fossil energy. It does not count the direct use of fossil energy, rather the fossil energy that is taken from the earth as a consequence of the activities in the value chain under scrutiny. Example: for a truck using diesel when transporting timber, the ADP_{fossil} will constitute the fossil feedstock energy in diesel (crude oil), in addition to the fossil energy needed for offshore operations, transport of crude oil onshore, refinery processes and transport of diesel for sale.
Use of primary energy: cumulative energy demand (CED)	MJ HHV in LCA	Cumulative Energy Demand v1.11 from ecoinvent (November 2018)	CED is short for Cumulative Energy Demand, and it is a resource indicator in the same way as ADP_{fossil}. However, the CED indicator includes not only fossil primary energy, but all forms of primary energy. As a consequence, the CED value is most often larger than the value for ADP_{fossil} when analysing the same system. In the diesel example above, renewable primary energy used for producing diesel will be included as well. This could, for example, be hydro power in electricity used by the offshore installations producing crude oil, which in turn is transformed into diesel in the refinery.

2.7 Modelling tool

The SimaPro 9.1.0.11 Multi user software has been used together with the ecoinvent 3.6 database in order to model and carry out the analyses.

3 Life cycle inventory

3.1 Use of generic and specific data

The foreground systems for the point source, capture plant and the transport and storage value chain for captured CO_2 are based on specific data regarding amounts used (see the system boundaries description in chapter 2.4). The same goes for transport distances, means of transport, and for energy use and emissions regarding storage of captured CO_2.

Data for production of methanol from CO_2 are taken from literature. Data for chemicals, energy, waste treatment, conventional production of methanol and transport emissions are taken from databases, as well as data for pipeline infrastructure.

3.2 Data and data sources

The inventory data used for modelling have been summarised in Table 3. The values and units given in this table have, as far as possible, been presented in the same form as provided to NORSUS.

Table 3 Inventory data used in modelling of the different processes

Process/case/parameter				Unit	Value	Comment
Point source		Norske Skog Saugbrugs	Magazine paper	tonne/year	387 330	
			Flue gas	Nm^3/year	$633.4*10^6$	
			CO_2 emission	tonne/year	198 900	
			Biogenic share of flue gas	%	99.3	Included as extracted CO_2 from air by wooden biomass.
			Emission of NOx	mg/Nm^3	139	
			Emission of particulates	mg/Nm^3	1.01	
			Emission of sulfur dioxide	mg/Nm^3	10.62	
			Emission of methane	tonne/year	2.0	Biogenic.
		SAE	Flue gas	Nm^3/year	$480*10^6$	$739*10^6$ m^3/year (84 401 m^3/h) at 150°C corresponds to $480*10^6$ Nm^3/year (54 472 Nm^3/h (0°C).
			CO_2 emission	tonne/year	95 900	
			Biogenic share of flue gas	%	56.3	Included as extracted CO_2 from air.
			Emission of NOx	kg/year	25 000	
			Emission of particulates	mg/Nm^3	n.a.	
			Emission of sulfur dioxide	mg/Nm^3	n.a.	
			Emission of methane	tonne/year	n.a.	
1	Capture at point source	Norske Skog Saugbrugs	Capture rate	%	90	CO_2 Capsol technology
			CO_2 emission	tonne	5 555	Per 50 000 tonne captured.
			Emission of NOx	mg/Nm^3	69.5	50% reduction
			Emission of particulates	mg/Nm^3	-	100% reduction
			Emission of sulfur dioxide	mg/Nm^3	5.31	50% reduction
			Emission of methane	tonne/year	2.0	No change. Biogenic.
			Sludge for treatment	tonne	4.5+44.0 +0.64+3.36	Per 50 000 tonne captured CO_2. Assumed as the sum of refilled potassium carbonate and captured NOx, particulates and SOx.
			Electricity (Norway)	GJ/tonne captured CO_2	1.0	Combining CC with liquefaction and heat recovery will lead to using 1.0 GJ for capture and 0.3 GJ for liquefaction.
			Use of potassium carbonate	kg/tonne captured CO_2	0.09	

Process/case/parameter				Unit	Value	Comment
			Use of boric acid	kg/tonne captured CO_2	3/25*0.09	Assumed as 3/25 of the potassium carbonate amount.
			Use of vanadium pentoxide	kg/tonne captured CO_2	1/25*0.09	Assumed as 1/25 of the potassium carbonate amount.
		Sarpsborg Avfalls-energi (SAE)	Capture rate	%		
			CO_2 emission	tonne		
			Emission of NOx	kg/year		
			Emission of particulates	mg/Nm^3		
			Emission of sulfur dioxide	mg/Nm^3		
			Emission of methane	tonne/year		
			Sludge for treatment	tonne		
			Electricity (Norway)	GJ/tonne captured CO_2		
			Steam	GJ/tonne captured CO_2		
			Use of monoethanolamine/MEA	tonne/year		
2	Lique-faction	Norske Skog Saugbrugs	Compression loss	%	1.0	Included as an emission. Reduces the amount going to logistics hub.
			Electricity	GJ/tonne captured CO_2	0.3	When combined with CC. Data from CO_2 Capsol.
		Sarpsborg Avfalls-energi (SAE)	Compression loss	%		
			Electricity	kWh/tonne captured CO_2		
3	Transport	Norske Skog Saugbrugs	Distance, on road	km	38	Biogas vehicle, 32 tonne load. Generic dataset, including infrastructure.
		Sarpsborg Avfalls-energi (SAE)	Distance, on road	km	17	Biogas vehicle, 32 tonne load. Generic dataset, including infrastructure.
4	Logistics hub		Leakage of CO_2 when loading from trucks	l/truck		Leakage during coupling/decoupling, per 30 tonne loaded CO_2. Due to small volumes, the modelling has not taken this leakage into account regarding downstream amount of CO_2.
			Leakage of CO_2 from tubes	tonne/year		Leakage caused by purging and depressuration of loading arms after operation, per 1 mill tonne CO_2 loaded. This leakage is taken into account when modelling the downstream amount of CO_2.
			Electricity (Norway)	MWh/year		Electricity consumption for ships at each terminal (this one is for Borg Havn), assuming two ships and 0.8 mill tonne CO_2 transported.
5	Transport		Leakage of CO_2 when loading to ship	tonne/year		Leakage caused by purging and depressuration of ship manifolds after operation, per 1 mill tonne CO_2 loaded. This leakage is taken into account when modelling the downstream amount of CO_2.
			Leakage of CO_2 from ship	tonne/year		Leakage caused by purging of tanks and cooling every 5 years, per year and per 1

Process/case/parameter			Unit	Value	Comment
					mill tonne CO_2 transported. This leakage is taken into account when modelling the downstream amount of CO_2.
		Electricity (Norway)	MWh/year	[redacted]	Electricity consumption for ships at each terminal (this one is for Kollsnes receiving terminal), assuming two ships and 0.8 mill tonne CO_2 transported.
		Distance, on sea	700	km	Ship, tanker for liquid goods. Generic dataset, including infrastructure.
6	Receiving terminal	Leakage of CO_2 at terminal	tonne/year	[redacted]	Leakage caused by maintenance operations at receiving terminal, for 1.5 mill tonne CO_2 handled. This leakage is taken into account when modelling the downstream amount of CO_2.
		Electricity (Norway)	MWh/year	[redacted]	Electricity consumption for injection of 1.5 mill tonne CO_2.
7	Transport	Pipeline infrastructure	km	100	Generic data for offshore petroleum pipeline from the ecoinvent database: Pipeline, petroleum, offshore (GLO)| market for | Cut-off, U
		Lifetime for infrastructure	years	20	Generic information for offshore petroleum pipelines from the ecoinvent database.
		Use and emission of mono ethylene glycol (MEG)	l/year	[redacted]	Per 1.5 mill tonne CO_2 for storage.
		Use and emission of other chemicals	l/year	[redacted]	Per 1.5 mill tonne CO_2 for storage.
		Use and emission of N_2	l/year	[redacted]	Per 1.5 mill tonne CO_2 for storage.
8	Storage	-	-	-	No resources or emissions.
9	-	-	-	-	Not in use.
10	Renewable power production	Wind power, high voltage	kWh	See Table 4	Generic dataset for onshore turbine, > 3 MW, including infrastructure (from ecoinvent).
11	Hydrogen production	Electricity	kWh/kg H_2	53.3	Simple modelling using 74% efficiency.
12	Transport	-	-	-	Not included.
13	Production of fuel (methanol/CH_3OH)	Use of H_2	kg/kg methanol	0.194	Corresponds to 83.4% efficiency based on energy content.
		Use of CO_2	kg/kg methanol	1.686	Corresponds to 0,263 kg CO2 used per kWh methanol produced.
		Excess heat	-	-	Not included. Could be used for energy optimization, for example by using the heat in the capture process.
14	Combustion of fuel	Emission of CO_2	kg/kg methanol	1.375	Simplified calculation based on stoichiometry and mol weights: one mol CH_3OH gives one mol CO_2, leading to 44/32=1.375 g CO_2 being made per g methanol combusted.
A	Conventional production of fuel	Methanol production, global	kg	See Table 4	Generic dataset based on the global market of methanol production, including infrastructure (from ecoinvent). Changed the feedstock energy substance to avoid inclusion as energy use.
B	Avoided production of power	Electricity based on natural gas, high voltage	kWh	See Table 4	Generic dataset for production of power from natural gas, conventional powerplant (gas turbine), in the Netherlands, including infrastructure (from ecoinvent).

Based on the CO_2 capture rates, losses of CO_2, as well as electricity used for producing methanol from captured CO_2, the amounts of produced fuel and renewable power production available for other utilities have been calculated (Table 4).

Table 4 Main values defining the functional units

Case	Scenario	Industrial production at point source		CO_2			Produced fuel (methanol)[2)]		Renewable power production and avoided production of power[2)]	
				Captured	Emitted					
Norske Skog Saugbrugs	Reference	108 000	tonne paper	-	55 555	tonne	29 400	tonne	302	GWh
	CCS[1)]			50 000	5 555	tonne			302	GWh
	CCU[1)]			50 000	5 555	tonne			-	GWh
Sarpsborg Avfalls-energi (SAE)	Reference	278*10^6	Nm^3 flue gas	-	55 555	tonne			302	GWh
	CCS[1)]			50 000	5 555	tonne			302	GWh
	CCU[1)]			50 000	5 555	tonne			-	kWh

1) For a capture rate of 90%, the released amount of CO_2 from the Reference scenario is 50 000 tonne/0,9 = 55 555 tonne.
2) Based on a compression loss of 1.0% for liquefaction.

As emphasised in chapter 2.2, the carbon capture processes have been modelled without relevant energy integration with external activities. Such energy integration could be relevant if 1) the process at Norske Skog Saugbrugs or the WtE process at SAE could provide steam for the capture process, or 2) a potential plant for utilisation of CO_2 for production of methanol is located nearby (excess heat from reaction of hydrogen with CO_2). As for now, both capture processes analysed have been modelled using electricity (Norwegian electricity mix) delivered from the grid as the energy carrier for the capture process.

The capture processes have also been modelled without pre-capture of NOx, SOx and particulates, which can lead to reduced efficiency, increased use of input chemicals and increased waste volumes. Hence, pre-capture of these emissions leads to a trade-off situation.

4 Results and discussion for CCS systems: production of paper and WtE

This chapter presents the results for the CCS systems as presented in Figure 5 (chapter 2.4.1). The goal is to assess the environmental performance of CCS at Norske Skog Saugbrugs paper mill and the Waste to Energy plant Sarpsborg Avfallsenergi, respectively, compared to a Reference system without CCS.

4.1 Results for climate change

The climate change[4] results (tonne CO_2-eq per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 7 and Figure 8, respectively. Both cases show the CCS scenarios compared to their respective Reference scenarios.

[4] For more information about the environmental impact category climate change, see Table 2.

The results are presented as positive and negative climate emissions from the different activities in the life cycle value chain. In Figure 7 and Figure 8 the burden from the different activities are presented by coloured bars. In addition, the net emissions, representing the total sum of positive and negative emission, are presented by the black lines in the figure. A short description of the different activities, numbered according to Figure 5, is given below:

1a Uptake of bio-CO_2	Negative emission occurring when the trees are growing
1b Exhaust, point source	Emissions occurring at the CO_2 source
1b CO_2 capture	Burdens connected with use of energy and chemicals, in addition to direct emissions and waste treatment, occurring at the CO_2 capture plant. The CO_2 not being captured is also included here.
2-4 Liquefaction and trp of CO_2 to logistic hub	Burdens connected with energy use in addition to direct emissions, occurring from the liquefaction process. Burdens (energy and direct emissions) also from transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn.
5-8 Trp and storage of CO_2	Burdens connected with use of energy and chemicals, in addition to direct emissions, from transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.
Total	Sum of burdens throughout the value chain.

Figure 7 shows the climate change results (tonne CO_2-eq per functional unit) for the Reference and CCS scenarios at Norske Skog Saugbrugs.

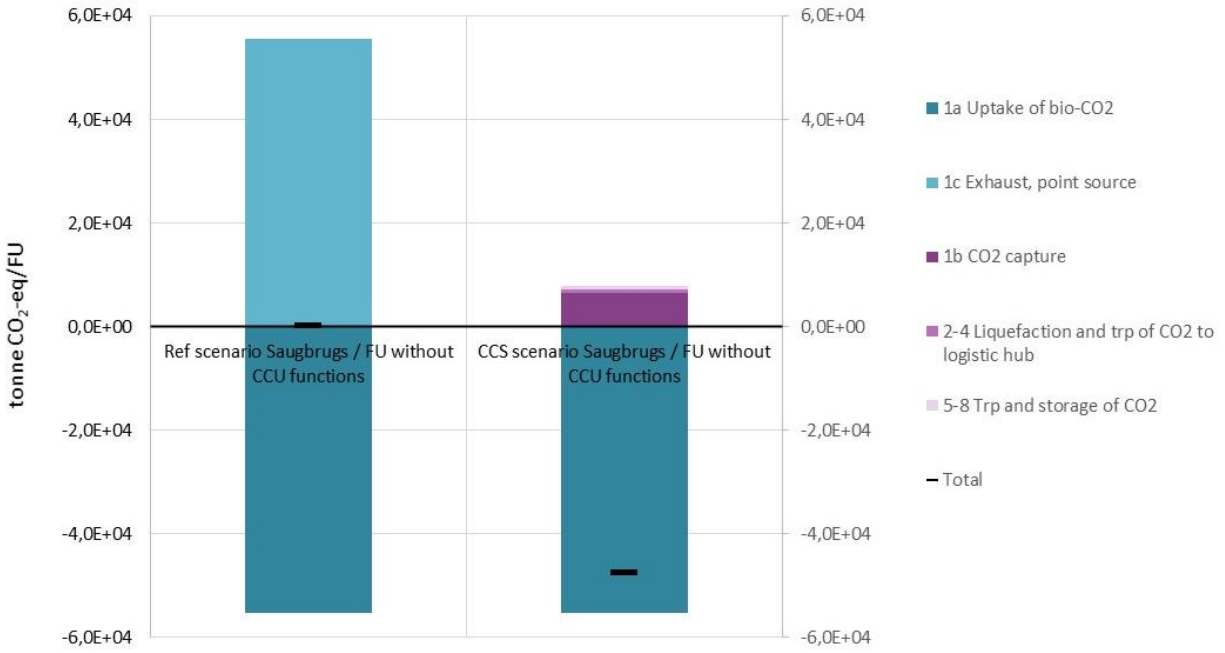


Figure 7 **Climate change result per functional unit (FU) for the CCS scenario for the Norske Skog Saugbrugs case (paper production) compared with its Reference scenario.**

Figure 7 shows that, in total, the CCS at Norske Skog Saugbrugs leads to negative emissions (shown by the Total legend), which means that the CCS system removes greenhouse gas emissions from the atmosphere. The corresponding result for the Reference case is approximately zero, which means that the CCS scenario gives a considerable better result. In the Reference scenario, the uptake of biogenic CO_2 and the emissions of CO_2 from the point source are almost equal (as the share of biogenic CO_2 emissions at Norske Skog Saugbrugs is 99.3%), leading to an almost net zero burden for the climate change indicator (400 tonne CO_2-eq/FU). The CCS case (when assuming 90% capture rate) gives a net negative climate change result of 47,400 tonne CO_2-eq/FU, which means a reduction of CO_2 in the atmosphere.

As seen from the figure, the most dominating life cycle phase for climate change in both cases is uptake of biogenic CO_2, which represents negative emissions (shown by the dark blue bar, 1a). In the Reference case these negative emissions are balanced by the exhaust emissions from Norske Skog Saugbrugs (light blue bar, 1c), resulting in approximately net zero burden.

For the CCS scenario, the second largest contributor is the capture process (dark purple bar, 1b) which includes the 10% emitted CO_2 (not captured as the assumed capture rate is 90%) as well as emissions from energy use, production of chemicals, etc. that are needed for running the capture process. Finally, Figure 7 shows that the activities 2-8 (liquefaction, transport of CO_2 to logistic hub and transport and storage of CO_2) contribute to a very small degree to climate change in the CCS scenario.

Based on the above analysis for the CCS scenario, the fossil CO_2 footprint throughout the value chain per tonne stored CO_2 has been calculated. As this calculation represents a functional unit of 1 tonne stored CO_2, which is different from the functional unit used in this study (50 000 tonne CO_2 captured), the numbers cannot be taken directly from Figure 7. The calculated fossil CO_2 footprint for the Norske Skog Saugbrugs case is 0.034 tonne fossil CO_2-eq per tonne stored CO_2[5]. This can be compared to results for Norcem and Fortum Oslo Varme (FOV) from (Gassnova 2020), for a lifetime of 25 years, having corresponding numbers of 0.047 and 0.061 tonne CO_2-eq per tonne stored CO_2, respectively.

The share of biogenic CO_2 in the flue gas at Norske Skog Saugbrugs is 99.3%. Hence, 0.993 tonne biogenic CO_2 is removed from the atmosphere per tonne CO_2 stored. This can also be expressed as -0.993 tonne bio-CO_2 per tonne stored CO_2 and be compared to the corresponding numbers from (Gassnova 2020) of -0.053 and -0.439 tonne bio-CO_2 per tonne stored CO_2 for Norcem and Fortum Oslo Varme, respectively.

Figure 8 shows the climate change results (tonne CO_2-eq per functional unit) for the Reference and CCS scenarios at SAE.

[5] Ideally, this indicator should reflect the climate burden per tonne stored biogenic CO_2 (the denominator should only include biogenic CO_2), to be in line with Zimmermann. However, to be able to compare to the numbers given by Gassnova, this study has chosen to use the same basis as Gassnova (per tonne total CO_2 stored)

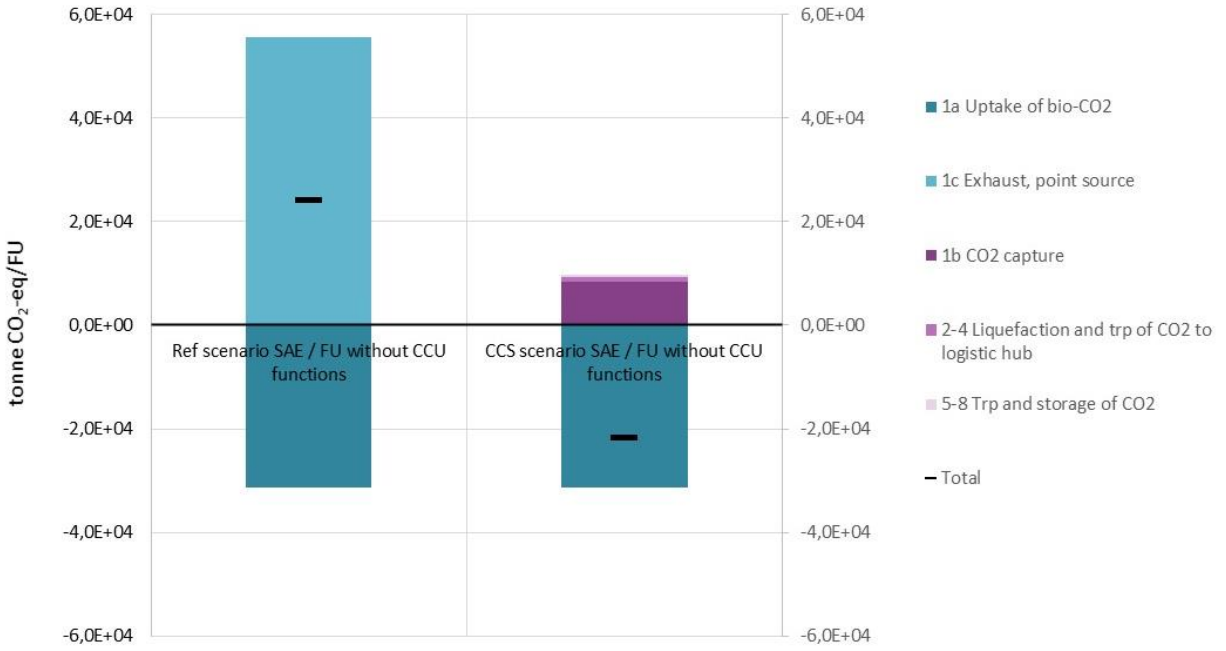


Figure 8 **Climate change result per functional unit (FU) for the CCS scenario for the SAE case (WtE) compared with its Reference scenario.**

The figure shows results that are clearly in line with the Norske Skog Saugbrugs case; the CCS scenario results in net negative emissions (shown by the Total legend), which means a considerable better result compared to the Reference scenario.

Unlike the results in Figure 7 from the Saubrugs case, Figure 8 shows that the uptake of biogenic CO_2 is less than the emissions of CO_2 from the point source. This is logic as the share of biogenic CO_2 emissions at SAE is 56.3% (compared to 99.3% at Norske Skog Saugbrugs). Hence, the net climate burden for the Reference scenario results in a positive number (24,300 tonne CO_2-eq/FU). Nevertheless, the CCS case (when assuming 90% capture rate) results in net negative emissions of about 21,500 tonne CO_2-eq/functional unit which means a reduction of CO_2 in the atmosphere.

When comparing Norske Skog Saugbrugs and SAE, one can conclude that the share of biogenic CO_2 in the point source is quite important for the potential of reaching net negative emissions, which means a reduction of CO_2 in the atmosphere. The higher share of captured biogenic CO_2, the higher is the potential for reaching net negative emissions from the value chain.

Based on the above analysis for the CCS scenario, the fossil CO_2 footprint throughout the value chain per tonne stored CO_2 has been calculated also for the SAE case. As this calculation represents a functional unit of 1 tonne stored CO_2, which is different from the functional unit used in this study (50 000 tonne CO_2 captured), the numbers cannot be taken directly from Figure 8. The calculated fossil CO_2 footprint for the SAE case is 0.128 tonne fossil CO_2-eq per tonne stored CO_2[6]. This can be compared to results for

[6] See footnote 5.

Norcem and Fortum Oslo Varme (FOV) from (Gassnova 2020), for a lifetime of 25 years, having corresponding numbers of 0.047 and 0.061 tonne CO_2-eq per tonne stored CO_2, respectively.

The share of biogenic CO_2 in the flue gas at SAE is 56.3%. Hence, 0.563 tonne biogenic CO_2 is removed from the atmosphere per tonne CO_2 stored. This can also be expressed as -0.563 tonne bio-CO_2 per tonne stored CO_2 and be compared to the corresponding numbers from (Gassnova 2020) of -0.053 and -0.439 tonne bio-CO_2 per tonne stored CO_2 for Norcem and Fortum Oslo Varme, respectively.

4.2 Results for acidification

The acidification[7] results (mol H^+-eq per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 9 and Figure 10, respectively. Both cases show the CCS scenarios compared to their respective Reference scenarios. The results are presented for the different activities in the life cycle value chain, presented by coloured bars in Figure 9 and Figure 10. A short description of the different activities, numbered according to Figure 5, is given below:

1a Uptake of bio-CO_2	N/R
1b Exhaust, point source	Emissions occurring at the CO_2 source
1b CO_2 capture	Burdens connected with use of energy and chemicals, in addition to direct emissions and waste treatment, occurring at the CO_2 capture plant.
2-4 Liquefaction and trp of CO_2 to logistic hub	Burdens connected with energy use in addition to direct emissions, occurring from the liquefaction process. Burdens (energy and direct emissions) also from transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn.
5-8 Trp and storage of CO_2	Burdens connected with use of energy and chemicals, in addition to direct emissions, from transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.

Figure 9 shows the acidification results (mol H^+-eq per functional unit) for the Reference and CCS scenarios at Norske Skog Saugbrugs.

[7] For more information about the environmental impact category acidification, see Table 2.

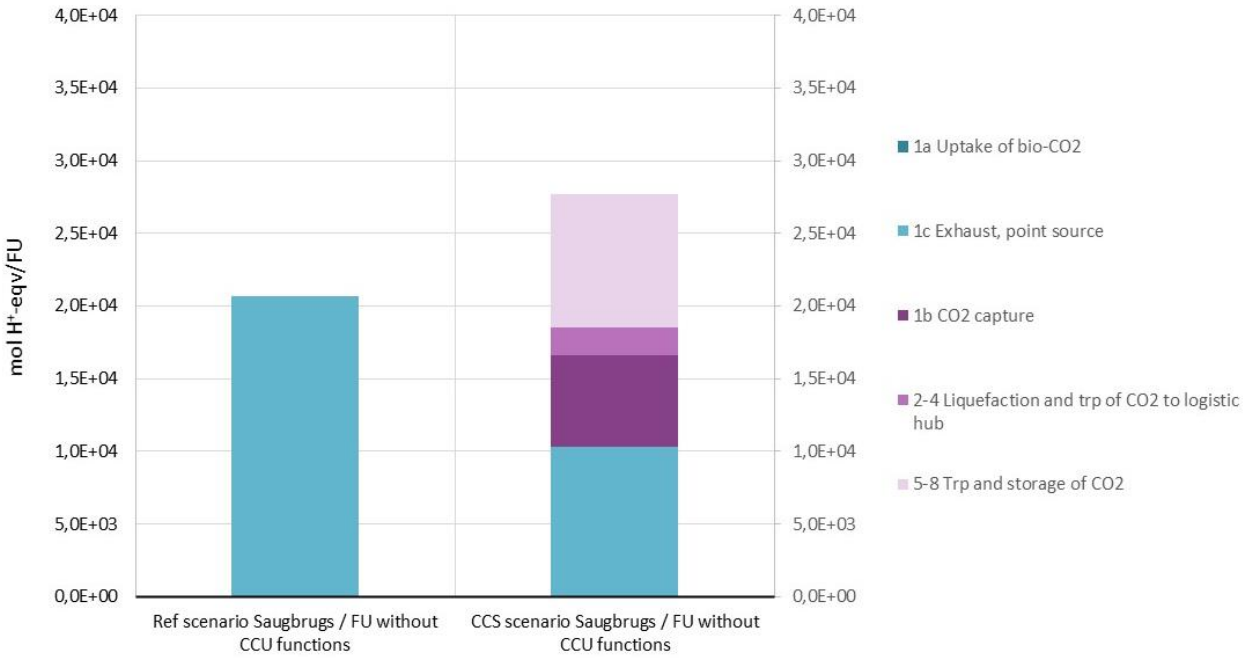


Figure 9 **Acidification results per functional unit (FU) for production of paper at Norske Skog Saugbrugs.**

As seen from the figure, the result for acidification is the opposite as for climate change as the Reference scenario gives the better result. This is logic and in line with other studies (Modahl, Askham et al. 2012, Petrescu, Bonalumi et al. 2017) as burdens from the capture plant and all related activities are added to the system in order to reduce greenhouse gas emissions only (not to reduce emissions contributing to acidification).

Figure 9 shows that the acidification potential from the point source (light blue bars, 1c) is partly reduced in the CCS scenario, but there are also additional emissions from the capture plant (dark purple bar, 1b). The contribution from the capture plant mainly comes from production of electricity used in the capture plant, where the small amount of imported electricity in the Norwegian electricity mix is the dominating factor.

In addition, the figure shows that both the liquefaction and transport of CO_2 to logistic hub activities (shown as purple bar, 2-4 in the figure) and the transport and storage of CO_2 activities (shown as light purple bar, 5-8 in the figure) contribute to the acidification potential.

Figure 10 shows the acidification results (mol H^+-eq per functional unit) for the Reference and CCS scenarios at SAE.

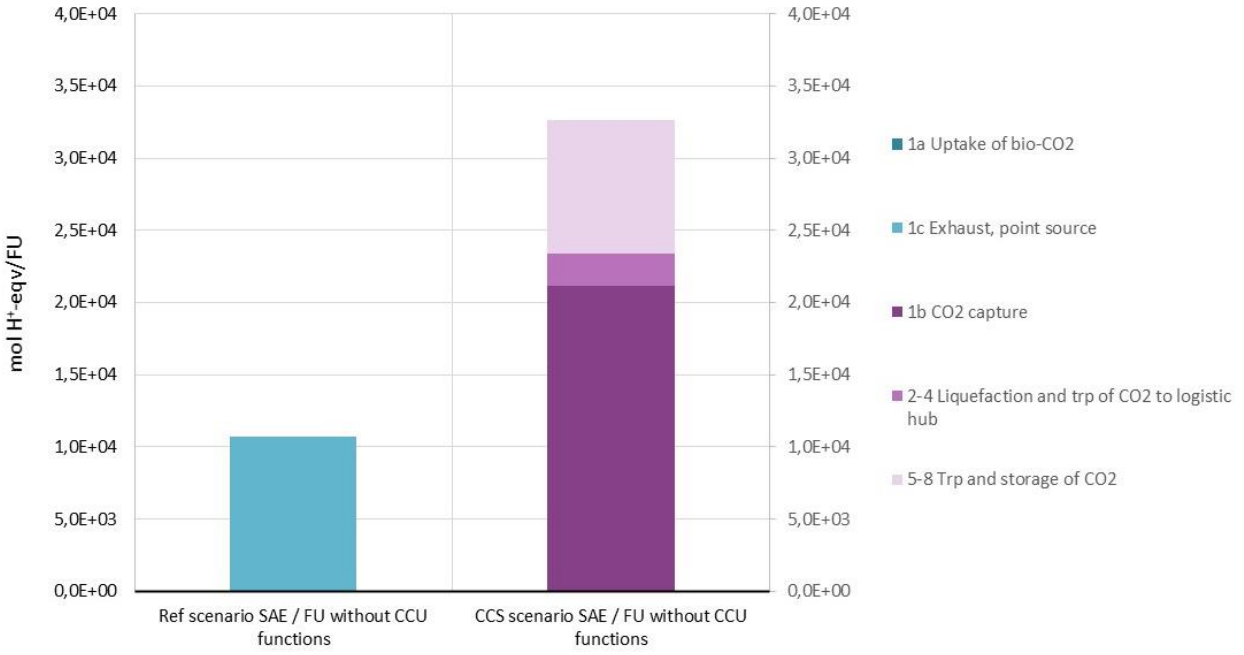


Figure 10 Acidification results per functional unit (FU) for WtE at SAE.

As seen from the figure, the results are generally in line with the Norske Skog Saugbrugs case, showing that the Reference scenario gives the better result for acidification due to extra effort added to the CCS system in order to reduce greenhouse gas emissions only (which has no positive impact on acidification).

In the CCS scenario, there is no acidification connected to the flue gas. This is because the solvent is assumed to react with NOx in a 1:1 stoichiometric relationship. This leads to more solvent being used, and increased amount of sludge from the capture plant to be treated (both issues are included, which affect other indicators). Hence, there is an economic trade-off whether to remove NOx before the capture plant (requires infrastructure) or not, which has not been assessed in this study.

4.3 Results for ADP_{fossil} (use of primary fossil energy)

The ADP_{fossil} results[8] (MJ per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 11 and Figure 12, respectively. Both cases show the CCS scenarios compared to their respective Reference scenarios. The results are presented for the different activities in the life cycle value chain, presented by coloured bars in Figure 11 and Figure 12. A short description of the different activities, numbered according to Figure 5, is given below:

1a Uptake of bio-CO_2	N/R
1b Exhaust, point source	N/R
1b CO_2 capture	Burdens connected with use of energy and chemicals, in addition to waste treatment, occurring at the CO_2 capture plant.

[8] For more information about the environmental impact category ADP_{fossil}, see Table 2.

2-4 Liquefaction and trp of CO_2 to logistic hub	Burdens connected with energy use for the liquefaction process. Burdens also from transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn.
5-8 Trp and storage of CO_2	Burdens connected with use of energy and chemicals for transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.

Figure 11 shows the ADP_{fossil} results (MJ per functional unit) for the Reference and CCS scenarios at Norske Skog Saugbrugs.

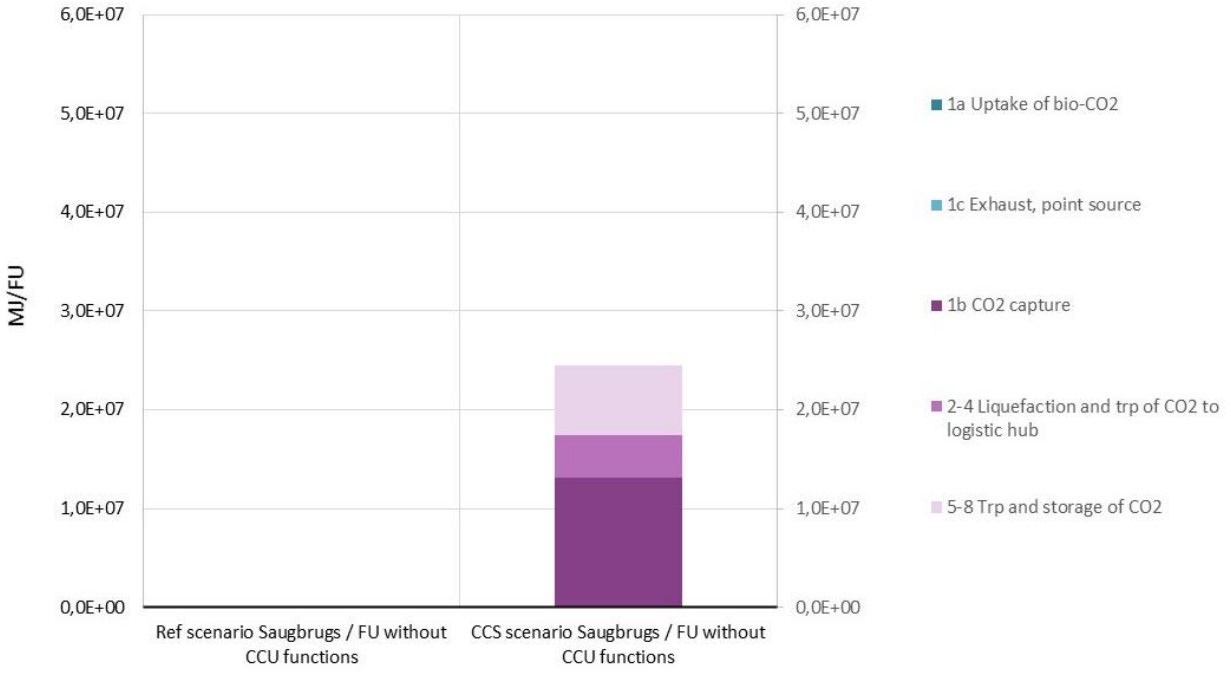


Figure 11 Results for ADP_{fossil} per functional unit (FU) for production of paper at Norske Skog Saugbrugs.

As seen from the figure, the results for ADP_{fossil} are in line with the acidification results: The Reference scenario gives the better result.

Figure 11 shows that ADP_{fossil} for the Reference scenario is zero. The reason for this is that the life cycle value chain for this scenario represents only the emissions at the point source (see Figure 5). As ADP_{fossil} is an impact indicator accounting use of primary fossil energy, and there is no such energy use inside the Reference scenario's system boundaries, the ADP_{fossil} result becomes zero for the Reference scenario.

The CCS scenario, on the other hand, requires use of primary fossil energy for all the activities 2-8, as seen in Figure 11. The capture plant (dark purple bar, 1b) requires energy (both direct and indirect) for running the process as well as for production of chemicals. Furthermore, the liquefaction and transport phases (shown as purple bar, 2-4 in the figure) and the transport and storage of CO_2 activities (shown as light purple bar, 5-8 in the figure) also requires energy (both direct and indirect) which contribute to the ADP_{fossil} indicator. These extra energy needs, which are not present in the Reference scenario, are added

to the CCS system in order to capture and store greenhouse gas emissions and might be seen as investments for reducing greenhouse gas emissions.

Figure 12 shows the ADP_{fossil} results (MJ per functional unit) for the Reference and CCS scenarios at SAE.

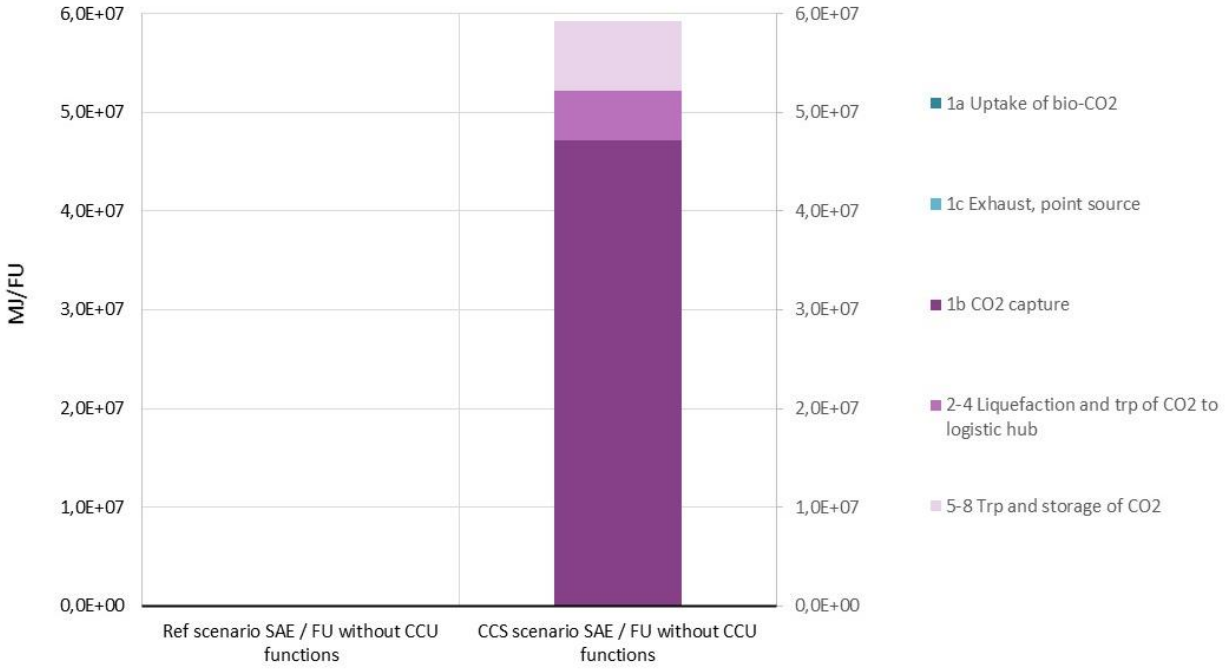


Figure 12 Results for ADP_{fossil} per functional unit (FU) for WtE at SAE.

As seen from the figure, the results are fully in line with the Norske Skog Saugbrugs case, showing that the Reference scenario gives the better result for ADP_{fossil}. The extra energy needed for capturing, transporting and storing CO_2 are added to the CCS system and might be seen as investments for reducing greenhouse gas emissions only (which has no impact on the ADP_{fossil} indicator).

4.4 Results for CED (cumulative energy demand)

The CED results[9] (MJ LHV per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 13 and Figure 14, respectively. Both cases show the CCS scenarios compared to their respective Reference scenarios. The results are presented for the different activities in the life cycle value chain, presented by coloured bars in Figure 13 and Figure 14. A short description of the different activities, numbered according to Figure 5, is given below:

1a Uptake of bio-CO_2	N/R
1b Exhaust, point source	N/R
1b CO_2 capture	Burdens connected with use of energy and chemicals, in addition to waste treatment, occurring at the CO_2 capture plant.

[9] For more information about the environmental impact category CED, see Table 2.

2-4 Liquefaction and trp of CO_2 to logistic hub	Burdens connected with energy use for the liquefaction process. Burdens also from transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn.
5-8 Trp and storage of CO_2	Burdens connected with use of energy and chemicals for transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.

Figure 13 shows the CED results (MJ LHV per functional unit) for the Reference and CCS scenarios at Norske Skog Saugbrugs.

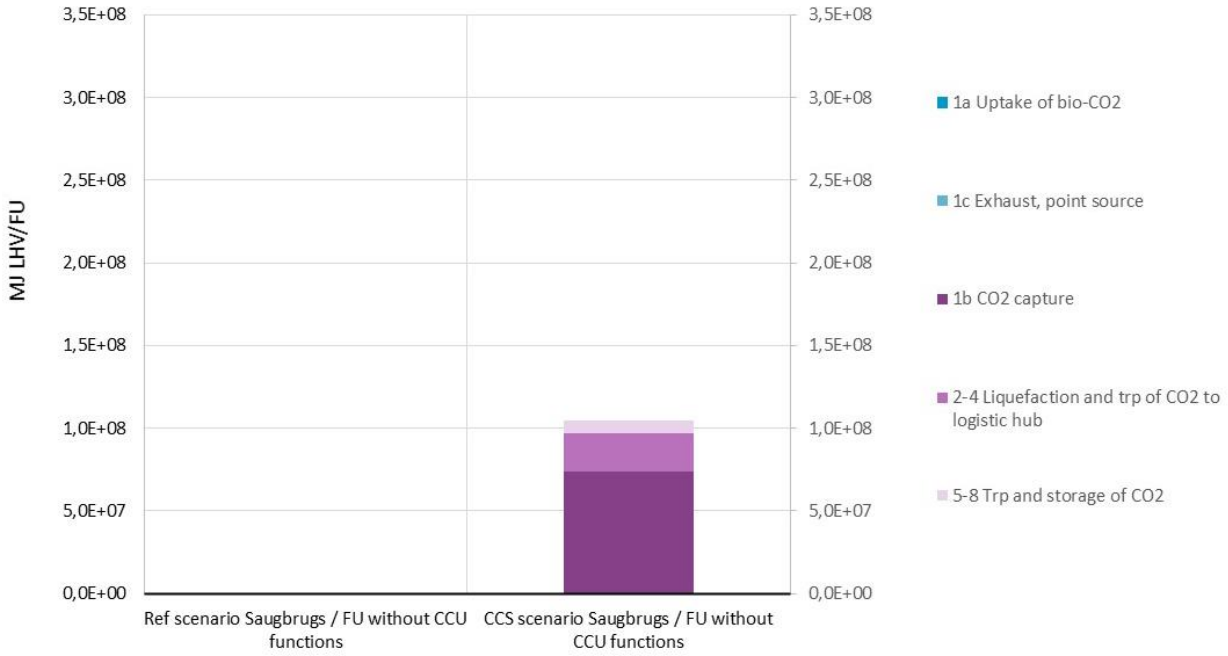


Figure 13 CED results per functional unit (FU) for production of paper at Norske Skog Saugbrugs.

As seen from the figure, the results for CED are in line with the results for ADP_{fossil} and acidification: The Reference scenario gives the better result.

Figure 13 shows that CED for the Reference scenario is zero. The reason for this is, similarly as for ADP_{fossil}, that the life cycle value chain for this scenario represents only the emissions at the point source (see Figure 5). As CED is an impact indicator accounting use of primary energy, and there is no energy use inside the Reference scenario's system boundaries, the CED result becomes zero.

The CCS scenario, on the other hand, requires use of primary energy for all the activities 1b-8, as seen in Figure 13. The capture plant (dark purple bar, 1b) requires energy (both direct and indirect) for running the process as well as for production of chemicals. Furthermore, the liquefaction and transport phases (shown as purple bar, 2-4 in the figure) and the transport and storage of CO_2 activities (shown as light purple bar, 5-8 in the figure) also requires energy (both direct and indirect), which all contribute to the CED indicator. Just like the situation for the ADP_{fossil} results, these extra energy needs, which are not

present in the Reference scenario, are added to the CCS system in order to capture and store greenhouse gas emissions and might be seen as investments for reducing greenhouse gas emissions.

Figure 14 shows the CED results (MJ LHV per functional unit) for the Reference and CCS scenarios at SAE.

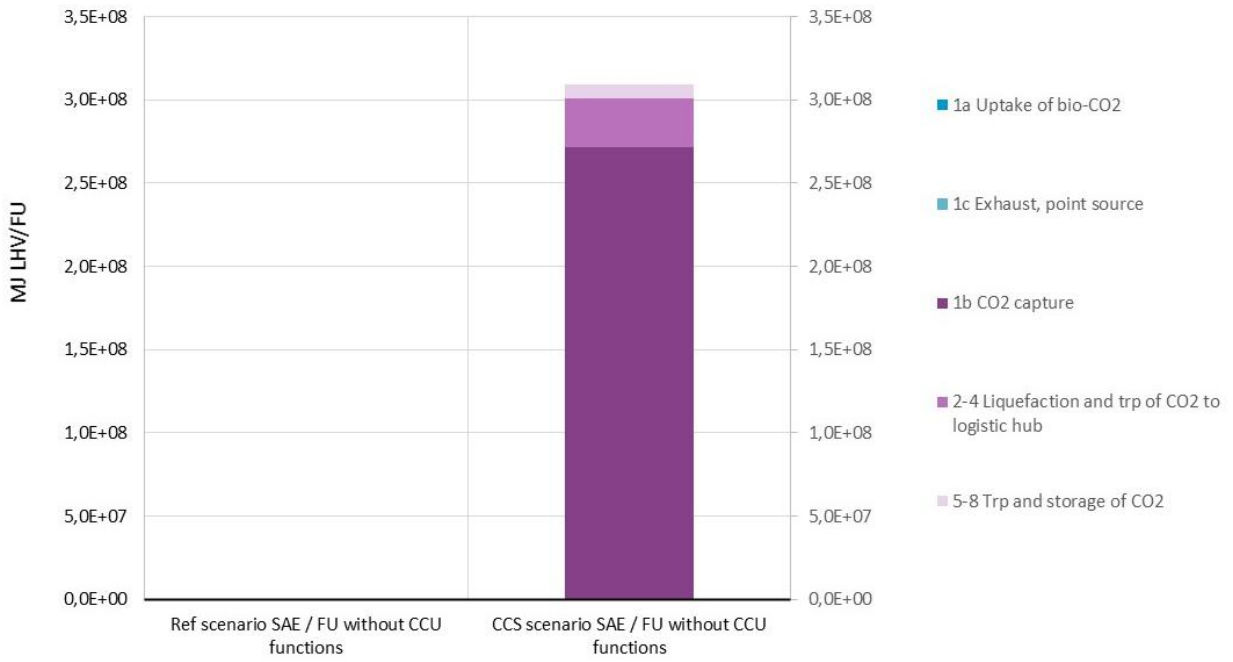


Figure 14 CED results per functional unit (FU) for WtE at SAE.

As seen from the figure, the results are fully in line with the Norske Skog Saugbrugs case, showing that the Reference scenario gives the better result for CED. The extra energy needed for capturing, transporting and storing CO_2 are added to the CCS system and might be seen as investments for capturing and storing greenhouse gas emissions.

5 Results and discussion for CCUS systems: production of paper and WtE, in addition to production of fuel (joint functional unit)

This chapter presents the results for the CCUS systems as presented in Figure 6 (chapter 2.4.2). The goal is to assess the environmental performance of CCS and CCU at Norske Skog Saugbrugs paper mill and the Waste to Energy plant Sarpsborg Avfallsenergi, respectively, compared to a Reference system without CCUS. The CCU scenario in this study uses the captured CO_2 as feedstock for methanol production (fuel) which needs large amount of renewable electricity. Hence, the comparable Reference and CCS scenarios must produce fuel and are provided with renewable electricity, which can be used to substitute other electricity sources. By the use of system expansion, all the CCUS scenarios provide the same functions and are provided with the same large amount of renewable electricity:

1. Producing either paper or heat (WtE)
2. Producing fuel (methanol)

3. Using renewable electricity

Before digging into the figures, it is important to distinguish between two categories of "negative burdens" which are used in the further chapters, namely negative emissions and avoided burdens. The first category, negative emissions, represents actual removal of CO_2 from the atmosphere, which of course relates only to the climate change impact category. The second category, avoided burdens, represents processes which contribute to avoided environmental burdens because they substitute more environmental burdensome processes/activities (e.g. as described in chapter 1.1, Figure 2 for CCU). Avoided environmental burdens might occur for all environmental impact categories (not only for climate change). The latter might lead to lower environmental impact compared to a Reference case. For climate change impact, the results might show lower CO_2 emissions compared to a Reference case, but these emissions can never be called negative emissions in the term removing CO_2 from the atmosphere, as they only reflect a comparison.

For the climate change impact category presented in chapter 5.1 (Figure 15 and Figure 16), both types of "negative burdens" are shown:

- Negative emissions represented by the dark blue bars (1a Uptake of bio-CO_2):
    - Represent the actual uptake of biogenic CO_2 when the trees are growing. Hence, they represent negative emission which, when burning the biomass, are emitted to the atmosphere, leading to a net emission of zero. If these emissions are captured and stored, they do not cancel out the uptake, hence the net emissions become negative (CO_2 is removed from the atmosphere), as is the case for the CCS scenario in chapter 4.1.
- Avoided burdens represented by the green bars (Renewable power production and avoided production of el):
    - Represent avoided emissions which arise when renewable power substitutes power made of fossil resources. These avoided emissions represent the environmental benefit from using renewable power instead of fossil resources (a comparison) and do not represent emissions being removed from the atmosphere.

As actual negative emissions only occur for CO_2-emissions, the results for the remaining impact categories (given in chapters 5.2 to 5.4) only include the avoided burden category.

5.1 Results for climate change

The climate change[10] results (tonne CO_2-eq per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 15 and Figure 16, respectively. Both cases show the CCS and CCU scenarios compared to their respective Reference scenarios.

The results are presented as positive and negative climate burdens from the different activities in the life cycle value chain. In Figure 15 and Figure 16 the different activities are presented by coloured bars. In addition, the net emissions, representing the total sum of positive and negative burdens, are presented

[10] For more information about the environmental impact category climate change, see Table 2.

by the black lines in the figure. A short description of the different activities, numbered according to Figure 6, is given below:

1a Uptake of bio-CO_2	Negative emission occurring when the trees are growing
1b Exhaust, point source	Emissions occurring at the CO_2 source
1b CO_2 capture	Burdens connected with use of energy and chemicals, in addition to direct emissions and waste treatment, occurring at the CO_2 capture plant. The CO_2 not being captured is also included here.
2-4 Liquefaction and trp of CO_2 to logistic hub	Burdens connected with energy use in addition to direct emissions, occurring from the liquefaction process. Burdens (energy and direct emissions) also from transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn.
5-8 Trp and storage of CO_2	Burdens connected with use of energy and chemicals, in addition to direct emissions, from transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.
11-13 Production of fuel (CCU)	Production of fuel based on the captured CO_2 and H_2 (CCU)
Production of fuel (conventional)	Conventional production of fuel (same amount as from CCU) based on fossil resources
14 Combustion of fuel	Combustion of fuel when used
Renewable power production and avoided production of el	Production of renewable power (same amount as used for H_2 production) and avoided production of electricity generation from natural gas (NG).
Total	Sum of burdens throughout the value chain

Figure 15 shows the climate change results (tonne CO_2-eq per functional unit) for respectively the Reference, CCS and CCU scenarios at Norske Skog Saugbrugs.

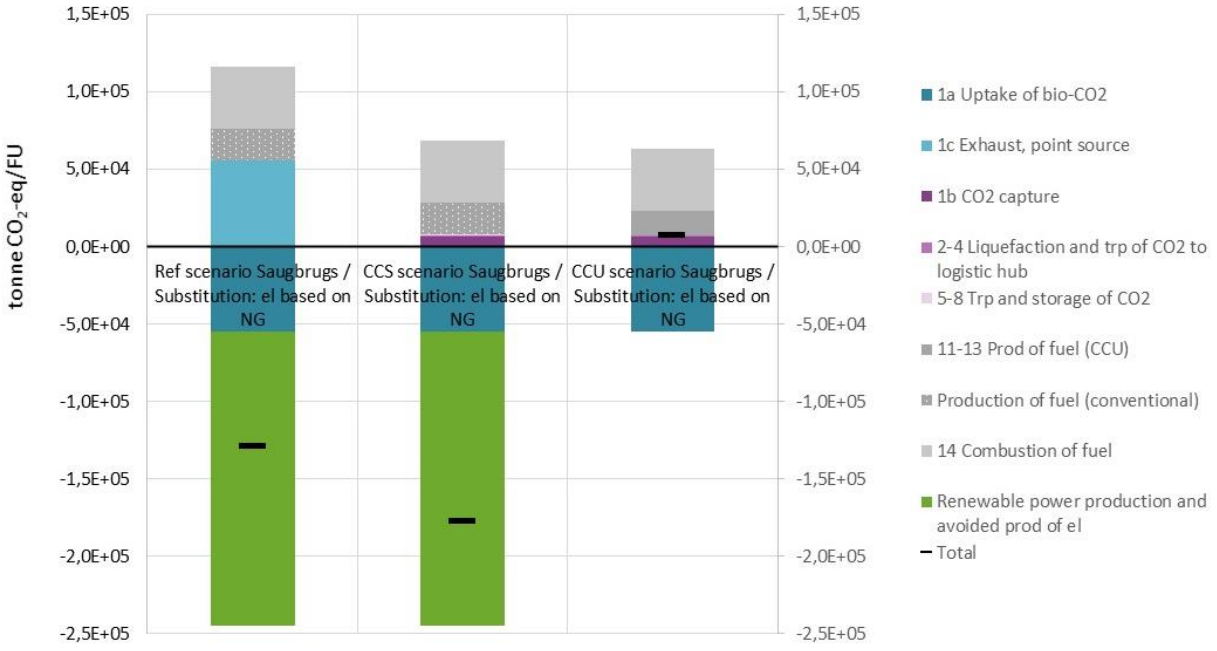


Figure 15 Climate change results for production of paper at Norske Skog Saugbrugs, in addition to production of fuel and use of renewable electricity (joint functional unit).

First of all, it is important to state that none of the scenarios presented in Figure 15 result in removed greenhouse gas emissions from the atmosphere. The net emissions (Total) from the CCU case are

positive, while the net emissions from the Reference and CCS case show net negative results due to the avoided emissions from natural gas being substituted by wind power (green bars). Interestingly, the figure clearly shows that the climate change burden from fuel production and use from CCU (dark grey bar, 11-13, and light grey bar, 14) is almost the same as the corresponding burden from conventional fuel production and use (dotted dark grey bars, and light grey bar, 14).

The results from the different scenarios are further discussed separately below.

CCU scenario

As seen from Figure 15, the uptake of biogenic CO_2 (shown by the dark blue bar, 1a) represents 55,200 tonne CO_2-eq. When burning the biomass at Norske Skog Saugbrugs, some fossil CO_2 is added, and it is assumed that 90% is captured and further transported and converted to fuel. Hence, the remaining 10% of the CO_2 is emitted (included in the capture activity, shown by the dark purple bar, 1b). Furthermore, the figure shows that the fuel converting process (shown by the dark grey bar, 11-13) contribute with 15,900 tonne CO_2-eq while re-emitting the greenhouse gas (firstly being captured) when using/burning the fuel contribute additionally 40,400 tonne CO_2-eq. In total this gives a net climate change result of 8,300 tonne CO_2-eq/FU.

CCS scenario

The figure shows that the results for the CCS scenario are similar to the CCU scenario for the activities uptake of biogenic (1a) and CO_2 capture (1b). As the captured emissions in this scenario are stored, they are not re-emitted. However, in order to fulfil the functional unit (also produce fuel), the defined amount of fuel has to be produced by conventional technology (showed by dotted grey bars) and more emissions are added when the fuel is used/burnt (light grey bars, 14). Finally, this system is provided with the same amount of wind power as is needed in the CCU system, which means that this renewable power can be used to substitute fossil power generation (as the system itself does not need this electricity). The green bar shows the benefit of this substitution effect. In total, the net climate impact of the CCS scenario is negative, which in this case does <u>not</u> mean that emissions are removed from the atmosphere. The CCS system performs considerably better than the compared CCU system.

Reference scenario

Figure 15 shows, similarly as for the Reference scenario in Figure 7, that the uptake of biogenic CO_2 (dark blue bar, 1a) and the emissions of CO_2 (light blue bar, 1c) from the point source are almost equal (as the share of biogenic CO_2 emissions at Norske Skog Saugbrugs is 99.3%). This means a net zero burden for the climate change indicator when only taking the point source into account. However, in order to fulfil the functional unit for this analysis, the defined amount of fuel has to be produced by conventional technology, which leads to greenhouse gas emissions both from the production phase (showed by dotted grey bar) and the use phase (light grey bar, 14). Just like the CCS scenario, the Reference scenario is also provided with the same amount of wind power as is needed for the CCU system. However, since the system itself does not need this electricity, it can be used to substitute fossil power generation. The green bar shows the benefit of this substitution effect. For the overall net climate impact results, the Reference scenario performs worse than the CCS scenario, but still considerably better than the CCU

scenario. The net negative result for the Reference scenario is caused by the substitution effect and does not mean that emissions are removed from the atmosphere.

From a climate change perspective, it can be concluded that the most beneficial way to fulfil the functional unit, is to store the captured CO_2, use wind power to substitute electricity from natural gas, and produce fuel by conventional technologies. This conclusion is based on the premise that the CCU product represents a short-lived product with a high energy intensity production process.

CCU products can be more or less long-lived and more or less energy intensive during production. These two factors can affect the results for CCU products. Our study has analysed a short-lived product with an energy-intensive production process. An extreme example in the opposite direction is represented by a long-lived CCU product with an energy-efficient production process. This will represent permanent storage and lead to an environmental performance close to the result for the CCS scenario. Such a CCU scenario might perform better than the CCS scenario if the production phase for the product being substituted by the CCU product has a higher environmental impact compared to the CCU production. Other CCU products will result in environmental impacts in between the abovementioned extremes. The impact of permanent and non-permanent storage as well as the energy-intensity of the CCU production processes are further discussed in a Brief from Bellona by Berstad and Eriksen (2021).

Figure 16 shows the climate change results (tonne CO_2-eq per functional unit) for the Reference, CCS and CCU scenarios at SAE.

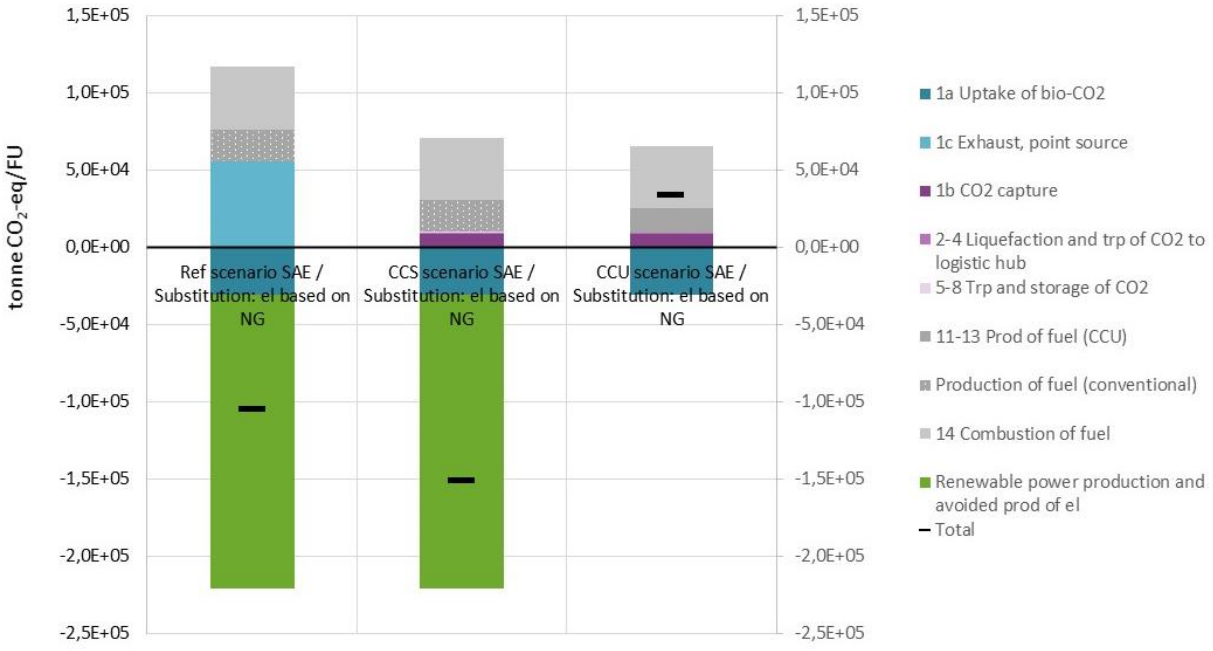


Figure 16 Climate change results for WtE at SAE, in addition to production of fuel (joint functional unit) and use of renewable electricity.

The figure shows results that are clearly in line with the Norske Skog Saugbrugs case; the CCS scenario performs best, followed by the Reference scenario, while the CCU scenario clearly performs worst.

Hence, the same conclusion regarding climate change applies for the SAE case as for the Norske Skog Saugbrugs case: *The most beneficial way to fulfil the functional unit, is to store the captured CO_2, use wind power to substitute electricity from natural gas, and produce fuel by conventional technologies*.

5.2 Results for acidification

The acidification[11] results (mol H^+-eq per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 17 and Figure 18, respectively. Both cases show the CCS and CCU scenarios compared to their respective Reference scenarios.

The results are presented for the different activities in the life cycle value chain, presented by coloured bars in Figure 17 and Figure 18. A short description of the different activities, numbered according to Figure 6, is given below:

1a Uptake of bio-CO_2	N/R
1b Exhaust, point source	Emissions contributing to acidification occurring at the CO_2 source
1b CO_2 capture	Emissions contributing to acidification occurring at the CO_2 capture plant (use of energy and chemicals, in addition to waste treatment).
2-4 Liquefaction and trp of CO_2 to logistic hub	Emissions contributing to acidification occurring from the liquefaction process (use of energy), as well as burdens from transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn
5-8 Trp and storage of CO_2	Emissions contributing to acidification (use of energy and chemicals) from transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.
11-13 Production of fuel (CCU)	Emissions contributing to acidification from production of fuel based on the captured CO_2 and H_2 (CCU).
Production of fuel (conventional)	Acidifying burdens from conventional production of fuel (same amount as from CCU) based on fossil resources
14 Combustion of fuel	Acidifying emissions from combustion of fuel when used
Renewable power production and avoided production of el	Burdens from production of renewable power (same amount as for H_2 production) and avoided burdens from production of electricity generation from natural gas (NG).
Total	Sum of burdens contributing to acidification throughout the value chain.

Figure 17 shows the acidification results (mol H^+-eq per functional unit) for respectively the Reference, CCS and CCU scenarios at Norske Skog Saugbrugs.

[11] For more information about the environmental impact category acidification, see Table 2.

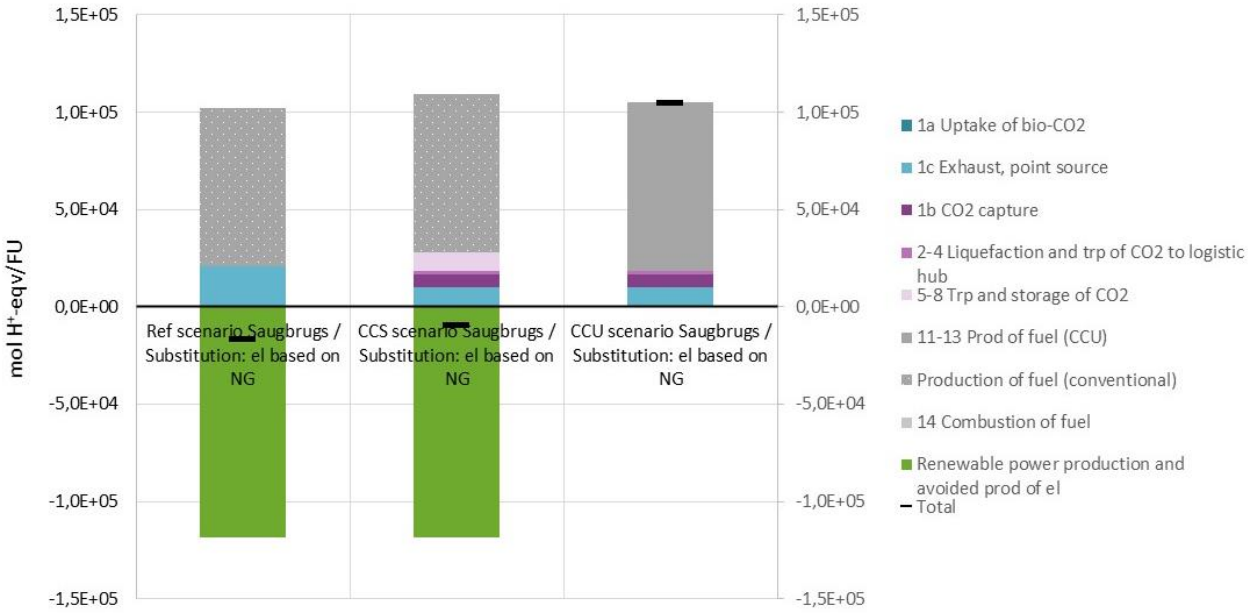


Figure 17 Acidification results for production of paper at Norske Skog Saugbrugs, in addition to production of fuel and use of renewable electricity (joint functional unit).

Figure 17 shows that also for acidification, the CCU scenario performs worst compared to the CCS and Reference scenarios. The major reason for the overall good performance of the Reference and CCS scenarios compared to the CCU scenario, is the avoided burden due to these scenarios' possibility of using wind power (the same amount as is needed in the CCU system) to substitute electricity from natural gas (shown by green bars). The figure further shows that also from an acidification perspective, the burden from fuel production from CCU (dark grey bar, 11-13) is approximately the same as the corresponding burden from conventional fuel production (dotted dark grey bars).

When it comes to the internal ranking between the CCS and Reference scenarios, the result for acidification is the opposite as for climate change as the Reference scenario gives the better result. This is in line with the results from chapter 4.2 and other studies (Modahl, Askham et al. 2012, Petrescu, Bonalumi et al. 2017) and can be explained as follows: the capture plant and all related activities are added to the system in order to reduce greenhouse gas emissions only, which means that these extra efforts might be seen as investments for this activity (which have no positive impact on acidification).

The overall conclusion from an acidification perspective is that the most beneficial way to fulfil the functional unit, is to skip the CO_2 capture and storage, use wind power to substitute electricity from natural gas, and produce fuel by conventional technologies.

Figure 18 shows the acidification results (mol H^+-eq per functional unit) for respectively the Reference, CCS and CCU scenarios at SAE.

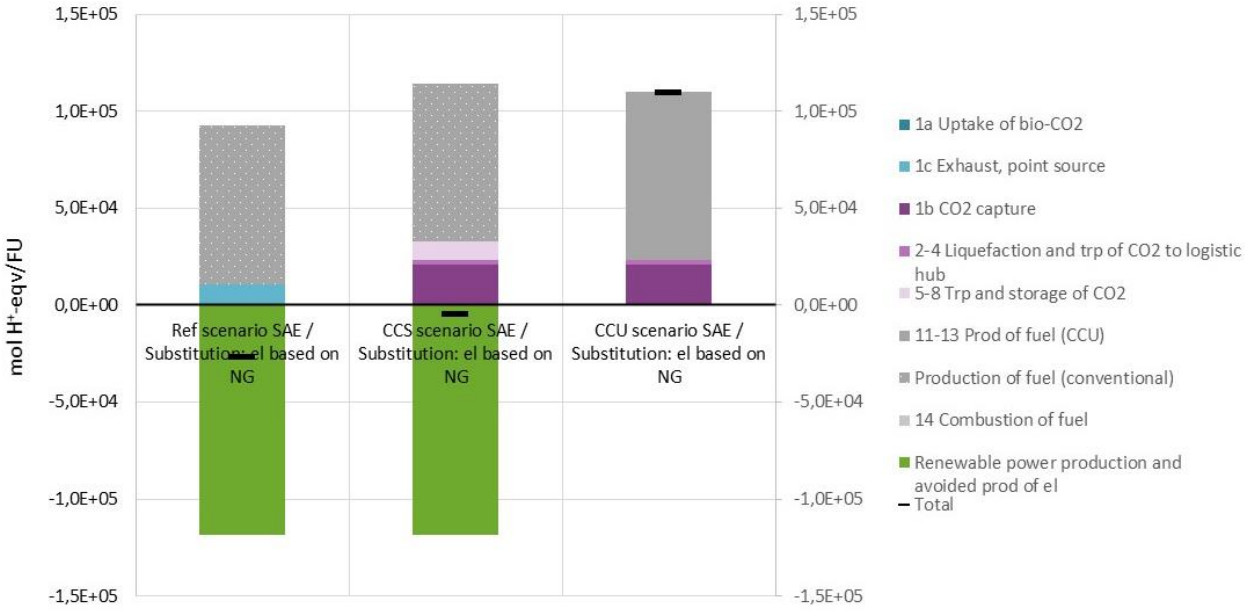


Figure 18 **Acidification results for WtE at SAE, in addition to production of fuel and use of renewable electricity (joint functional unit).**

As seen from the figure, the acidification results are fully in line with the Norske Skog Saugbrugs case: *Hence, the overall conclusion from an acidification perspective is that the most beneficial way to fulfil the functional unit, is to skip the CO_2 capture and storage, use wind power to substitute electricity from natural gas, and produce fuel by conventional technologies*.

5.3 Results for ADP_{fossil} (use of primary fossil energy)

The ADP_{fossil} results[12] (MJ per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 19 and Figure 20, respectively. Both cases show the CCS and CCU scenarios compared to their respective Reference scenarios.

The results are presented for the different activities in the life cycle value chain, presented by coloured bars in Figure 19 and Figure 20. A short description of the different activities, numbered according to Figure 6, is given below:

1a Uptake of bio-CO_2	N/R
1b Exhaust, point source	N/R
1b CO_2 capture	Use of primary fossil energy related to the CO_2 capture plant (use of energy and chemicals, in addition to waste treatment).
2-4 Liquefaction and trp of CO_2 to logistic hub	Use of primary fossil energy related to the liquefaction process and to transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn.
5-8 Trp and storage of CO_2	Use of primary fossil energy related to transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.

[12] For more information about the environmental impact category ADP_{fossil}, see Table 2.

11-13 Production of fuel (CCU)	Use of primary fossil energy related to production of fuel based on the captured CO_2 and H_2 (CCU).
Production of fuel (conventional)	Use of primary fossil energy related to production of conventional fuel (same amount as from CCU) based on fossil resources.
14 Combustion of fuel	Use of primary fossil energy related to combustion of fuel when used.
Renewable power production and avoided production of el	Use of primary fossil energy related to production of renewable power (same amount as for H_2 production) and avoided production of electricity generation from natural gas (NG).
Total	Sum of primary fossil energy throughout the value chain.

Figure 19 shows the ADP_{fossil} results (MJ per functional unit) for respectively the Reference, CCS and CCU scenarios at Norske Skog Saugbrugs.

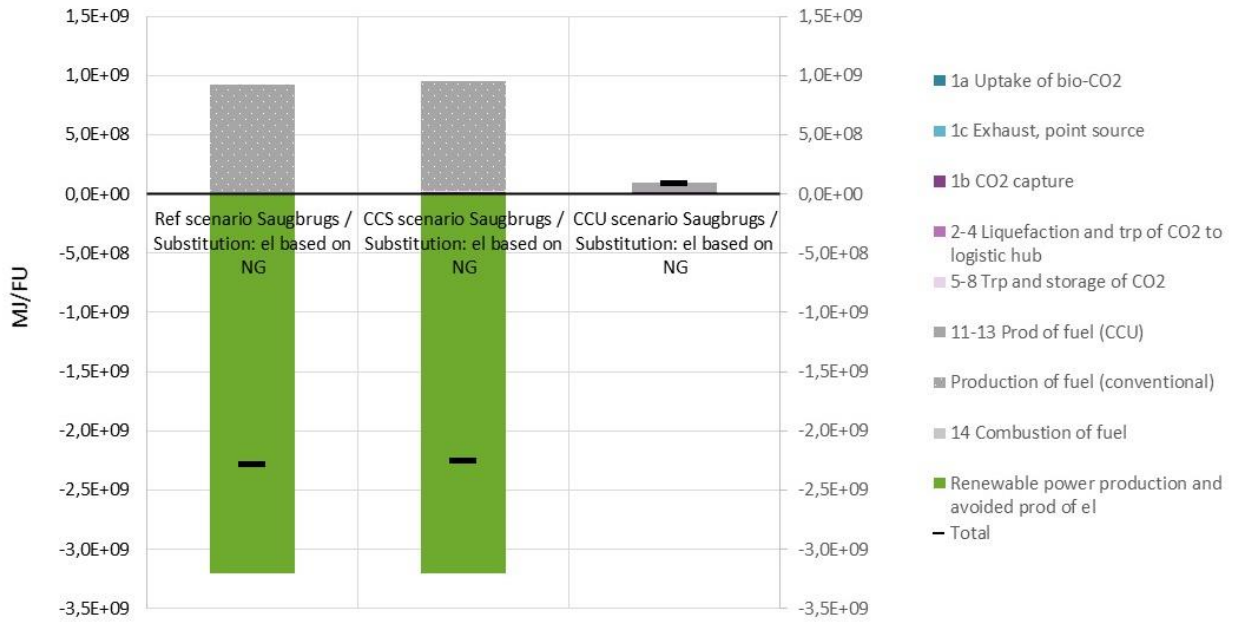


Figure 19 Results for ADP_{fossil} for production of paper at Norske Skog Saugbrugs, in addition to production of fuel and use of renewable electricity (joint functional unit).

Figure 19 shows that also for ADP_{fossil}, the CCU scenario performs worst compared to the CCS and Reference scenarios. CCU represents carbon recycling, which in the figure can be seen by the considerably smaller need for primary fossil energy (ADP_{fossil}) in the CCU scenario (dark grey bar, 11-13) compared to conventional fuel production (dotted dark grey bars). However, the avoided burden from using wind power to substitute electricity from natural gas gives a considerably larger ADP_{fossil} benefit.

When it comes to the internal ranking between the CCS and Reference scenarios, the difference is too small to conclude. However, it is no doubt that, also from a perspective of ADP_{fossil}, the CCU case performs worst.

The overall conclusion also from the perspective of demand for primary fossil energy (ADP_{fossil}) is that the most beneficial way to fulfil the functional unit is to use wind power to substitute electricity from natural gas and produce fuel by conventional technologies. This can be achieved either by the Reference scenario or by the CCS scenario.

Figure 20 shows the ADP_{fossil} results (MJ per functional unit) for respectively the Reference, CCS and CCU scenarios at SAE.

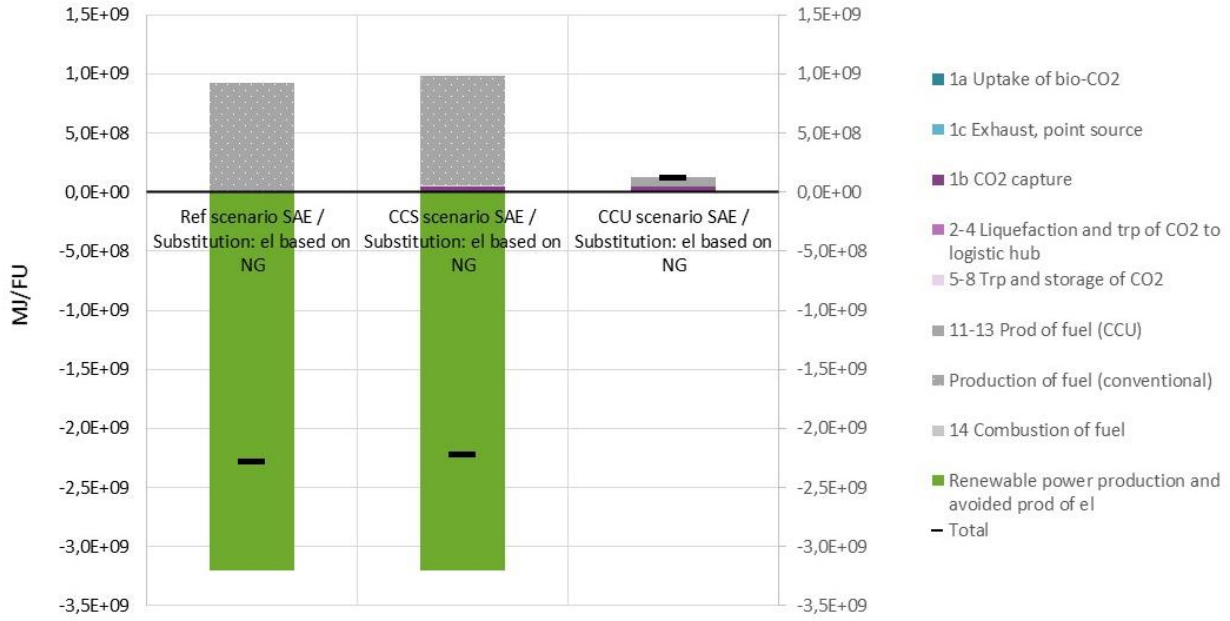


Figure 20 Results for ADP_{fossil} for WtE at SAE, in addition to production of fuel and use of renewable electricity (joint functional unit).

As seen from the figure, the results are fully in line with the Norske Skog Saugbrugs case, showing that, from a perspective of ADP_{fossil}, the CCU case in overall performs worst, while the Reference and CCS cases perform almost equal. *Hence, it is most beneficial to use wind power to substitute electricity from natural gas and produce fuel by conventional technologies. This can be achieved either by the Reference scenario or by the CCS scenario.*

5.4 Results for CED (cumulative energy demand)

The CED results[13] (MJ per functional unit) for the Norske Skog Saugbrugs and SAE cases are presented in Figure 21 and Figure 22 respectively. Both cases show the CCS and CCU scenarios compared to their respective Reference scenarios.

The results are presented for the different activities in the life cycle value chain, presented by coloured bars in Figure 21 and Figure 22. A short description of the different activities, numbered according to Figure 6, is given below:

1a Uptake of bio-CO_2	N/R
1b Exhaust, point source	N/R
1b CO_2 capture	Use of primary energy related to the CO_2 capture plant (use of energy and chemicals, in addition to waste treatment).
2-4 Liquefaction and trp of CO_2 to logistic hub	Use of primary energy related to the liquefaction process and to transporting liquefied CO_2 from the capture/liquefaction plant to the logistics hub at Borg Havn.
5-8 Trp and storage of CO_2	Use of primary energy related to transport of CO_2 from Borg Havn to the receiving terminal at Kollsnes and further to final storage.
11-13 Production of fuel (CCU)	Use of primary energy related to production of fuel based on the captured CO_2 and H_2 (CCU).
Production of fuel (conventional)	Use of primary energy related to production of conventional fuel (same amount as from CCU) based on fossil resources.
14 Combustion of fuel	Use of primary energy related to combustion of fuel when used.
Renewable power production and avoided production of el	Use of primary energy related to production of renewable power (same amount as for H_2 production) and avoided production of electricity generation from natural gas (NG).
Total	Sum of primary energy throughout the value chain.

Figure 21 shows the CED results (MJ LHV per functional unit) for respectively the Reference, CCS and CCU scenarios at Norske Skog Saugbrugs.

[13] For more information about the environmental impact category CED, see Table 2.

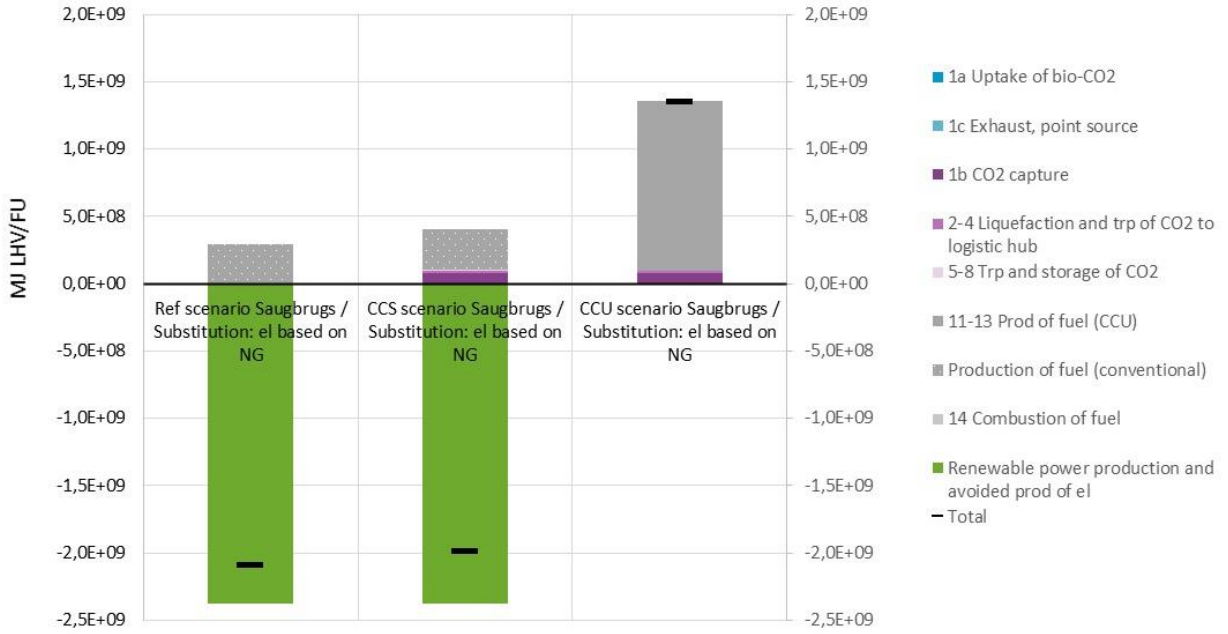


Figure 21 CED results for production of paper at Norske Skog Saugbrugs, in addition to production of fuel and use of renewable electricity (joint functional unit).

Figure 21 shows that also for CED, the CCU scenario performs worst compared to the CCS and Reference scenarios. Furthermore, the figure clearly shows that the CED result for fuel production from CCU (dark grey bar, 11-13) is the opposite as for the ADP_{fossil} result, showing considerably larger impact than the corresponding impact from conventional fuel production (dotted dark grey bars). This is explained by the large wind power consumption for the CCU process. As renewable energy is included in the CED indicator, this is clearly seen in the above figure. This contrasts with the results presented for ADP_{fossil} in chapter 5.3, as renewable energy is not included in the ADP_{fossil} indicator.

Although CCU represents carbon recycling, the recycling process is very energy intensive requiring large amounts of electricity. Even though the electricity comes from renewable sources (assumed wind power in this analysis), the figure clearly shows that also from a CED perspective (assessing use of primary energy), it is better to use this renewable to substitute electricity from natural gas (green bars).

When it comes to the internal ranking between the CCS and Reference scenarios, the difference is too small to conclude. However, it is no doubt that, also from a perspective CED, the CCU case performs worst.

The overall conclusion also from the perspective of demand for primary energy (CED) is that the most beneficial way to fulfil the functional unit, is to use wind power to substitute electricity from natural gas and produce fuel by conventional technologies. This can be achieved either by the Reference scenario or by the CCS scenario.

Figure 22 shows the CED results (MJ LHV per functional unit) for respectively the Reference, CCS and CCU scenarios at SAE.

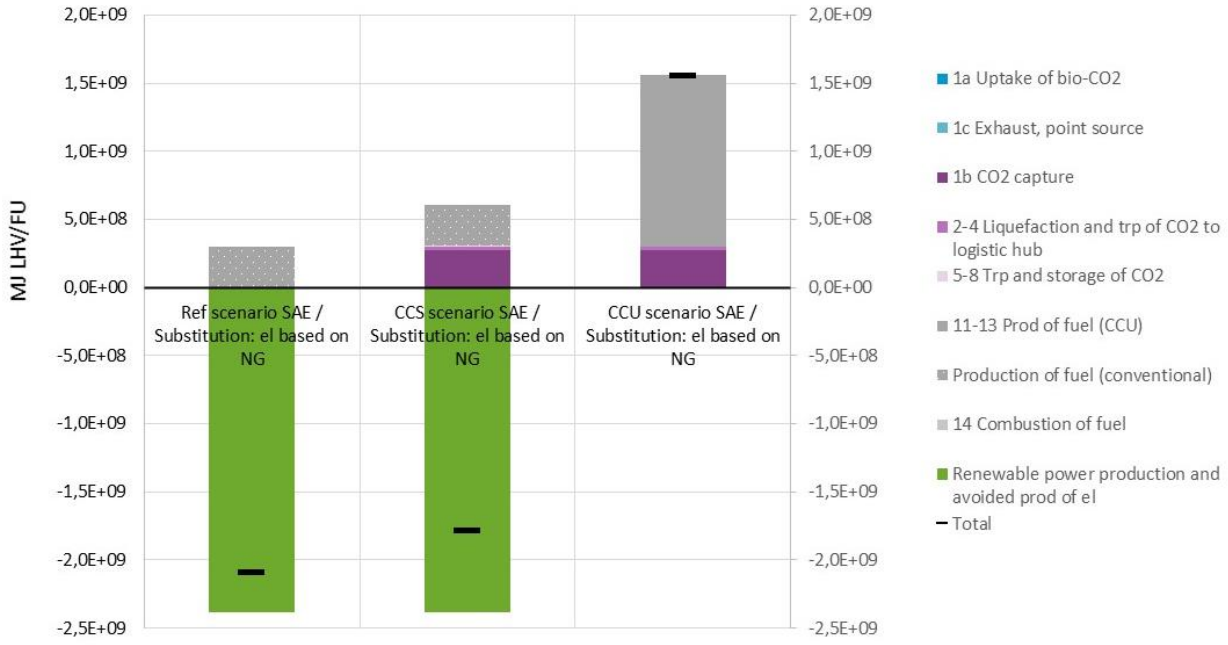


Figure 22 CED results for WtE at SAE, in addition to production of fuel and use of renewable electricity (joint functional unit).

As seen from the figure, the results are fully in line with the Norske Skog Saugbrugs case, showing that, from a CED perspective, the CCU case clearly performs worst, while the Reference and CCS cases perform much better. *Hence, the overall conclusion also from the perspective of demand for primary energy (CED) is that the most beneficial way to fulfil the functional unit, is to use wind power to substitute electricity from natural gas and produce fuel by conventional technologies. This can be achieved either by the Reference scenario or by the CCS scenario*.

5.5 Sensitivity analyses

This chapter presents the results of sensitivity analyses carried out for varying climate intensities (g CO_2-eq/kWh) for the substituted electricity and varying compression losses (%) in the liquefaction process.

5.5.1 Climate change effect of substituted electricity

In chapters 5.1 to 5.4 the result for the Reference, CCS and CCU cases for the different impact categories are presented. The avoided impact from the substituted electricity from natural gas produced in a conventional power plant (more details in Table 3) plays an important role for the overall results for all impact categories. Based on this, a sensitivity analysis for varying climate intensities (g CO_2-eq/kWh) for

the substituted electricity has been carried out for the Norske Skog Saugbrugs case and presented in Figure 23.

The figure presents the *CCU scenario* by the grey, horizontal line, as this case use all the provided wind power for its fuel production which means that no extra electricity is available for substituting other technologies. The *CCS and Reference scenarios* are presented by the purple and blue lines, respectively. The figure shows how the net climate change results (tonne CO_2-eq per functional unit) for these scenarios vary as a function of climate intensity (g CO2-eq/kWh) for the substituted electricity. As described in chapter 2.1, these scenarios are provided with the same amount of wind power as is needed in the CCU system. Since the systems do not need this electricity, it can be used to substitute power generation elsewhere.

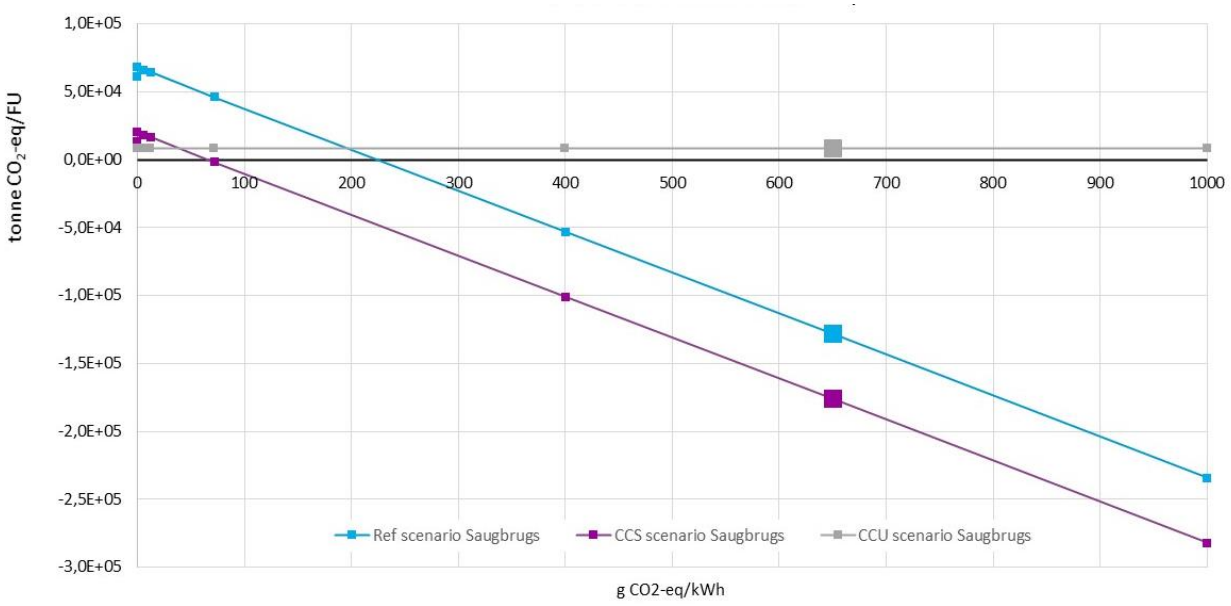


Figure 23 Sensitivity analysis; the effect of substituted electricity for Norske Skog Saugbrugs' scenarios.

As described above, the result for the CCU scenario (grey line) is independent of the climate intensity for substituted electricity. The net climate change result for the CCU scenario is 8,300 tonne CO_2-eq/functional unit (also presented in chapter 5.1). The CCS and Reference scenarios presented in chapter 5.1 are assumed to substitute electricity from natural gas (climate intensity of appr 650 g CO_2-eq/kWh) and the net climate change result represents -176,000 and -129,000 tonne CO_2-eq/functional unit, respectively. Figure 23 shows that the same results are given for a climate intensity of 650 g CO_2-eq/kWh for the substituted electricity in the sensitivity diagram.

The main message from Figure 23 is, however, that the CCS scenario is beneficial over the CCU scenario as long as the wind power (same amount as used for CCU) substitutes electricity with a climate intensity > 40 g CO_2-eq/kWh (the point where the lines for CCS and CCU scenario lines cross). A climate intensity of about 40 g CO_2-eq/kWh is below the mean value and within the range of climate intensity for photovoltaic power (Silva and Raadal 2019). Similarly, the figure shows that the Reference is beneficial

over the CCU scenario as long as the wind power (same amount as used for CCU) substitutes electricity with a climate intensity > 200 g CO_2-eq/kWh (the point where the lines for the Reference and CCU scenario lines cross). It can therefore be concluded that as long as there is a possibility for the renewable electricity to replace fossil electricity generation, this should be prioritised before using it for CCU fuel production.

The above conclusion is confirmed in the article *On the climate change mitigation potential of CO_2 conversion to fuels* (Abanades, Rubin et al. 2017) which states: "The CCS option avoids far more emissions than the CCU system as long as fossil fuel power plants remain on the grid. Not until the CO_2 emission rate of the most carbon intensive components of the power system falls below 55 g CO_2-eq/kWh, a point at which the electric power system is effectively decarbonized, does the CCU system begin to avoid more emissions than the full CCS system."

Figure 24 presents the sensitivity analysis for varying climate intensities (g CO_2-eq/kWh) for the substituted electricity for the SAE case.

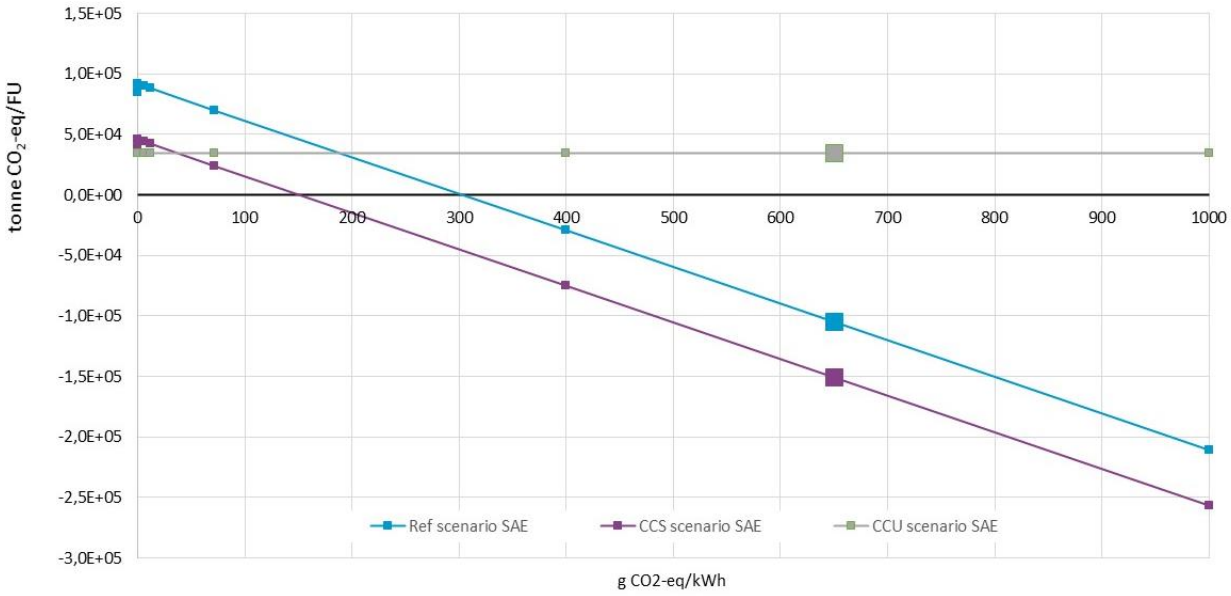


Figure 24 Sensitivity analysis; the effect of avoided electricity for SAE's scenarios.

Figure 24 confirms the conclusion taken from Figure 23: The CCS scenario is beneficial over the CCU scenario as long as the wind power (used for CCU) substitutes electricity with a climate intensity > 40 g CO_2-eq/kWh (the point where the lines for the CCS and CCU scenario lines cross). Furthermore, the Reference scenario is beneficial over the CCU scenario as long as the wind power (used for CCU) substitutes electricity with a climate intensity > 190 g CO_2-eq/kWh (the point where the lines for Reference and CCU scenario lines cross).

Hence, the above figure draws the same conclusion: As long as there is a possibility for the renewable electricity to replace fossil electricity generation, this should pe prioritised before using it for CCU fuel production.

5.5.2 Climate change effect of compression loss

The main analyses presented in chapters 4 and 5.1 assume 1% compression loss in the liquefaction phase (see Table 3). This means that 1% of the captured CO_2 is emitted while the remaining 99% is either transported further with the purpose of being permanently stored or used for fuel production. In Figure 25, the results from a sensitivity analysis for varying compression losses (%) in the liquefaction process for the Norske Skog Saugbrugs case is presented for the *Reference, CCS and CCU scenario* by the blue, purple and grey lines, respectively. The figure shows how the net climate change results (tonne CO_2-eq per functional unit) vary as a function of the compression loss in the liquefaction phase for the respective scenarios.

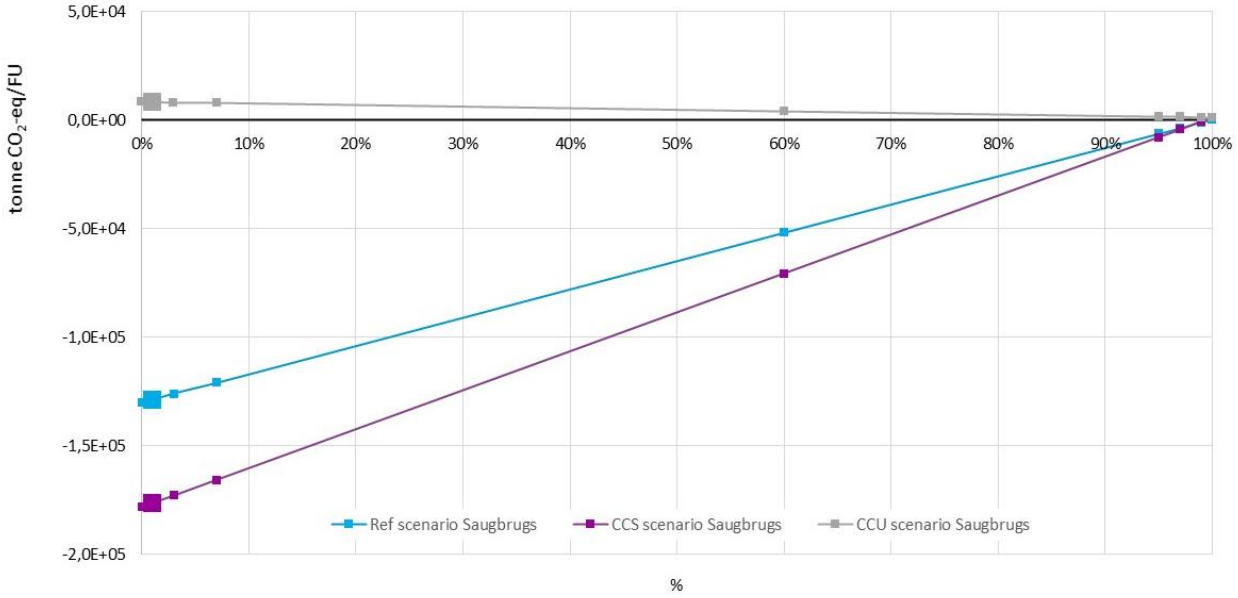


Figure 25 Sensitivity analysis; the effect of compression loss in the liquefaction process for the Norske Skog Saugbrugs case.

As seen in the figure, increased compression loss affects all the scenarios:

For the CCU scenario (grey line) the increased compression loss results in slightly reduced climate change impact. Hence, the higher compression loss, the better result. The major reason for this is the reduced burden from CCU fuel production due to reduced feedstock (CO_2) to be converted (as more and more CO_2 is emitted in the liquefication phase).

For the Reference and CCS cases, the increased compression loss results in considerably less negative climate change impact. Hence, the higher compression loss, the worse results. Before going into the details, it is important to emphasise that the amount of CCU fuel produced and the related required

electricity are affected by the compression loss. Hence, the extra functions delivered by the Reference and CCS scenarios will also be affected by this, and the functional unit of the systems are changing as the compression loss increases. The major reasons for the changed climate change result for the Reference and CCS scenarios are therefore (1) the reduced avoided emissions from the substituted electricity as the produced fuel from CO_2 in the CCU scenario decrease and needs less wind power, and (2) the reduced burden from conventional fuel production due to reduced feedstock (CO_2) to be converted and hence also reduced conventional fuel to be produced. The climate effect caused by (1) is much larger than (2), and in total they therefore lead to an overall increased burden as a function of increased compression loss.

It looks like the lines meet at 100% compression loss; however the Reference scenario is a little lower than the others at that point. When all captured CO_2 is lost in the CCS and the CCU scenario, the Reference scenario comes out better because it needs no energy to capture the CO_2 in the first place.

A sensitivity analysis of compression loss for the SAE case has also been carried out and shows the same results as for the Norske Skog Saugbrugs case, only with different values at 0% and 100% loss.

This sensitivity analysis has used extreme values, and it should be stated that 100% compression loss is totally unrealistic. The large values are nevertheless included to better understand the principles of the different scenarios. In real life, the compression loss will probably always be less than 10%. This will affect the results somewhat, but the conclusions still hold.

6 Conclusions

This study has analysed systems for CCS (carbon capture and storage) and CCU (carbon capture and utilization) to be compared with their respective reference scenarios. Since a CCS and a CCU system provide different functions, the functional unit for performing LCAs for CCS and CCU systems also differ.

The function of a CCS system is to reduce CO_2-emissions from a specific point source by storing the captured CO_2. A CCU system, on the other hand, represents a multi-functional system, providing two functions: 1) capture and removal of the CO_2 from a specific point source, and 2) use the captured CO_2 as feedstock for a new product (in this study: fuel). On this basis, two functional units with corresponding system boundaries for the respective CCS and CCU systems, and their respective reference scenarios, have been analysed:

1. CCS analyses: industrial production with or without capture of 50 000 tonne CO_2, with corresponding transport and storage of CO_2.
2. CCUS analyses: industrial production with or without capture of 50 000 tonne CO_2, with corresponding transport and storage or use of CO_2; production of fuel corresponding to the captured amount of CO_2; and use of renewable electricity for internal purposes or for substitution.

The CCU scenario in this study uses the captured CO_2 as feedstock for methanol production (used as fuel). As methanol is one product from the CCU scenario, the comparable Reference and CCS scenarios also must provide this function, and this is solved by system expansion (see chapter 1.2). The CCU

scenario additionally needs large amount of renewable electricity, and the CCS and Reference scenarios are therefore also provided with renewable electricity, which can be used to substitute e.g., other electricity sources. Hence, by the use of system expansion, all the CCUS scenarios provide the same functions and are provided with same large amount of renewable electricity:

1. Producing either paper or heat (WtE)
2. Producing fuel (methanol)
3. Using renewable electricity

The above-described functional units have been analysed for the CCS, CCUS and references scenarios for two industrial production cases; paper production at Norske Skog Saugbrugs and WtE at Sarpsborg Avfallsenergi (SAE).

Conclusions from the CCS systems

For climate change, the CCS scenarios perform considerably better than the Reference scenario (no CCS) and results in negative emissions. The results for all the other analysed impact categories are the opposite. This is logic and in line with other studies, as burdens from the capture plant and all related activities are added to the system in order to reduce greenhouse gas emissions only.

CO_2 losses in the capture plant and during the value chain lead to a less advantageous result, however the losses have to be large (>90%) to outweigh the climate change effect of storing CO_2.

Still, CCS for biogenic CO_2 is the only possibility for reaching negative emissions (removing CO_2 from the atmosphere); the larger share of biogenic CO_2 in the flue gas, the more negative emissions can be obtained. Therefore, the Norske Skog Saugbrugs case gives larger negative emissions than the SAE case.

Conclusions from the CCUS systems

For all the analysed impact categories, the CCU scenarios perform worse compared to the Reference and CCS scenarios. The main reason for this is that converting CO_2 to fuel is very energy intensive and ultimately it leads to re-emitting the captured CO_2-emissions. For climate change, the most beneficial way to fulfil the goal for the CCUS system, is to store the captured CO_2, use renewable power to substitute electricity from fossil sources, and to produce fuel by conventional technologies.

This study documents that as long as there is a possibility for renewable electricity to replace fossil electricity generation, this should be prioritised over CCU fuel production. If still fuel production based on CCU is chosen, an important criterion should be to document that the CCU fuel production process uses renewable excess electricity (not available for other purposes).

This study clearly shows that recycling of CO_2 into fuel is not a sustainable way to move forward as the captured CO_2 is re-emitted after going through energy intensive processes. When first being captured, the CO_2 should be stored rather than be used for short-lived products with a high energy intensity production process. CCU products can be more or less long-lived and more or less energy intensive during production. These two factors can affect the results for CCU products. Our study has analysed a short-lived product with an energy-intensive production process. An extreme example in the opposite direction is represented by a long-lived CCU product with an energy-efficient production process. This

will represent permanent storage and lead to an environmental performance close to the result for the CCS scenario. Such a CCU scenario might perform better than the CCS scenario if the production phase for the product being substituted by the CCU product has a higher environmental impact compared to the CCU production. Other CCU products will result in environmental impacts in between the abovementioned extremes

Potential of reaching negative greenhouse gas (GHG) emissions

A major message from the study is that a CCS system has the potential of resulting in negative CO_2-emissions (removing CO_2 from the atmosphere) when storing biogenic CO_2. CCU has not this potential, but it might lead to reduced emissions compared to alternative production routes.

7 References

Abanades, J. C., E. S. Rubin, M. Mazzotti and H. J. Herzog (2017). "On the climate change mitigation potential of CO2 conversion to fuels." Energy & Environmental Science **10**(12): 2491-2499.

Agency), E. D. E. and Energinet (2017). Technology Data Renewable fuels, Energistyrelsen (Danish Energy Agency) and Energinet**:** 260.

Berstad, E. and C. Eriksen (2021). Brief: Problemer med karbonfangst og –bruk (CCU)/ Brief: Clallenges with cabon capture and use (CCU), Bellona.

Equinor (2020). Northern Lights FEED Report RE-PM673-00057 (internal) by the Northern Lights project team, Equinor**:** 178.

Gassnova (2020). Updated CO_2 footprint calculations. Memorandum to 'Full chain CO2 footprint' report from Gassnova (25.11.2019). Memorandum date: 22.10.2020. H. Anvik. Porsgrunn, Gassnova**:** 2.

ISO (2006). ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines. Brussels, Belgium.

ISO (2006). ISO 14048:2006 Environmental management -- Life cycle assessment -- Data documentation format. Brussels, Belgium, ISO.

Korberg, A. D. (2020). Process data e-fuel processes (personal communication by e-mail november 2020). H. L. Raadal, Aalborg University.

Modahl, I. S., C. Askham, K.-A. Lyng and A. Brekke (2012). "Weighting of environmental trade-offs in CCS—an LCA case study of electricity from a fossil gas power plant with post-combustion CO2 capture, transport and storage." The International Journal of Life Cycle Assessment **17**(7): 932-943.

Petrescu, L., D. Bonalumi, G. Valenti, A.-M. Cormos and C.-C. Cormos (2017). "Life Cycle Assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage." Journal of Cleaner Production **157**: 10-21.

Pinturier, L. (2021). Personal communication by Teams and e-mails during March 2021 regarding data input based on the Northern Lights FFED report, Equinor.

Raadal, H. L., G. K. Booto and F. M. Johnsen (2020). Status for CCU og bruk av LCA innen CCS og CCU. Litteraturstudie, Ostfold Research (now NORSUS).

Silva, M. and H. L. Raadal (2019). Life cycle GHG emissions of renewable and nonrenewable electricity generation technologies, Ostfold Research.

von der Assen, N., J. Jung and A. Bardow (2013). "Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls." Energy & Environmental Science **6**(9): 2721-2734.

Zimmermann, A., L. J. Müller, A. Marxen, K. Armstrong, G. Buchner, J. Wunderlich, A. Kätelhön, M. Bachmann, A. Sternberg and S. Michailos (2018). Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO2 Utilization.