LCA methodology application to assess the environmental impact of CCS and CCU: a review

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Abstract

This article is a literature review on the state of the art of LCA (life cycle assessment) methodology application to study the environmental impact of CCS (carbon capture and storage) and CCU (carbon capture and use), regarded as two promising solutions to limit CO_2-emissions to the atmosphere from power-plants. In order to avoid burden shifting, CCS and CCU options have been examined and compared not only in terms of GHG (greenhouse gases) emissions, but also considering many other environmental impacts, and considering the whole life cycle of each application from raw materials extraction up to the end of life. The effect of different possible technologies for carbon capture is discussed too. At the end, a comparison between the main environmental impacts of CCS and different CCU options is provided, including the general considerations that can be drawn and that should guide future research on the topic. The big uncertainty that is still present in the available data, due to a lack of uniformity in the methodology followed in different LCAs, is underlined as the greatest limitation.

1. Introduction

One of the greatest deals we have to face in these years is certainly how to limit CO_2 emissions to the atmosphere: it has been estimated that worldwide emissions of CO_2 have grown with an average of 2.7% every year, reaching values that are 60% higher with respect to the ones registered 30 years ago (Cuéllar-Franca and Azapagic, 2015). Electricity accounts for the 33% of the overall emissions, transport for 34%, industry for 15% and commercial and residential activities for 10% (https://www.epa.gov). Among main CO_2 emitters, power generation plants play a key role, generating about 40% of the total worldwide emissions. A 50% cut-off of greenhouse gases emissions is urgently required to limit to a maximum of 2°C the world temperature increase. Among the available options to meet this target, the so-called CCS (carbon capture and storage) and CCU (carbon capture and usage) are getting more and more interest. CCS means to capture CO_2 and store it in geological formations. CCU is a step forward and comprehends a further transformation of the captured CO_2 (Gibbins and Chalmers, 2008).

In order to evaluate the potentiality in terms of environmental impact reduction of CCS and CCU, it is advisable to apply the life cycle assessment (LCA) methodology, possibly with a “from cradle to grave” approach: this methodology can address different kinds of impact categories and takes into account every step of the life cycle, from the raw materials extraction up to the final disposal or recycle.

The aim of this article is to collect the main LCA studies performed on the application of CCS and CCU in power plants, in order to understand the major pros and drawbacks from an environmental point of view. A case study, related to formic acid formation, is discussed in detail with the aim of making a consistent comparison between CCS and CCU to identify the most promising route. The discussion also includes a small insight into different possible technologies and innovative solvents for carbon capture.

2. Overview on CCS and CCU technologies

2.1. CCS: the main available CO_2 capture options

The core of CCS is CO_2 sequestration. Three main technological solutions can be distinguished, all applicable to power plants: post-conversion capture, pre-conversion capture and oxy-fuel combustion (Zakuciová et al., 2016). Post-conversion capture means separating CO_2 from waste gaseous streams: this is typically performed through absorption into amines (especially MEA (mono-ethanol-amine) in power plants) or physical solvents, but membrane permeation, cryogenic technologies and calcium-looping, which exploits a reaction between CO_2 and a CaO solid sorbent at high temperatures leading to calcium carbonate formation, can be exploited too. Pre-conversion capture means to capture the CO_2 that is formed as an intermediate co-product during a conversion process, while oxy-fuel combustion consists in performing combustion in oxygen instead of air.

2.2. CCU: emerging possible uses for captured CO_2

CCU options aim at exploiting the captured CO_2 for transformation into a valuable product. A good CCU is a process able to convert high amounts of CO_2 and to tolerate the presence of impurities. Enhanced oil and gas recovery (EOR and EGR) are very promising possibilities: they consist in CO_2 injection, typically in supercritical conditions, into oil or gas fields to favour the extraction of the remaining oil/gas thanks to a re-pressurization of the field. An alternative route is CO_2 use as a reactant in carboxylation reactions to get polymers (acrylates, elastomers, and carbonates, such as dimethyl carbonate (DMC)) or to produce formic and oxalic acid, foams, or fuels (Zimmermann et al., 2018). Hoppe et al. (2017) propose a photocatalytic conversion of CO_2 captured from power plants to produce methanol and methane. Another option is mineral carbonation: CO_2 can react with magnesium or calcium oxides, normally present in nature in the form of silicates minerals, to form carbonates. Stable forming carbonates can be used just to store CO_2, but they can be also furtherly used, i.e. in constructions.

Finally, CO_2 can also be used to cultivate microalgae exploitable for biofuels production: these microalgae are able to fix CO_2 directly from the flue gases.

3. Life cycle assessment applied to CCS

3.1. Comparative assessment of power plants with and without CCS

A lot of studies have evaluated the environmental benefit in terms of global warming (GW) reduction associated to the introduction of a CO_2-capture facility in different kinds of power plants and for different CO_2 capture options (Cuéllar-Franca and Azapagic, 2015, Petrescu et al., 2017 and Yang et al., 2019). In order to allow a meaningful comparison between the different options, we selected those studies that have the same functional unit (1 MWh of electricity produced) and the same system boundaries (from power plant fuel extraction up to CO_2 transportation and storage). However, the comparison can be only qualitative, due to the wide freedom left to each author to define assumptions, allocation methods, final storage site, etc. For example, no precise information on key parameters like transportation distances and purity of the CO_2 to be pumped are available. Moreover, the studies refer to process data of existing plants in different world areas, and different storage sites (geological or under the seabed) are considered.

The average GW for PC (pulverised coal), CCGT (combined cycle gas turbine) and IGCC (integrated gasification combined cycle) power plants without CCS are estimated to be on average 876, 471 and 1009 kg CO_2 eq., respectively (Cuéllar-Franca and Azapagic, 2015). When CCS is introduced, the greatest GW reduction (82%) can be achieved by oxy-fuel combustion in PC plants (that is, however, one of the most expensive options), while the lowest one (about 40%) by post-combustion capture in CCGT plants. However, many other indicators considerably increase if a post-combustion CCS facility is introduced: depending on the type of power plant, the increase is in the range 1-28 times for freshwater aquatic ecotoxicity (FAET), 2-58% for abiotic resources depletion (AD), 1-366% for eutrophication (E) and 0.35-500 times for ozone depletion (OD). The main reasons are the production and use of MEA, which is a toxic compound that during the process is unavoidably emitted (even if in very small quantities) to atmosphere, land and water, and the overall loss of efficiency of the power plant, due to the fact that a higher amount of raw materials has to be treated to produce the same final amount of electricity. For other impact categories, the results are not univocal: according to Yang et al. (2019), by introducing post-combustion capture in a PC plant, a significant increase can be experienced also in acidification (A), terrestrial ecotoxicity (TET), human toxicity (HT) and marine aquatic ecotoxicity (MAET), while according to Cuéllar-Franca and Azapagic (2015) TET and MAET are 36% and 90% lower, respectively.

3.2. Comparison between MEA-based CO_2 capture and other innovative technologies

Recent research has focused on studying innovative CO_2-capture technologies. For example, Zhang et al. (2014) performed a comparative LCA evaluating how the main environmental impact indicators change when MEA-absorption, membranes or hybrid membrane-cryogenic technique are exploited to treat flue gas from a power plant (Figure 1). In this study, the functional unit is defined as 1 kWh of electricity produced and the whole life cycle has been considered, from raw materials collection up to CO_2 transportation via pipeline (200 km) and storage into an offshore 800 m deep injection well. The observed GW reduction is more or less the same for all the three alternatives (about two thirds of the equivalent CO_2 emissions of the base plant without CCS). Such a result means that, even if the absolute CO_2 capture capacity in the processed flue gases is equal to 90%, the total reduction of CO_2 emissions can be limited to about 66%: this is because LCA takes into account also the emissions associated to the carbon capture infrastructure development and, even more important, long-distances CO_2 transportation and energy requirements associated to CO_2 capture and storage under pressure, which have a relevant impact. Using MEA, higher GHG emissions are associated both to the CO_2 capture supply chain and to the coal combustion. However, everything considered, MEA's process overall net emission is not much higher with respect to the one of membranes and hybrid technologies, because a slightly higher CO_2-emission saving is achievable in the capture process, due to MEA's higher capture performances.

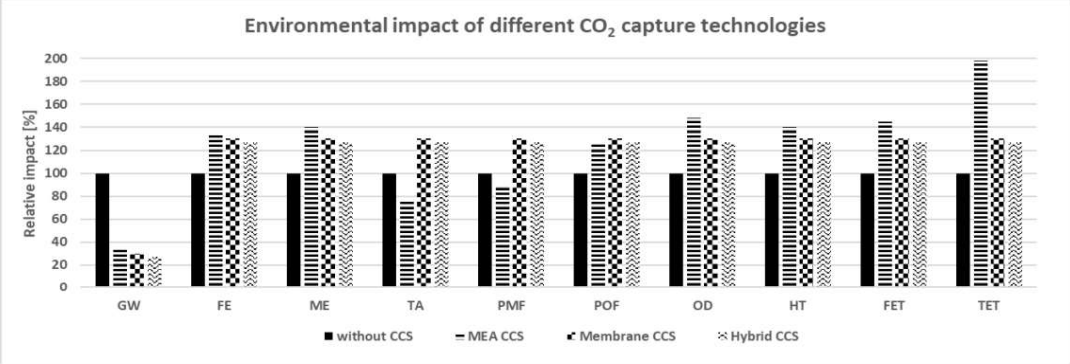

Figure 1: comparative LCA, including different impact categories, of CCS systems with MEA, membrane and hybrid CO_2 capture in comparison with a CCS-free power plant. Data by Zhang et al. (2014).

Concerning the other impact categories, it can be noted that MEA absorption generates an extremely high TET (approaching 200% if a 100% contribution is assigned to the process without CCS), but at the same time it is the only process allowing to obtain terrestrial acidification (TA) and particular matter formation (PMF) indicators that are lower with respect to the ones of the CCS-free power plant. Membrane and hybrid CCS show instead practically the same relative impact. Another study by Petrescu et al. (2017) claims that a valid alternative in terms of environmental impact reduction for carbon capture is calcium-looping:

this technology can be associated with a 19% lower GW with respect to the amine-based capture, and an impact reduction is observed also for A, E, OD, AD, HT, TET, MAET and photochemical oxidation (POF).

4. Life cycle assessment applied to CCU

In the recent years, many LCA studies concerning the environmental impact of different CCU options have been performed. Hidayatno et al. (2017) analysed CO_2 utilization in EOR, pointing out that the greatest impact contributions are associated to A, photo-oxidant formation (POF) and AD. Concerning GW, Liu et al. (2020) have estimated that the recovery of 1 metric ton of oil can be associated with a net emission of -1.68 tCO_2eq if a gate-to-gate approach is followed (CO_2 capture is excluded from the study, the required electricity is supposed to be taken from a coal-fired power plant, while the presence of a CO_2 liquefaction facility, transportations (overall 1-way distance of 400 km), injection, oil production and recycling are accounted for). Sminchak et al. (2020) have documented the emissions of an EOR site in the Northern Michigan Basin, in which CO_2 comes from a natural gas processing facility: a net balance of about -160000 tCO_2eq has been reached in 22 years accounting for the GW associated to CO_2 capture, compression, injection and recycle, pipeline transport, construction and well drilling, oil processing refining and transport. Such studies show the great potentiality associated to EOR.

Huang et al. (2019) claim the strong environmental impact reduction associated to the production of concrete Portland Cement blocks by CO_2-cured mineral carbonation: when compared to conventional steam curing, the CO_2-based treatment can lead to a GW reduction of 13% for ordinary blocks and 30% for Wollastonite blocks production. This study neglects the final block transportation to the use site and assumes an equal lifetime for all the blocks.

However, not all CCU paths seem to provide environmental benefits. For example, Artz et al. (2018) report a cradle-to-grave LCA on DMC synthesis by electrochemical conversion and by urea transesterification: the GW is 5 and 20 times higher, respectively, than with benchmark oxidative carbonylation. For what concerns the synthesis of methane and methanol, Hoppe et al. (2017) claim that GW can be effectively reduced with respect to conventional fossil-derived chemicals only if renewable power is used to supply the required huge amounts of electricity. However, solar and wind power are not largely available, and in addition the eventual GW reduction is counterbalanced by a significant increase in the required abiotic resources.

At the state of the art, it is very difficult to draw any final conclusion on the different CCU scenarios since the different assumptions in the LCAs do not allow to compare consistently the studies and to reach an efficient decision making for the development of the best technologies for climate change mitigation. To overcome this limit, recently Zimmermann et al. (2018) and Müller et al. (2020) have developed specific guidelines to be followed when making an LCA on CCU applications.

5. A comparison between the environmental impacts of CCS and CCU

5.1. Formic acid synthesis by CO_2 utilization: a case-study

Aldaco et al. (2019) performed a dynamic LCA on formic acid (FA) production by CO_2 capture and electrochemical reduction (ER), with the aim of comparing the environmental impact of this process with the one of traditional formic acid synthesis by hydrolysis of ethyl formate and the one of the storage of the captured CO_2, accounting for time-changing performances according to the decarbonization pathways compatible with the Paris target. This case study is of special interest for the scope of this article since a consistent and direct comparison between a CCS and a CCU scenario is performed under the same assumptions. The selected functional unit is the current European production of FA, while CO_2 is supposed to be captured by post-combustion with MEA from a 500 MW capacity coal plant, which supplies energy to the grid. Efficiency of the capture technology is supposed to be 89%. CO_2 conversion requires a series of three processes: ER, the distillation of the obtained products and, finally, the treatment of the forming by-products. As supporting electrolytes to favour the ER reaction, KOH (as anolyte) and $KHCO_3$ and KCl (as catholyte) are employed and recirculated in the process. The CO_2 conversion site is supposed to be located close to the capture unit (no transport required). The environmental impact of the FA synthesis, in terms of tonnes of emitted CO_2 per functional unit, has been assessed, considering a scenario in which the electricity required to meet the overall energy requirements comes only from the grid and another one in which solar power is employed in the electrochemical reactor (grid energy still considered for the other operations). Concerning carbon storage, CO_2 is supposed to be compressed to 11 MPa by means of a compression train with intermediate cooling and then transported in supercritical state via a 95 cm thick pipeline for 5 km onshore and 95 km offshore up to the permanent storage site. Transport is very important in addressing the environmental impact of CCS since it is a dominant contribution to GW. Figure 2 compares the GW of conventional formic acid synthesis, the one of ER synthesis, the one of CCS and two intermediate options (part of CO_2 is sent to storage and part is transformed). Nowadays the conventional formic acid synthesis is still associated to a lower GW with respect to the ER-based one but starting from 2028 ER route is forecasted to become less impacting. In a solar power scenario, the ER route can lead to a GW reduction up to about 35% with respect to the ethyl-formate hydrolysis one. However, both in a grid and in a photovoltaic energy scenario, CCS is the option associated to the lowest GW.

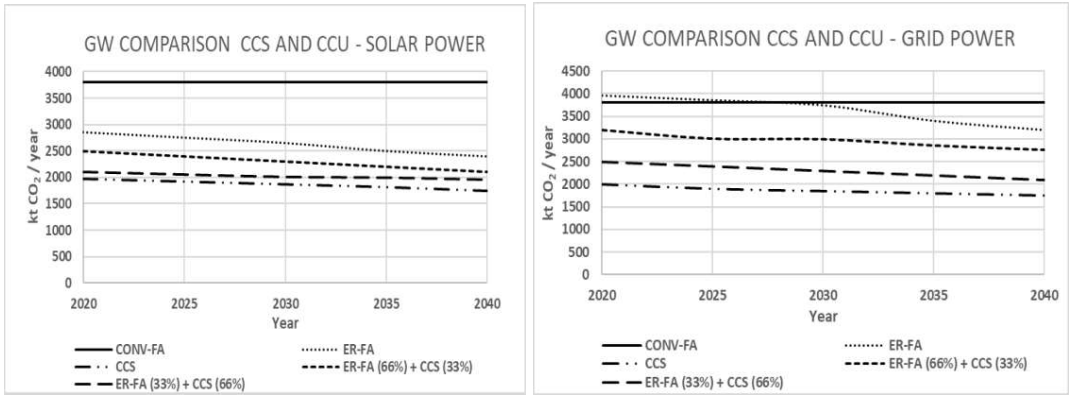

Figure 2: comparative LCA between CCS, CO_2 utilization to produce formic acid by ER and traditional formic acid synthesis using fossil raw materials. Data by Aldaco et al. (2019).

5.2. Another comparative case-study accounting for CCS and CCU

Another study (Cuéllar-Franca and Azapagic, 2015) has compared the potential GW of CCS and different CCU options (EOR, DMC synthesis, mineral carbonation, biofuels from microalgae), assuming 1 tonne of CO_2 removed from flue gas as functional unit. The option showing the highest impact in terms of all indicators is DMC production, for which the GHG emissions are increased by 216 times with respect to CCS (59.4 tonnes of CO_2 eq.): the main reason is that 2 tonnes of DMC have to be generated to convert 1 tonne of captured CO_2, and this conversion requires very big amounts of reactants like NH_3 and naphtha. It is interesting to note that all proposed CO_2 transformations are associated with a much higher GW with respect to CO_2 storage. However, on the other hand, apart from DMC synthesis, all the other CCU options show better performances in terms of many other impact indicators (Figure 3). The greatest limitation of this study is that, even if the authors have rescaled the results obtained in the different studies to make a consistent comparison, it is impossible to ensure the homogeneity of all assumptions. In particular, there is no clear indication of the reference energy systems (fossil or carbon-free). Therefore, the results must be used only to derive general trends more than for a quantitative analysis.

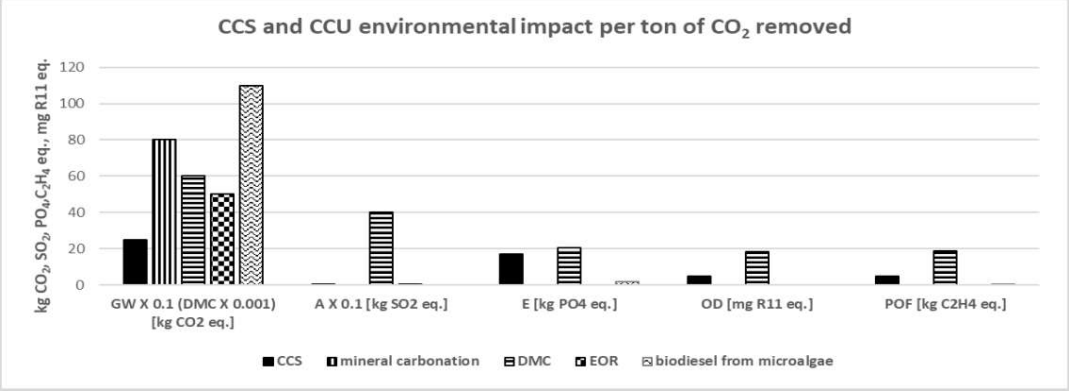

Figure 3: comparison between the environmental impacts, referred to 1 tonne of CO_2 removed, of CCS and CCU following an LCA approach. Data by Cuéllar-Franca and Azapagic (2015).

6. Conclusions

In this paper a short review of LCAs performed in the literature for CCS and CCU has been presented. It has been shown that CCS, both in pre-conversion, post-conversion and oxy-fuel systems, allows a very deep reduction (from 40% up to 92%) of GHG emissions associated to power plants, but at the same time it causes a not negligible increase in many other impact categories, mainly due to the need for compensating the power plant efficiency loss that is generated. The eventual substitution of MEA absorption with other innovative capturing technologies does not seem to provide a significant environmental impact reduction. Considering CCU, it has been shown that both GW and the other impact categories strongly depend on the specific application. At the state of the art, few consistent comparisons between CCS and CCU scenarios can be done, due to the uncertainty related to the collected results, given the wide freedom left to each author to define autonomously system boundaries, functional units, allocation methods, and assumptions. Only in the work by Aldaco et al. (2019) a comparative discussion with respect to a specific and well-defined application is available. This is a great limitation because no precise quantitative conclusions can be drawn. In this sense, the detailed recently published guidelines on the methodology to be followed (see chapter 4) can significantly improve the comparability among different studies in the future years. We believe comprehensive and consistent comparative LCAs including both CCS and many different utilization options starting from the same power plant and under the same conditions and assumptions should be performed in order to allow identifying the most promising applications for the future. What emerges from the available studies is that GW impact is higher in a CO_2 transformation with respect to a CO_2 storage scenario. At the same time, however, it seems that, compared to CCS, CCU is able to reduce many other environmental impacts in mineral carbonation and EOR applications, while the synthesis of chemicals like FA and DMC seems to be a less promising route. In addition, CCU does not carry the uncertainty related to CO_2 leakage in time, which instead is a threat for CCS. In any case, considering their really strong potentiality in reducing the environmental impact of many industries and power plants, CCS and CCU are both strategies that worth more attention and can potentially gain a key role in addressing the issue of climate change.

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