LCA of CCS and CCU compared with no capture: How should multi-functional systems be analysed?

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Abstract. CCS (carbon capture and storage) is a means of reducing greenhouse gas emissions by capturing and subsequently storing the CO_2, while CCU (carbon capture and utilisation) is a way of recycling the carbon in the captured CO_2 by converting it into new products. CCS aims at improving the results for one environmental indicator while CCU represents a multi-functional system. It is therefore crucial, when comparing CCU with CCS or no capture, that more than one indicator is used. Also vital is the need to establish relevant system boundaries and to define a joint functional unit, so as to create a robust decision basis for the selection of the environmentally preferable option.

1 Introduction

The emission of greenhouse gases (GHG) from human activities is one of the most important environmental issues of the twenty first century. CCS (carbon capture and storage) is a means of reducing greenhouse gas emissions by capturing and subsequently storing the CO_2. CCU (carbon capture and utilisation) represents a way of recycling carbon in the captured CO_2 by converting it into fuels, chemicals or other products.

Most of the existing LCA studies of CCS analyse capture and storage of CO_2 from the generation of electricity from combined cycle gas turbine (CCGT), integrated coal gasification combined cycle (IGCC) and pulverised coal (PC) power plants [1-13]. Other studies focus on capture from the production of hydrogen [14, 15] and cement [16, 17].

Cuéllar-Franca and Azapagic [18] present a review of investigated LCA studies assessing CCS, as well as CCU for various applications, such as direct utilisation of CO_2; enhanced oil and coal-bed methane recovery; conversion of CO_2 into chemicals and fuels; mineral carbonation; biofuels from microalgae; and enhanced oil recovery (EOR). In order to make the results from the CCS and CCU studies comparable, they were recalculated for a common functional unit: '1 tonne of CO_2 removed'. The authors concluded that CCS systems performed better when compared with CCU, but they emphasised that comparisons should be used as a guide only, as inconsistencies in the system boundaries and functional units made it difficult to compare them on an equivalent basis. Furthermore, they confirmed that there is a need for the development of specific guidelines or 'product category rules' for the

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LCA methodology, especially with regard to system boundaries. A wider range of environmental indicators are also required, to enable consistent comparisons and to avoid problem shifts. Zimmermann, Müller [19] provide specific guidelines for CCUS (carbon capture, usage and storage) value chains considering that CCU systems are multi-functional. This also corresponds with the findings of von der Assen, Jung [20], who describe typical pitfalls for life-cycle assessment of carbon capture and utilisation (CCU).

This paper is an original article, based on a presentation at the the LCM 2021 conference. It aimed to assess the environmental performance of CCS and CCU value chains when compared with no capture, for steam production at a Norwegian paper mill, by employing LCA methodology on the basis of the relatively new guidelines provided by Zimmermann, Müller [19]. The results will be discussed in light of these guidelines and will pinpoint where pitfalls might have arisen if guidelines had not been applied.

2 Methodology and assumptions

The study was carried out using life cycle assessment (LCA) methodology in accordance with the ISO-standards 14044/48 [21, 22] and the guidelines provided by Zimmermann, Müller [19] and von der Assen, Jung [20] for CCUS value chains. The guidelines focus on the importance of joint evaluation of all the functions in the CCU system through the use of system expansion, in addition to classifying feedstock CO_2 as an economic flow (sic), rather than intuitively considering utilised CO_2 as a negative GHG emission. The flue gas in the study comprises 99.3% biogenic CO_2 caused by the combustion of wood. These emissions are assumed to have the same climate change effect as fossil CO_2 when emitted and are neutralised when CO_2 is removed from the atmosphere while the trees are growing.

2.1 Goal and scope

The goal of this study was to make a comparison between the environmental performance of CCS and CCU systems for steam production at Norske Skog Saugbrugs paper mill and to compare the resulting outcome with no capture, focusing on system boundaries as an important prerequisite for fair comparability. The climate change impact category has been used (EN 15804 + A2 method), but the study has also included the use of primary energy (Cumulative Energy Demand, CED as MJ LHV) in order to investigate possible trade-offs. Other indicators might reveal other issues, like for instance impacts from permanent storage, but for principal considerations two indicators have been used for simplification.

The CCU scenario utilises the captured CO_2 as feedstock for methanol production (e-fuel[†]), and it therefore represents a multi-functional system. The comparable Reference and CCS scenarios must therefore also provide fuel, and this is achieved by extending these systems to include conventional methanol production. As the CCU scenario additionally requires considerable quantities of renewable electricity, the CCS and Reference scenarios are provided with the same amount of renewable electricity, which in turn is able to substitute electricity sources elsewhere, since these two systems have no need for this electricity. Ultimately, all scenarios deliver the same functions (steam and fuel) and are provided with the same amount of renewable electricity. The inclusion of the same amount of renewable electricity in all three systems is a modelling decision and the implication on the results is further discussed in chapter 3.2.

[†] Electrofuels (e-fuels) are synthetic fuels made by storing electrical energy in the chemical bonds of liquid or gas fuels (Power-to-Gas (PtG) and Power-to-Liquid (PtL). The term e-fuel refers here to the fuel production process rather than the fuel itself, as the 'final' fuels are identical.

The study has focused on the principal issues in relation to CCS and CCUS systems; which life cycle phases are most important for the different indicators, and where pitfalls might occur if inconsistent system boundaries are chosen.

2.2 Functional unit

The functional unit (FU) is defined as: *point source emissions from steam 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*.

2.3 System boundaries and data sources

For all analysed systems, system boundaries cover the following functions: steam production, production of fuel (methanol) and the use of renewable electricity (wind power), as defined by the system expansion approach. Electricity based on natural gas is used as the substituted electricity. Data have been provided by different actors along the value chains, in addition to being gathered from relevant literature, see detailed information in [23].

3 Results

3.1 Climate Change (CC) and Cumulative Energy Demand (CED)

Figure 1 shows the climate change and cumulative energy demand results for all scenarios throughout their value chain. Net burdens are represented as black lines and these show that the CCS scenario performs best or similarly to the Reference scenario. The CCU scenario performs worst for both climate change and cumulative energy demand.

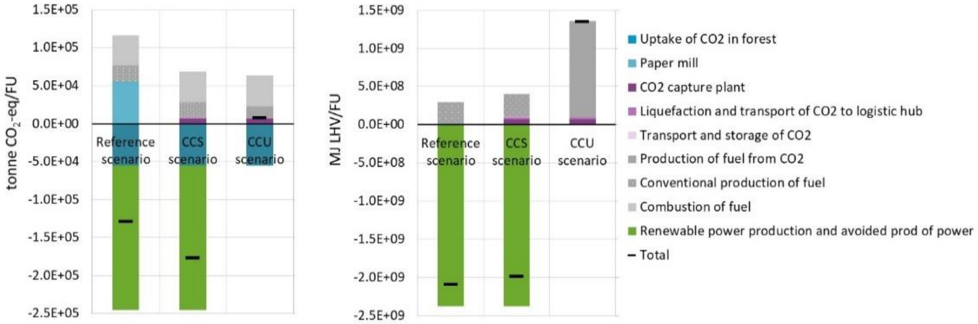

Fig. 1. Climate change results for the joint functional unit.

For **climate change**, uptake of biogenic CO_2 is shown as a negative value (dark blue), representing 55,200 tonne CO_2-eq for all the scenarios. For the Reference scenario, these greenhouse gases are directly emitted when the biomass is burnt for steam production (light blue). This means that there is a net zero climate burden when taking only the point source into account. For the CCS and CCU scenarios, a capture rate of 90% is assumed, and the remaining CO_2 in the flue gas is emitted. These emissions are added to the emissions relating to the capture activity itself, shown by the dark purple bar.

For the **CCU scenario**, production of fuel from the CO_2 (dark grey) leads to 15,900 tonne CO_2-eq, while the re-emitting during combustion of the greenhouse gases that initially were captured in the fuel, contributes an additional 40,400 tonne CO_2-eq (light grey). In total, this gives a net climate change result of 8,300 tonne CO_2-eq/FU.

For the **CCS scenario**, the captured emissions are not re-emitted. To fulfil the functional unit, however, fuel is produced by conventional technology (dotted grey) and more emissions are added when the fuel is combusted during the use phase (light grey). Finally, as this system is provided with the same amount of wind power as is required in the CCU system, avoided emissions are added from the substitution of fossil power (green bar). In total, the net climate impact of the CCS scenario is considerably better than the CCU system.

The **Reference scenario** is also required to produce fuel by conventional technology, leading to greenhouse gas emissions both from the production phase (dotted grey) and from combustion in the use phase (light grey). As in the case of CCS, the system is provided with wind power which substitutes fossil power (green). Overall, the Reference scenario performs worse than the CCS scenario, but nevertheless considerably better than CCU.

For the **CED indicator**, the ranking of the CCU scenario is in line with the climate change result. The principal differences between these two indicators are: i) no negative burdens are included for CED during the uptake phase (dark blue), ii) no burdens are included for CED at the steam boiler (light blue) or during the combustion of fuel (light grey), and iii) the CED burden during production of fuel from CO_2 is quite pronounced. There is a marked contrast between the results for climate change and CED, as CED includes both fossil and renewable energy, while the renewable energy makes only a very small contribution to the climate change category. For the CED indicator, the major difference between the CCU result and the two other scenarios is explained by the CCU fuel production process (dark grey) and the avoided burden for substituted electricity (green).

Although CCU represents carbon recycling, it is more energy efficient to produce conventional fuel (grey dotted bars) and to use the renewable electricity to substitute fossil power (green) owing to the considerable energy intensive recycling process.

3.2 Sensitivity analysis of the substituted electricity

As shown in chapter 3.1, the avoided impact from the substituted electricity (natural gas produced in a conventional power plant) plays an important role in the overall results, and a sensitivity analysis for varying climate intensities (g CO_2-eq/kWh) was carried out (see Figure 3). The CCU scenario is shown as the grey, horizontal line while the CCS and Reference scenarios are represented by the purple and blue lines, respectively. The base analysis' net results are shown as large squares at 650 g/kWh.

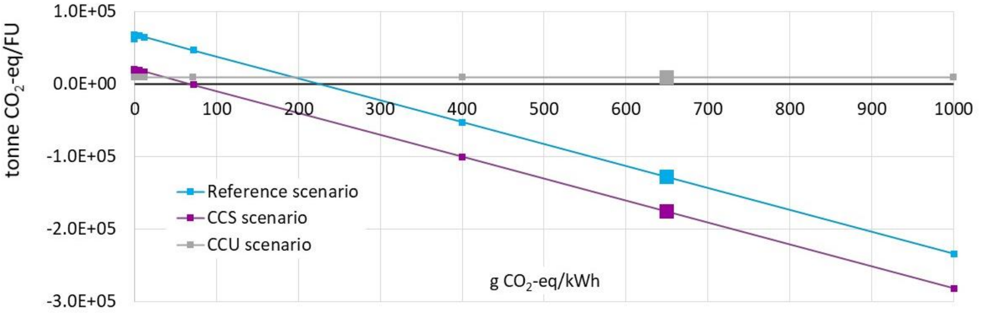

Fig. 3. Sensitivity analysis for climate change; the effect of substituted electricity.

The figure reveals how the net climate change results (tonne CO_2-eq/FU) vary as a function of climate intensity (g CO_2-eq/kWh) for the substituted electricity. CCS is beneficial over CCU when the provided wind power substitutes electricity with a climate intensity > 40 g CO_2-eq/kWh (~ photovoltaic [24]). Similarly, the Reference scenario is beneficial over CCU when substituting electricity with a climate intensity > 200 g CO_2-eq/kWh.

A common pitfall [20, 25] is the use of inconsistent system boundaries, by, for example omitting the significant amount of electricity required for upgrading CO_2 to a product. On the other hand, this choice can be regarded a modelling decision. The effect of omitting the use of renewable electricity for substitution (exclude it from the FU) can be seen in Figure 3 as this corresponds to zero emission substituted electricity.

It can be concluded that where renewable electricity can be used to replace fossil electricity generation, this should be prioritised over the recycling of captured CO_2 into fuel, and the captured CO_2 should instead be permanently stored. This is in line with results from Abanades, Rubin [25]. If, however, the choice of not providing the CCS system with the same amount of renewable electricity for substitution, the CCU system turns out best.

4 Discussions and conclusions

CCS focuses on improving the results for one indicator only and CCU represents a multi-functional system. It is therefore crucial to analyse the use of more than one indicator and to establish relevant system boundaries when comparing the environmental performance of CCS and CCU systems. The application of system expansion ensures that the compared systems provide the same functions to society and the analysis shows that CCS in general is beneficial over CCU as long as fossil electricity is a part of the grid mix. However, if the use of renewable electricity for substitution is decided not to be included in the system expansion boundaries, CCU will represent the best option. The choice of modelling decision therefore represents an important issue when comparing multifunctional systems.

An important aspect, when moving towards the future's increased electrified and multifunctional community, is the prioritising of the "correct" use of important/scarce resources, such as renewable electricity, and the means by which this is carried out. One of the relevant questions requiring an answer might, for example, be: What is the "most environmentally friendly" use of electricity? As the community is moving towards a circular economy, there will be an increased focus on the ranking of the environmental performance of use, reuse and recycling of our common goods and resources. It is to be expected that LCA methodology will be an important tool for this purpose, and that the expansion of the system boundaries will be crucial for the correct assessment of the systems. This study shows that, although CCU represents carbon recycling, it is today more climate friendly and energy efficient to produce conventional fuel and to use the renewable electricity to substitute fossil power, than to produce fuel from captured CO_2. In cases, however, where substituting fossil electricity generation is less relevant, CCU is the best option. This can, for example, be the case in the future as production of fossil power decreases.

Finally, it should be mentioned that the system expansion perspective makes it difficult to create separate environmental footprints relating to the specific actors along the value chains. This is, however, outside the scope of this study.

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