SHORT COMMUNICATION

Journal of Fundamentals of Renewable Energy and Applications

2020

Vol.10 No.7

CO_2 and Carbon Capturing, Utilization and Valuation

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ABSTRACT

This paper presents a first comprehensive comparison of environmental impacts of carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies. Life cycle assessment studies found in the literature have been reviewed for these purposes. In total, 27 studies have been found of which 11 focus on CCS and 16 on CCU. The CCS studies suggest that the global warming potential (GWP) from power plants can be reduced by 63–82%, with the greatest reductions achieved by oxy-fuel combustion in pulverised coal and integrated gasification combined cycle (IGCC) plants and the lowest by post-combustion capture in combined cycle gas turbine (CCGT) plants. However, other environmental impacts such as acidification and human toxicity are higher with than without CCS. For CCU, the GWP varies widely depending on the utilisation option. Mineral carbonation can reduce the GWP by 4–48% compared to no CCU. Utilising CO_2 for production of chemicals, specifically, dimethylcarbonate (DMC) reduces the GWP by 4.3 times and ozone layer depletion by 13 times compared to the conventional DMC process. Enhanced oil recovery has the GWP 2.3 times lower compared to discharging CO_2 to the atmosphere but acidification is three times higher. Capturing CO_2 by microalgae to produce biodiesel has 2.5 times higher GWP than fossil diesel with other environmental impacts also significantly higher. On average, the GWP of CCS is significantly lower than of the CCU options. However, its other environmental impacts are higher compared to CCU except for DMC production which is the worst CCU option overall.

Keywords: Carbon capture and storage, Carbon capture and utilisation, Life cycle assessment, Climate change, Environmental impacts.

INTRODUCTION

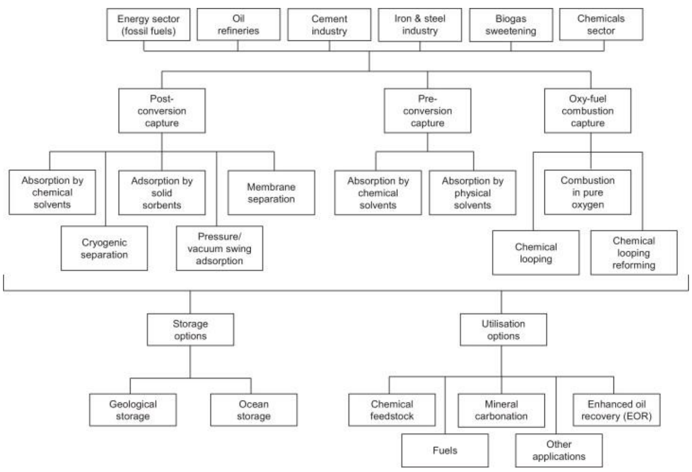
Global emissions of carbon dioxide (CO_2) from fossil fuels have been increasing by 2.7% annually over the past decade and are now 60% above 1990 levels, the reference year for the Kyoto Protocol [1]. By contrast, it is estimated that the CO_2 emissions should be reduced by at least 50% to limit the rise of the global average temperature to 2 °C by 2050 [2]. A range of different options that could help towards this target for mitigating climate change are considered worldwide, including carbon capture and storage (CCS) [3], [4]. One of the main economic obstacles is the fact that it is an unprofitable activity that requires large capital investment [5]. In the UK, for example, there are no incentives or subsidies for CCS which is going to make its development and deployment difficult. On the technical side, CO_2 leakage rates are uncertain and in some countries CCS is not a viable option as their geological storage capacity is limited or in some cases only available offshore, thus increasing transportation and injection costs [5], [6].

More recently, a related alternative carbon capture and utilisation (CCU) – has started to attract attention worldwide because it can turn waste CO_2 emissions into valuable products such as chemicals and fuels, while at the same time contributing to climate change mitigation. One of the advantages of CCU over CCS is that utilisation of CO_2 is normally a profitable activity as products can be sold [5]. Even though conversion of CO_2 to various products is energy intensive owing to its thermodynamic stability, the potential for providing a secure supply of chemicals and fuels, along with the escalating fossil-fuel prices, could become a powerful driver for CCU [5], [7]. Nevertheless, the current global demand for chemicals does not have the capacity to sequester enough CO_2 emissions to contribute significantly to meeting the carbon reduction targets. Furthermore, using CO_2 for fuel production only delays its emissions rather than removing it over long timescales needed for mitigating climate change. Similarly, the 'storage' in some chemicals is also short-lived, depending on their use. This is important to ensure that climate change is not mitigated at the expense of other environmental issues. It is also important that the impacts be assessed on a life cycle basis, to avoid shifting the environmental burdens from one life cycle stage to another.

OVERVIEW OF CCS AND CCU TECHNOLOGIES

CCS and CCU aim to capture CO_2 emissions from point sources such as power plants and industrial processes, to prevent the release into the atmosphere [9]. In CCS, captured CO_2 is transferred to a suitable site for long-term storage [9], [10], [11], [12], [13], [14], [15], while in CCU, captured CO_2 is converted into commercial products [5], [9]. Note that it is not the intention of this paper to provide an in-depth technical review of the CCS and CCU technologies but rather to provide the background and set the context for the main aim of the paper which is a critical review and analysis of the life cycle environmental impacts of these options.

Figure 1: Different carbon capture, storage and utilisation options.

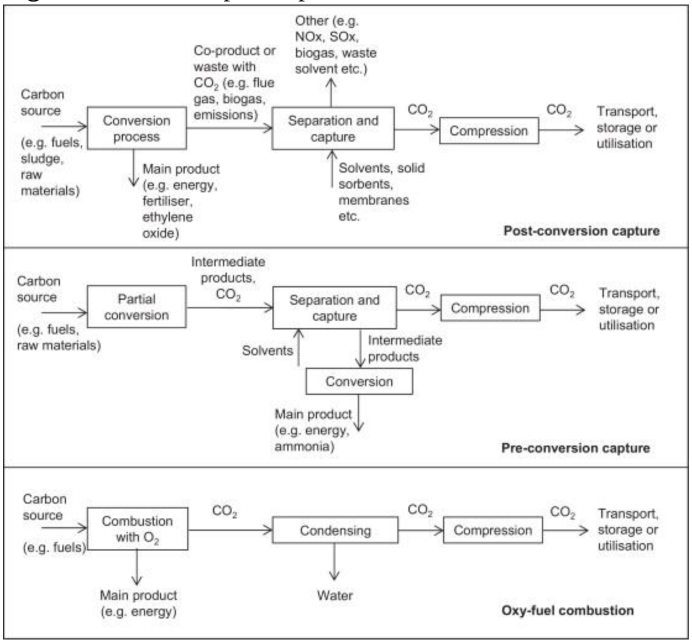


CO_2 CAPTURE OPTIONS

The main industrial sources of CO_2 are power plants, oil refineries, biogas sweetening as well as production of ammonia, ethylene oxide, cement and iron and steel [5], [9]. For example, over 40% of the worldwide CO_2 emissions are caused by electricity generation in fossil-fuel power plants [9]. Therefore, these sources are the main candidates for a potential application of CCS or CCU. As for the CO_2 capture, a one-size-fit-all technology would not be feasible owing to the diversity of the industrial processes generating CO_2 emissions. For that reason, there is a wide variety of CO_2 capturing systems, to ensure compatibility with the specific industry. However, the level of maturity among different capturing systems varies across industries. For example, power plants and oil refineries are getting closer to implementing CO_2 capturing systems at a large-scale, while the cement and the iron and steel industry will still have to overcome the transition from small-scale demonstration plants to industrial deployment [18].

The CO_2 capture options can be classified as post-conversion, pre-conversion and oxy-fuel combustion [18], [19], [20]. Therefore, arguably, this is a CCU rather than CCS option as microalgae would not be cultivated merely to capture CO_2. Thus, CO_2 fixation by microalgae and the related biofuel production are discussed in Section 2.3 which provides an overview of CCU options.

Figure 2: Carbon capture options.



Post-conversion capture

Post-conversion capture involves separation of CO_2 from waste gas streams after the conversion of the carbon source to CO_2 for example, via combustion of fossil fuels or digestion of wastewater sludge. It can be used to remove CO_2 from various industries, including power plants, production of ethylene oxide, cement, fuels, iron and steel as well as biogas sweetening [10], [21]. When used in power plants, post-conversion capture is also known as post-combustion capture [19].

Pre-conversion capture

Pre-conversion capture means capturing CO_2 generated as an undesired co-product of an intermediate reaction of a conversion process [18]. Some examples include the production of ammonia and coal gasification in power plants [10], [19], [26]. In ammonia production, CO_2 that is co-produced with hydrogen during steam reforming must be removed before the ammonia synthesis can take place – absorption in MEA is commonly used for these purposes [10], [27]. Similarly, in an integrated gasification combined cycle (IGCC) power plant, CO_2 must be separated from hydrogen. As indicated in Table 1, this is typically achieved using physical solvents such as selexol and rectisol [19], [26], [28], [29]. Note that, when applied in power plants, pre-conversion capture is also referred to as pre-combustion capture [19].

CO_2 UTILISATION OPTIONS

As mentioned earlier, as an alternative to storage, captured CO_2 can be used as a commercial product, either directly or after conversion. Examples of direct utilisation include its use in the food and drink industry and for EOR; CO_2 can also be converted into chemicals or fuels. These and other applications shown in Fig. 1 are described next.

Direct utilisation of CO_2

Several industries utilise CO_2 directly. For example, in the food and drink industry, CO_2 is commonly used as a carbonating agent, preservative, packaging gas and as a solvent for the extraction of flavours and in the decaffeination process [42]. Other applications can be found in the pharmaceutical industry where CO_2 can be used as a respiratory stimulant or as an intermediate in the synthesis of drugs [7], [42]. However, these applications are restricted to sources producing CO_2 waste streams of high purity such as ammonia production [7], [9], [10].

Enhanced oil and coal-bed methane recovery

EOR and ECBM are other examples of direct utilisation of CO_2 where it is used to extract crude oil from an oil field or natural gas from unmineable coal deposits, respectively. While the latter is not commercially available yet [10], the former has been widely practiced for over 40 years in several oil-producing countries, including Norway, Canada and the USA [10], [43].

Also known as tertiary recovery, EOR is used to extract otherwise unrecoverable oil reserves. It involves injection of different agents into the reservoir, including CO_2, natural gas nitrogen, polymers (e.g. polyacrylamides) and surfactants, to remove the oil trapped in the rocks [44]. EOR can extract 30–60% more of the crude originally available in the well, compared to primary and secondary extraction which recover 20–40%. Among the different agents, naturally occurring CO_2 is used most commonly because of its low cost and wide availability [43]. However, most CO_2 returns back to the surface with the pumped oil – although it recycled for economic reasons, some of gas is emitted into the atmosphere. With the advent of climate change, the possibility of utilising CO_2 from anthropogenic sources in EOR has been considered in recent years [2]. Nevertheless, the switch from using naturally to anthropogenic sources of CO_2 will depend mostly on the capture costs and incentives for the oil and gas industry.

Conversion of CO_2 into chemicals and fuels

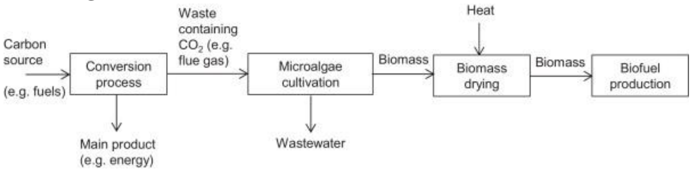
CO_2 can also be utilised by processing and converting it into chemicals and fuels. This can be achieved through carboxylation reactions where the CO_2 molecule is used as a precursor for organic compounds such as carbonates, acrylates and polymers, or reduction reactions where the Cdouble bondO bonds are broken to produce chemicals such as methane, methanol, syngas, urea and formic acid [5], [7], [9], [41]. Furthermore, CO_2 can be used as a feedstock to produce fuels, for example, in the Fischer–Tropsch process [46].

However, although CO_2 can replace petrochemical feedstocks for production of chemicals and fuels [5], a disadvantage is that its conversion is energy intensive and it requires high-selectivity catalysts since CO_2 is thermodynamically highly stable. Furthermore, chemicals and fuels offer limited storage periods for captured CO_2 because of their short life span (typically less than six months). Consequently, CO_2 is released into the atmosphere before the benefits of the capture can be realised. For that reason, future research efforts should focus on the synthesis of materials and products with longer lifespans.

Biofuels from microalgae

CO_2 can be used to cultivate microalgae used for the production of biofuels [5], [48], [49]. Microalgae have the ability to fix CO_2 directly from waste streams such as flue gas as well as using nitrogen from the gas as a nutrient [5], [50]. Cultivation of microalgae can be carried out in open raceway ponds and photo-bioreactors (flat-plate, annular or tubular) [51]. The former require a large land area and process control is difficult, limiting productivity [5]. As shown in Fig. 3, before microalgae can be converted into fuels, the biomass content has to be harvested and dried [5]. Biochemical conversion relies on biological and chemical processes, such as anaerobic digestion, fermentation and esterification [48], [51]. Furthermore, large-scale production of biofuels from microalgae is currently not available because of the high production costs, mainly owing to the high energy requirements in the harvesting stage [5], [48], [49].

Figure 3: Utilisation of CO2 to produce biofuels from microalgae.



CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This paper has analysed the life cycle environmental impacts of various CCS and CCU options for the capture, storage and/or utilisation of CO_2 emitted by power plants and other industrial sources. The captured CO_2 can be stored in geological formations, also known as geological storage, or in the oceans. The former represents a more viable option as the properties of depleted oil and gas reservoirs and deep saline aquifers are better understood. Besides storage, CO_2 can be used directly in different industrial sectors, including the food and beverage as well as pharmaceutical industry. It can also be converted into high-demand products such as urea, methanol and biofuels.

The results of the LCA studies of different CCS options found in the literature indicate that the GWP from power plants can be reduced by 63–82% per unit of electricity generated, depending on the CO_2 capture option. The GWP for pre-combustion capture and oxy-fuel combustion in IGCC plants is similar: 190 and 200 kg CO_2 eq./MWh, respectively, while the average without CCS is 1009 kg CO2 eq./MWh. Therefore, the greatest GWP reductions (up to 82%) can be achieved by oxy-fuel combustion in PC and IGCC plants and the lowest by post-combustion capture in CCGT plants (63%).

The results for the other environmental impacts vary across the studies. However, the large majority reported higher impacts for the plants with than without CCS. This is mainly attributed to the additional coal mining and shipping needed to compensate for the energy efficiency losses from the use of CCS, MEA production and ammonia emissions released during the absorption of CO_2 in MEA. Therefore, the impacts are transferred from power plants, further up or downstream from the power plants.

In conclusion, even though both CCS and CCU technologies seek to mitigate climate change, they can only be regarded as temporary solutions, particularly those options which merely delay the emissions of CO_2 rather than eliminate them permanently. Although from an economic perspective, CCU would appear to be a better option than CCS as the latter is an unprofitable activity, the cost-effectiveness as well as the environmental impacts of CCU have to be evaluated carefully on a life cycle basis to ensure a positive economic and environmental balance. As demonstrated in this analysis, the latter in particular may not always be the case. Moreover, the potential of CCU is still limited as the current global demand of chemicals and other products does not have the capacity to sink enough CO_2 emissions to contribute significantly to meeting the carbon reduction targets. A further significant issue for CCU is that the ‘storage’ time of CO_2 is limited by the short lifespans of the chemicals and fuels produced. Therefore, future research should focus on the development of materials and products with longer lifetimes to enable long-term storage of CO_2. While CCS overcomes this problem through long-term storage, there is a risk of CO_2 leakage which could potentially cause more damage than if dilute emissions were to continue unabated. Equally significant is the fact that deployment of large-scale CCS is not expected until well into the 2020s by which time it may be too late to reverse the impacts of climate change. Nevertheless, if the above concerns can be addressed, both CCS and CCU could play a role in mitigating climate change, together with other options such as energy demand reduction, renewables and other low-carbon technologies.

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