Carbon Capture and Sequestration and Carbon Capture and Use

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Abstract

Carbon capture and sequestration (CCS) as ais a viable mitigation strategy for reducing greenhouse gas (GHG) emissions in fossil-fuel power plants. Although CCS technology can mitigate the anthropogenic GHG emissions, the technologies are associated with additional water requirements for chemical and physical processes to capture and separate CO2 and other environmental impacts like introduction of parasitic loads imposed by carbon capture on power plants hence reduced efficiency and more cooling requirements and groundwater contamination due to CO2 leakage during geologic sequestration. The energy transition requires the decarbonizing of the power, transport, and industry sectors. Carbon capture and storage (CCS) and carbon capture and utilization (CCU) technologies will play a major role in this energy transition by cutting down emissions from new fossil fuel power plants. Main challenges facing the CCS and CCU include low oil price to make CO_2-enhanced oil recovery profitable, lack of financial incentives for CO_2 geological storage, limited acceptance, lack facilitating government policy and CCS regulations, and high capital investment.

Key Words:

Carbon capture and storage; Carbon capture; Life cycle assessment; Climate change; Environmental impacts

Introduction

Greenhouse gas emission (GHG)from anthropogenic activities are the most important environmental issues of the twenty-first century. This has made the CCS (carbon capture and storage) and carbon capture and use (CCU) important technologies and approaches particularly in power generation and industrial operations to cut down emissions released to the atmosphere. CCS (carbon capture and storage) is a means of reducing greenhouse gas emissions by capturing and subsequently storing CO_2., while CCU (carbon capture and utilization) is a way of recycling carbon in the captured CO_2 by converting it into products like fuels, chemicals, or other products(Lerche Raadal & Saur Modahl, 2022). The climate change resulting from anthropogenic emissions of greenhouse gases (GHGs) is one of the most significant long term environmental challenges today. The greenhouse gas emissions (GHG) from the electricity sector have been growing to ever increasing electricity demands and while fossil fuels remain the dominant source for electricity generation. There are various mitigation strategies developed aimed at reducing CO_2 emissions with technological alternatives for to reduce emissions from power plants to the atmosphere being.

i.) Switching to less carbon-intensive fuels, e.g., natural gas instead of coal.
ii.) Increasing the use of renewable energy sources or low carbon nuclear energy, which emit less or no net CO_2; and
iii.) Capturing and sequestrating carbon emissions.

The CCS is a promising approach for reduction of GHG emissions by capturing carbon dioxide (CO_2) at the point of power generation and transporting to an injection site, and sequestrating for long-term storage in suitable formations. A CCS unit at thermal plants can efficiently capture about 85–95% of the CO_2 processed in a capture plant(Eldardiry & Habib 2018).

Emissions from fossil fuels have been increasing by 2.7% annually over the past decade and now are 60% above 1990 levels. By reducing emissions by at least 50%, we can limit the rise of the global average temperature to 2 °C by 2050. Carbon capture and sequestration (CCS) faces technical and economic barriers that must which overcome before large scale deployment since it is an unprofitable activity that requires large capital investment, yet some countries like UK, has no incentives or subsidies for CCS. Technically the CO_2 leakage is uncertain and in some countries it is not a viable option since geological storage capacity is limited or in some cases only available offshore, which increases the transportation and injection costs for countries like . the UK, Norway, Singapore, Brazil, and India.

Recently, carbon capture and utilization (CCU) is used to turn waste CO_2 emissions into valuable products like chemicals and fuels, and contribute to climate change mitigation. The utilization of CO_2 is usually a profitable activity with the possibility of selling the products. When compared with conventional petrochemicals feedstocks, CO_2 is a 'renewable' resource on condition that it is continuously emitted by various industrial activities, it is low in cost and is non-toxic. The thermodynamic stability of CO2 making conversion to various products an energy intensive activity. However, the potential of a secure supply of chemicals and fuels, along with the increasing fossil-fuel prices is a powerful driver for CCU.

The main challenge is that the current global demand for chemicals has no capacity to sequester enough CO_2 emissions to contribute significantly to meeting CO2 reduction targets. The annual production of urea and methanol, the two most commercially important chemicals, can consume just 0.5% of the current 34.5 Gt/yr of the anthropogenic CO_2 emitted globally. The use of CO_2 for fuel production only delays its emissions instead of removing it over long timescales for mitigating climate change., while 'storage' in some chemicals is short-lived in some chemicals based on , n their use(Cuéllar-Franca & Azapagic 2015).

We also have other sustainability issues that should be considered before large-scale deployment of either CCS or CCU, particularly the environmental impacts to ensure that ensure that climate change mitigation is not done at the expense of other environmental factors. Impacts should be assessed on a life cycle basis, to avoid shifting the environmental burdens from one life cycle stage to another (Cuéllar-Franca & Azapagic 2015; Kabeyi 2020).

Carbon dioxide removal (CDR) and Greenhouse gas removal (GGR)

All emission pathways seek to limit global warming to 1.5 °C or 2 °C by the year 2100 assume the use of CDR approaches in combination with emission reduction. There are two main strategies for removing carbon directly from the atmosphere i.e., by planting and forest restoration, which is referred to as conservation efforts, and by direct air capture (DAC). Carbon dioxide removal (CDR) which is also known as negative CO_2 emissions, involves the removal of carbon dioxide gas (CO_2) from the atmosphere and storing in geological, terrestrial, or ocean reservoirs, or in products

Carbon dioxide Removal (CDR)

CDR methods are applied to remove CO_2 from the atmosphere, some of which are explored below. CDR is also known as Greenhouse Gas Removal (GGR) when used to refer to greenhouse gases in general, although the focus is quite often atmospheric removal and subsequent storage of CO_2. Carbon dioxide removal (CDR) refers to anthropogenic activities that remove CO2 from the atmosphere and store it in geological, terrestrial, or ocean reservoirs, or in products. They include existing and potential anthropogenic enhancement of biological or geochemical sinks as well as direct capture from air and storage. This however does not include natural CO_2 uptake not directly caused by human activities. Similar definitions are commonly used for "net negative greenhouse gas emissions", "net zero CO_2 emissions and "net zero greenhouse gas emissions". Geoengineering or climate engineering is used for both CDR or SRM (solar radiation management, if used at a global scale, but they are no longer used in IPCC reports addresses the root cause of climate change and is a major strategy in reducing net emissions and managing risks related to high CO_2 levels in the atmosphere. In CDR, CO_2 is removed from the atmosphere and locked away for decades or centuries in plants, soils, oceans, rocks, saline aquifers, depleted oil wells, or long- lived products like cement(Moses Kabeyi & Oludolapo Olanrewaju 2022).

Greenhouse gas removal (GGR) or negative greenhouse gas emissions refers to the removal of greenhouse gases (GHGs) from the atmosphere through human activities, which is in addition to what occurs via natural carbon cycle or atmospheric chemistry processes. Within the context of net zero greenhouse gas emissions targets, carbon dioxide removal (CDR) is increasingly integrated into climate policy new element of mitigation strategies.

Bothe CDR and GGR methods are referred to as negative emissions technologies (NET), and may be cheaper than preventing some agricultural greenhouse gas emissions(Cuéllar-Franca & Azapagic, 2015; M. J. B. Kabeyi & O. A. Olanrewaju 2023b).

Carbon dioxide removal (CDR) methods includes carbon sequestration methods like afforestation, carbon farming (agricultural practices that sequester carbon in soils), enhanced weathering, etc. and direct air capture combined with storage. A comprehensive life cycle analysis of the process must be performed. to assess whether net negative emissions are achieved by a particular process.

It was concluded by the 2019 consensus report by the US National Academies of Sciences, Engineering, and Medicine (NASEM) that applying existing CDR methods at scales that can be safely and economically deployed, can remove and sequester up to 10 gigatons of carbon dioxide per year which can offset . greenhouse gas emissions at about a fifth of the rate at which they are being generated.

Direct air Capture

Direct air capture (DAC) applies chemical or physical processes to extract carbon dioxide from the atmospheric air. If the CO_2 is then sequestered in safe long-term storage it is called direct air carbon capture and sequestration (DACCS). The process achieves a "negative emissions technology" (NET). As of the year 2022, DAC is loss making process since the cost of using DAC to sequester carbon dioxide is far much more than the carbon price(Zong et al., 2023). Figure 1 shows the growth in direct air capture operating capacity from 2010 to 2021.

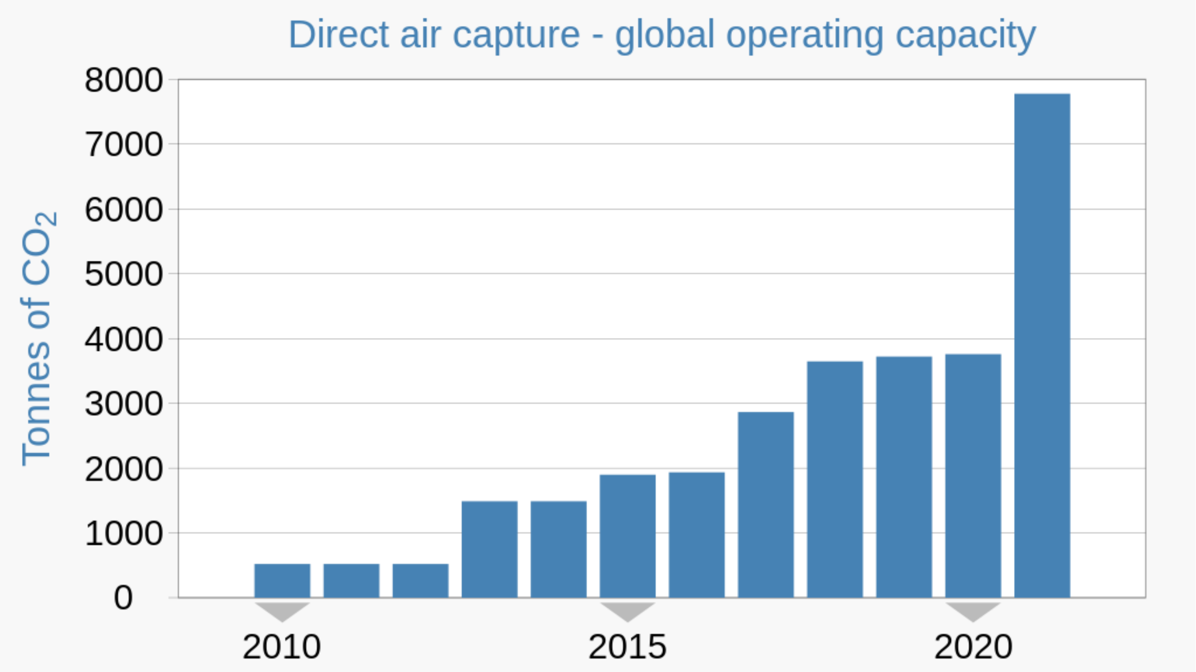

Figure 1. Potential for climate change mitigation

From figure 1, it is noted that the global direct air carbon capture capacity improved from about 500 tons of CO_2 in 2010 to over 7,500 tons. Of CO2 per year in 2021

CDR Technics and Measures

Carbon dioxide removal (CDR) methods are referred to as negative emissions technologies (NETs), although not all NETs effect CDR. Greenhouse gas removal (GGR) is used as a synonym for NETs, that encompass the removal of all GHGs present in the atmosphere(de Richter et al., 2023). By using CDR in parallel with greenhouse gas emissions reduction measures, like deployment of renewable energy, makes it less expensive and disruptive than using other efforts alone. Studies show that CDR techniques other than ocean fertilization can remove up to 10 gigatons of CO_2 per year if deployed fully globally which is about 20% of the 50 giga-tons of CO_2 emitted per year by human activities. All mitigation pathways analyzed in 2018 that aimed at achieving 1.5 °C of warming involved CDR measures.

Higher rates of mitigation by CDR are also proposed but require hundreds of millions of hectares of land for biofuel crops. Research into direct air capture, geologic sequestration of carbon dioxide, and carbon mineralization can yield technological advancements necessary for higher rates of CDR. Reliance on large-scale deployment of CDR is generally risky to achieving target of less than 1.5 °C of warming, due to uncertainties over quick largescale deployment. Therefore strategies that rely less on CDR and more on sustainable use of energy are less risky.

Available CDR measures

The CDR methods in order of their technology readiness level. Include:

i.) Afforestation/ reforestation
ii.) Carbon sequestration in grasslands and croplands
iii.) Restoration of Peatland and coastal wetland
iv.) Improved forest management and Agroforestry
v.) Application or use of biochar
vi.) Bioenergy with carbon capture, direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS)
vii.) Enhanced weathering (EW)
viii.) Restoration of vegetation in coastal ecosystems ‘Blue carbon management’ in coastal wetlands which is an ocean-based biological CDR method which consisting of mangroves, salt marshes and seagrass beds.
ix.) Fertilisation of the ocean and enhancing alkalinity of the ocean

The CDR methods having the greatest potential to limit climate are the land-based biological CDR methods i.e. afforestation/reforestation (A/R)) and/or bioenergy with carbon capture and storage (BECCS). Some proposed pathways include direct air capture and storage (DACCS). Land based agricultural CDR methods reduce emissions from sector called "agriculture, forestry and other land use" (AFOLU).

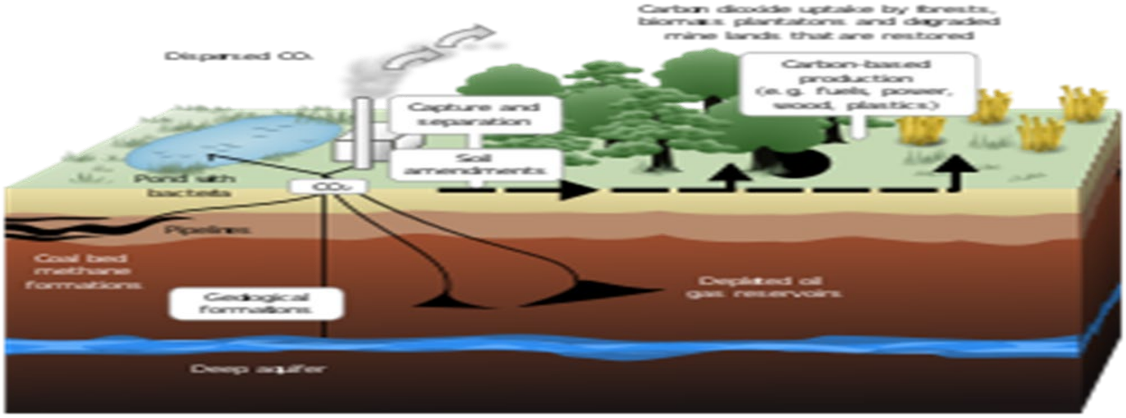

Figure 2. Geologic and biologic carbon sequestration of the excess carbon dioxide

Through halting loss and degradation of natural systems and promoting their restoration can contribute over one-third of the total climate change mitigation strategies by 2030. Forests are important because trees keep the air clean, help regulate the local climate and supply habitat for numerous species. Carbon dioxide is converted by trees and plants into oxygen, using photosynthesis. Plants remove and store carbon from the air hence without them, the atmosphere would heat up quickly and destabilize the climate. Figure 2 shows geologic and biologic sequestration processes.

From figure 2, Carbon sequestration (or carbon storage) involves storing carbon, particular atmospheric carbon dioxide in a carbon pool in a process that acts like carbon sink. Carbon sequestration is naturally occurring but can be enhanced or achieved with technology, like carbon capture and storage projects. Carbon sequestration can be classified into geologic and biologic/ bio sequestration).

Carbon dioxide (CO_2) is naturally captured through biological, chemical, and physical processes which can be accelerated by changes in land use and agricultural practices like growing fast maturing plants. Artificial processes have also been developed large-scale, artificial capture and sequestration of industrially produced CO_2 and storage in subsurface saline aquifers or aging oil fields. Other technologies applied are bio-energy with carbon capture and storage, biochar, enhanced weathering, direct air carbon capture and sequestration (DACCS).

Removal Of Methane and Other Non-CO_2 GHGs

The natural elimination of non-CO_2 GHGs and organic compounds is largely initiated by the by reaction with the sunlight generated hydroxyl (OH) radicals and chlorine atoms (Cl and through heterogenous) reactions occurring on mineral dust aerosols. Several technologies for methane (CH4) removal include enhancing the natural hydroxyl and chlorine sinks and through use of photocatalysis (de Richter and Caillol 2011). The products of non-CO_2 GHGs degradation are very low concentrations and can be left in the atmosphere without additional risks, although technologies are available for implementation at a climate related scale. N_2O for having a tropospheric concentration of ~335 ppb, is transformed into nitrogen and oxygen, which are main constituents of air, while the oxidation of the whole atmospheric CH_4 inventory to CO_2 can increase the CO_2 concentration by less than 0.5%, while reducing the radiative forcing substantially. No issues of storage, sequestration, and monitoring for possible leakage would therefore arise with the large-scale implementation of these NETs.(de Richter et al. 2023)

However, based on on the future prices of CO_2e removals, ideally b based on the 20 year global warming potential to reflect the 10 year lifetime of atmospheric CH_4, further development in technology may lead to more cost competitive CO_2e removal options with CDR(de Richter et al. 2023).

Carbon Sequestration in Oceans

Technologies that can be used to enhance carbon sequestration by oceans the include artificial upwelling, Seaweed farming, ocean fertilization, basalt storage, mineralization and deep sea sediments, and adding of bases to neutralize acids but not is being practiced at largescale(de Richter et al. 2023).

Agricultural practices

Carbon farming is an important component of agriculture. Carbon refers to agricultural methods used to sequester atmospheric carbon into the soil and in crop parts. Carbon farming increases the rate at which carbon is sequestered into soil and plant material to create a net loss of carbon from the atmosphere. More carbon in soil improves soil water retention capacity and reduces fertilizer needs. Carbon farming can be done by individual landowners provided with incentives to invest in carbon sequestration. Carbon framing can be mixed with land management techniques like planting/restoring forests, biochar burying and restoring wetlands like peatlands and marshes(de Richter et al. 2023).

Biochar

Biochar is charcoal formed by pyrolysis of biomass, and is an established method of carbon sequestration. Pyrolysis is high temperature heating and degradation of biomass in a low oxygen environment leading to formation of a material known as char, which is like charcoal but made by a sustainable process from biomass. Estimates by UK Biochar Research Center showed that at conservative level, biochar can store 1 gigaton of carbon per year but with great marketing effort and acceptance biochar can store 5–9 gigatons of carbon dioxide in the soil.

Magnesium silicate/oxide in cement

The replacement carbonate in cement facilitates potential absorption of carbon dioxide over the lifecycle of concrete although the lifecycle quantities are not yet fully established.

Economic Aspects

CDR costs substantially differ based on the e maturity of the technology employed and economics of voluntary carbon removal markets and the physical output. As an example, biomass pyrolysis generates biochar which has several commercial applications like soil regeneration and wastewater treatment. DAC cost between $250 and $600 per ton, compared to $100 for biochar and below $50 for nature-based solutions like reforestation and afforestation in the year

2021. Biochar is more carbon since it is a more durable sink with the ability to sequester carbon for hundreds or even thousands of years compared to more volatile nature-based solutions(de Richter et al. 2023).

Forests can be used to create carbon credits and geospatial analytical systems can be used determine carbon offsets by conserving a forest area or a reforestation initiative. Individuals and institution can purchase carbon credits using verified retailers like ACT4. In 2021, businessman Elon Musk announced he was donating \$100m for a prize for best carbon capture technology. Some of the "negative-emission technologies" are already in large scale application with Congress passing the 45Q tax, that gives \$50 credit per ton of carbon dioxide fixed and stored hence the need for technologies that would cost less than \$50. to fix a ton of carbon dioxide(de Richter et al. 2023).

Capture from Power Generation

Large fossil-fueled power plants account for almost half of the total CO_2 emissions from the fossil fuel combustion. These large power plants are those that emit >0.1 Mt-CO_2/year and are essential point of application for CSS and CCU emissions(Rackley, 2017). The thermal efficiency of this type of plant is limited to ~46%–48% by the achievable temperature of the working fluid (steam) which in turn is limited by the availability and cost of suitable materials needed to withstand the high temperatures and pressures, with current technology limiting steam temperatures and pressures to ~625°C and 250 bar, although by 2025, technological progress will raise this to 700°C and 350 bar by 2025(Moses Kabeyi & Oludolapo Olanrewaju, 2022a; M. J. B. Kabeyi & O. Olanrewaju, 2023; Rackley, 2017). Figure 3 demonstrates the flow of oil, air, ash, flue gases and water into out out of fossil fuel power plants.

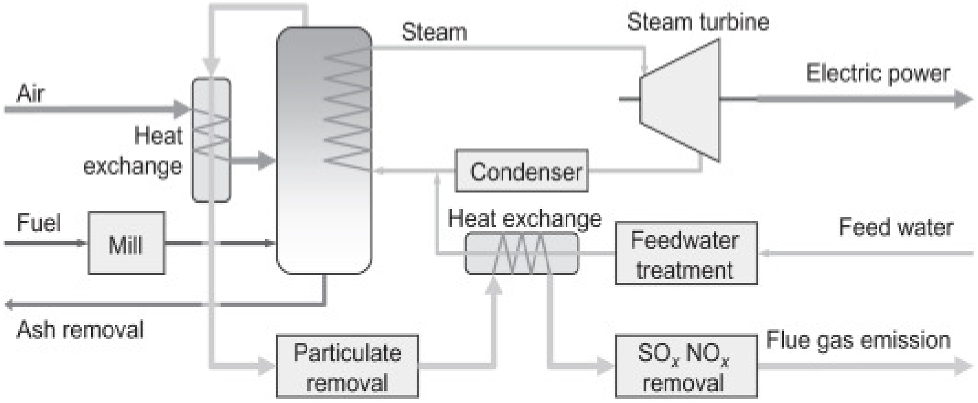

Figure 3. Schematic fossil-fueled electric-generation plant with points of carbon capture in power plants

The generation efficiency is better for technologies like the combined cycle power plant, in which flue gases are used to drive a gas turbine while exhausts are used to produce steam in a heat-recovery steam generator for extra power generation through a steam turbine and can achieve a thermal efficiency of 60% and even >80% if low-temperature waste heat is also recovered in a combined heat and power (CHP) application. With such efficiency, the impact per unit power generation is reduced(M. J. B. Kabeyi & O. A. olanrewaju, 2022b, 2022c).

Flue gas Properties

Flue gas from power plants has various components in addition to carbon dioxide. They include CO, Sox, particulates, N_2, and O_2. The typical characteristics of flue gas from fossil fuel combustion are presented in table 1

Table 1. Typical fossil fuel combustion flue gas characteristics.(Rackley 2017)

Parameter	Typical range of values
Pressure	At or slightly above atmospheric pressure
Temperature	30–80°C or higher, depending on the degree of heat recovery
CO_2	Coal-fired, 14%
	Natural gas-fired, 4%
O_2	Coal-fired, 5%
	Natural gas-fired, 15%
N_2	~81%
SO_x	Coal-fired, 500–5000 ppm
	Natural gas-fired, <1 ppm
NO_x	Coal-fired, 100–1000 ppm
	Natural gas-fired, 100–500 ppm
Particulates	Coal-fired, 1000–10,000 mg/m^3
	Natural gas-fired, 10 mg/m^3

From table 1, it is noted that CO2 content ranges from 3% to 15%, with gas fired plants having typically (3%–5%) at the lower end. Coal fired plants have the higher range of (12%–15%). Application of CO_2 capture from power generation can reduce these values.

Post combustion CO_2 capture is the capture from flue gases. This involves techniques that been developed and implemented in the natural gas processing industry applicable to existing power plants. Post combustion technologies include use chemical and physical sorbents and membranes, and hybrid approaches like combining membranes with solvent or cryogenic methods(Lerche Raadal & Saur Modahl 2022).

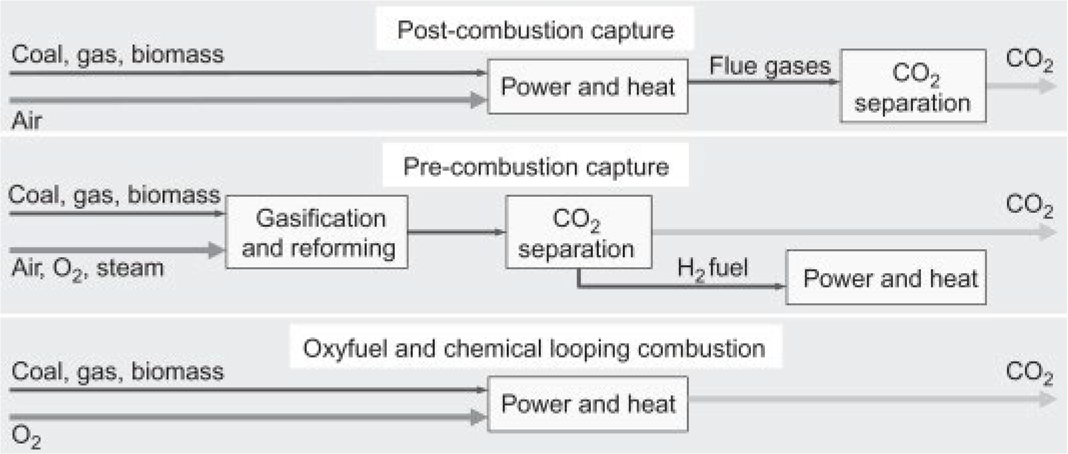

Figure 4. Approaches to CO_2 capture from power generation plants.

Precombustion

There are two alternatives to post-combustion capture whose aim is to modify the combustion process to produce pure or high-concentration CO_2 stream is generated. These include.

i.) The first option involves combustion of the fuel using pure oxygen instead of air leading to a near-pure CO_2 combustion gas stream which requires minimal further processing before being compressed for transportation and storage. Combustion Oxygen may be delivered either as a gas (oxyfueling) or as an oxide called chemical looping combustion (Rackley, 2017).

ii.) In the second pre-combustion capture option, the fuel is partially oxidized and reacted with steam to form a CO_2 and H_2 mixture consisting of 15%–60% CO_2, from which the CO_2 can be separated by methods for post-combustion capture. These produces a hydrogen fuel stream for combustion in a conventional boiler or gas turbine, or put to other fuel uses. (Lerche Raadal & Saur Modahl, 2022; Rackley, 2017).

The theoretical minimum energy needed to separate CO_2 from flue gases or syngas stream is a function of CO_2 concentration in the gas stream,. Separation of CO^2 from natural gas combustion flue gases has theoretical minimum because of low [CO_2] while post-combustion capture has higher energy requirements for different coal-fired options(Rackley, 2017). The relationship between separation work and CO2 concentration is demonstrated in figure 5 below.

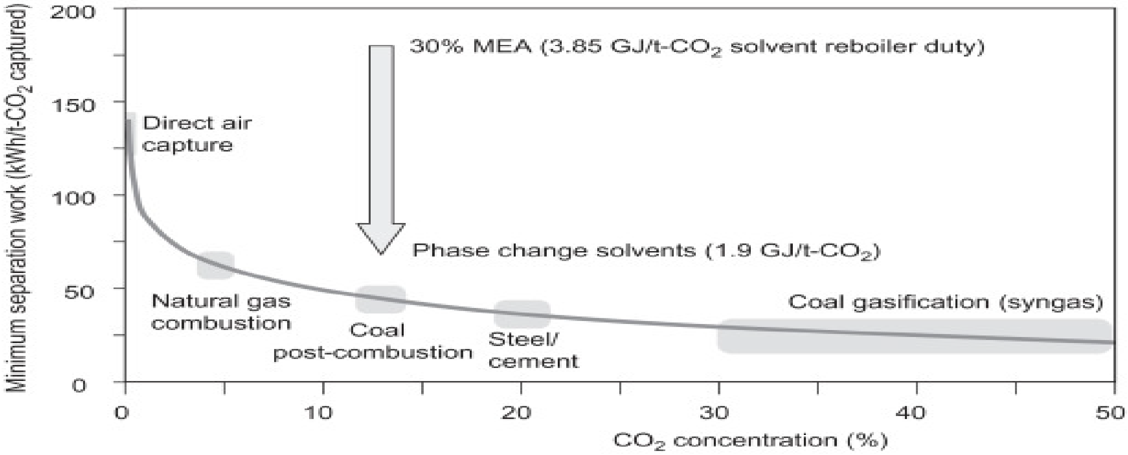

Figure 5. Minimum work required for CO_2 separation.

From figure 5, it is noted that coal gasification (syngas has the lowest minimum separation work compared to direct air capture and natural gas combustion The figure also demonstrates the impact of technological progress in reducing the energy cost in the case of coal-fired post-combustion capture, from the benchmark amine capture process to the emerging phase change solvents(Rackley, 2017).

CCS and CCU Technologies

Carbon capture and sequestration (CCS) and (CCU) seek to capture CO_2 from point of sources like power plants and industrial processes, to avoid release into the atmosphere. In CCS, the captured CO_2 is moved to suitable site for long-term storage, while for CCU, captured CO_2 is changed to commercial products. The different methods for carbon capture and sequestration and CCU are shown I figure 6.

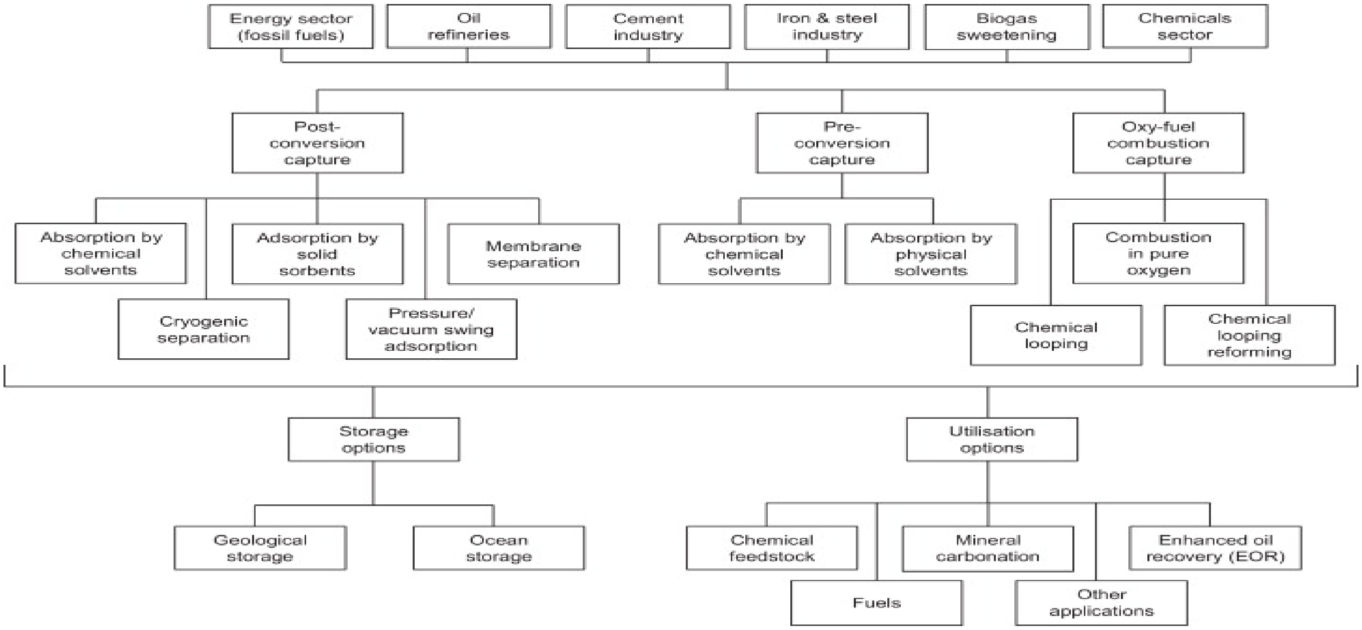

Figure 6. Different carbon capture, storage, and utilization option

Figure 6 shows the various technologies for CCS and CCU. The main storage options are geological storage and ocean storage. The various utilization options are chemical feedstock, mineral carbonation, enhanced recovery, use in fuels and other applications.

Lifecycle Assessment of CCU and CCA

Life cycle assessment (LCA) studies of different CCS options indicate that GWP from power plants can be reduced by 63–82% per unit of electricity produced based on the CO_2 capture option applied. The average GWP for pulverized coal (PC) power plants that are not equipped with CCS is 876 kg CO_2 eq./MWh while for the post-conversion capture via MEA the average value is 203 kg CO_2 eq. while oxy-fuel combustion it is 154 kg CO_2 eq. The equivalent average values for CCS at CCGT power plants is about 120 kg CO_2 eq./MWh for oxy-combustion and 173 kg for post-combustion, and 471 kg CO_2 eq./MWh without CCS. The GWP for pre-combustion capture and oxy-fuel combustion in IGCC plants is 190 and 200 kg CO_2 eq./MWh, but without CCS is 1009 kg CO_2 eq./MWh. These demonstrates a GWP reductions of up to 82% using oxy-fuel combustion in PC and IGCC plants while the lowest by post-combustion capture in CCGT plants (63%)(Lerche Raadal & Saur Modahl, 2022).

The results for the other environmental impacts vary but large majority show a higher impact for the plants with CCS than without CCS because of an additional coal mining and shipping required to compensate for the energy efficiency losses from the use of CCS, MEA production and ammonia emissions during absorption of CO_2 in MEA. This implies that impacts are transferred from power plants, further up or downstream from the power plants(M. J. B. Kabeyi & O. A. Olanrewaju, 2022e, 2023c).

The CO_2 utilization option in CCU systems influences the CO2 savings e.g., mineral carbonation to produce $MgCO_3$ reduces the GWP by 4% to 48% compared to no CCU. Estimated GWP varied from 524 kg CO_2 eq. per ton of CO_2 removed for the carbonation of CO_2 directly from a power plant to 1073 kg eq./t removed when CO_2 is first absorbed in MEA then recovered for use in the carbonation process. Studies also indicated that using CO_2 recovered after the capture in MEA for production of DMC in the urea-based process can reduce GWP by 4.3 times compared to the conventional synthesis of DMC from phosgene (3 vs 132 kg CO_2 eq./kg DMC). By utilizing CO_2 from power plants for EOR, GWP can be reduced significantly (on average, by 2.3 times) compared to discharging CO_2 to the atmosphere. The CCU via microalgae capture to produce biodiesel, leads to the average GWP estimated at 209 kg CO_2 eq./MJ, which is 2.5 times higher than for conventional fossil diesel(M. J. B. Kabeyi & O. A. Olanrewaju, 2023a).

The results for the other environmental impacts of CCU differs based on the utilization options e.g. production of DMC from CO_2 reduces eutrophication by 3.6 times, acidification and photochemical oxidants by four times and ozone layer depletion by 13 times when compared to the conventional phosgene-based processes because of lower energy requirements for DMC than phosgene -based process by four times. EOR, acidification is three times higher than without utilization because of the ammonia emissions from the CO_2 capture plant. The CCU via microalgae capture for biodiesel, eutrophication is higher than for conventional diesel due to energy intensive harvesting operations. The creation of photochemical oxidants potential is both higher and lower than for conventional because of different assumptions made for aerial productivity(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021; Rackley 2017)..

It was established that on environmental impacts of CCS and CCU the average GWP of all CCS options is about 276 kg CO_2 eq./t CO_2 removed**,** which is significantly lower than the GWP of all CCU options considered. The average GWP of CCU via chemicals production (DMC) is about 59.4 t CO_2 eq./t CO_2 removed, which is 216 times higher than for CCS which indicates that compared to CCS, CCU is not an efficient method for removing CO_2 emissions because almost two tons of DMC need to be produced to remove one ton of CO_2. This leads to use of huge quantities of reactants, like ammonia and naphtha, that generate additional CO_2 eq. emissions. Biodiesel production has higher GWP than CCS, by four times on average, although the impact varies significantly among based on technologies and process conditions applied. For CCU via EOR and carbon mineralization, the average GWP is 1.8 and 2.9 times higher than for CCS, respectively(Lerche Raadal & Saur Modahl, 2022; Rackley, 2017)..

Just like the GWP, the other environmental impacts of CCU to produce DMC are significantly higher e.g., acidification is 320 times higher, ozone layer depletion and photochemical oxidants is about 2.8 times higher and eutrophication 20% higher than for CCS. CCU via biodiesel from microalgae has 9.6 times lower eutrophication and 13 times more photochemical oxidants than CCS. For EOR, only acidification is found to be 14% lower than for CCS.

Results and Discussion

CCS (carbon capture and storage) is a strategy for reducing greenhouse gas emissions by capturing and subsequently storing while CCU (carbon capture and utilization) involves recycling the carbon in the captured CO_2 by changing it into new products. The objective of CCS is to improve at improving the results for one environmental indicator, but CCU represents a multi-functional system. Therefore, comparing CCU with CCS or no capture should involve more than one indicator. It is also vital to establish relevant system boundaries and to define a joint functional unit, so as to establish a robust decision basis for application in selecting environmentally preferable option(M. J. B. Kabeyi & A. O. Olanrewaju, 2023; Lerche Raadal & Saur Modahl 2022).

The aim of CCS and CCU is to capture CO_2 emissions from point sources like power plants and industrial processes, to stop their release into the atmosphere. The destination is the main difference between CCS and CCU. In CCS, the captured CO_2 is moved to a suitable site for long-term storage(Cuéllar-Franca & Azapagic, 2015). The main CO_2 capture options are post- and pre-conversion capture and oxy-fuel combustion processes. The Post-conversion apply chemical absorption using monoethanolamine (MEA). It is the most mature and widely applied technique, in power power planst but the use and regeneration of MEA contributes to the emissions of CO_2 and related global warming potential (GWP), hence the development of more environmentally sustainable sorbents remain a challenge for both CCS and CCU(Cuéllar-Franca & Azapagic, 2015; M. J. B. Kabeyi & O. A. Olanrewaju 2022d).

The CO_2 captured is stored in geological formations, in geological storage, which is most viable, or in the oceans, a limited by lack of knowledge on long term implications to the oceans in terms of acidity and marine species. CO_2 captured can also be used directly industrial sectors, like food and beverage , pharmaceutical industry as well as conversion into high-demand products such as urea, methanol and biofuels(Moses Kabeyi & Oludolapo Olanrewaju, 2022b; M. J. B. Kabeyi & O. A. Olanrewaju, 2022a).

CCS focuses on improving the results for one indicator only and CCU represents a multi-functional system. It is therefore crucial to analyze the use of more than one indicator and to establish relevant system boundaries when comparing the environmental performance of CCS and CCU systems. By applying system expansion, the compared systems provide the same functions to society with the analysis demonstrating that CCS is more beneficial over CCU if fossil electricity are part of the grid mix. However, if renewable electricity used for substitution is decided nis not included in the system expansion boundaries, CCU offers the best option. Hence the choice of the modelling decision is an important issue when comparing multifunctional systems. As the society moves 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, with LCA methodology playing an important role as a tool for this purpose, and that the expansion of the system boundaries will be crucial for the correct assessment of the systems(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2021; Lerche Raadal & Saur Modahl, 2022).

Comparisons between CCS and CCU should be used as a guide only since inconsistencies in the system boundaries and functional units make it difficult to compare them on an equivalent basis. Therefore specific guidelines or ‘product category rules’ are needed for application of the LCA methodology to CCS and CCU technologies. Very important are the guidelines on the definition of the system boundaries and functional units should be established for different systems(Lerche Raadal & Saur Modahl, 2022; Masanet et al., 2013).

Conclusions

Both CCS and CCU technologies seek to mitigate climate change, but are regarded as temporary solutions, especially options which merely delay the emissions of CO_2 instead of eliminating them permanently. The CCU appears a better option than CCS since CCU is unprofitable activity, but the cost-effectiveness and the environmental impacts of CCU need to be carefully evaluated on a life cycle basis to ensure a positive economic and environmental balance. The global demand of chemicals and other products cannot provide enough capacity to capture CO_2 emissions to contribute to effectively contribute to the carbon reduction targets. Another significant challenge with CCU is that the ‘storage’ time of CO_2 which is limited by short lifespans of the chemicals and fuels produced. Therefore, there’re is need focus research on the development of materials and products having longer lifetimes to facilitate long term storage of CO_2. Although CCS overcomes this challenge through long-term storage, CO_2 leakage is a prevailing risk that can potentially cause more damage. Also significant is the fact that deployment of large-scale CCS may come 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.

The Life cycle assessment studies established that CCS could reduce the global warming potential (GWP) from power plants by 63–82%, with greatest reductio in oxy-fuel combustion in pulverized coal and integrated gasification combined cycle (IGCC) plants. The lowest reduction is achieved by post-combustion capture in combined cycle gas turbine (CCGT) plants. Environmental impacts like acidification and human toxicity for CCS, while for CCU, the GWP varies widely based on utilization option. Mineral carbonation may reduce the GWP by 4–48% compared to the no CCU. By using CO_2 for production of chemicals, like dimethylcarbonate (DMC), the GWP can be reduced by 4.3 times and ozone layer depletion by 13 times when compared to conventional DMC process. The Enhanced oil recovery yields GWP 2.3 times lower compared to discharging CO_2 to the atmosphere but leads to higher acidification by three times. Capturing CO_2 by microalgae to produce biodiesel leads to 2.5 times higher GWP compared with fossil diesel, while other environmental impacts are significantly higher. On average basis, the GWP of CCS is significantly lower compared to CCU options, but has other environmental impacts being higher compared to CCU except for DMC production which is the worst CCU option overall.

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