Method, Cost and Energy Consumption: A Review of Carbon Capture Technologies

Introduction

Carbon capture (CC) is the removal of carbon dioxide from industrial exhausts before they reach the atmosphere. The carbon is then either recycled into a product or stored underground. Despite its proposal as a sustainable solution to help reach net-zero, there are economic and environmental concerns with its energy intensity. An important distinction is to be made from carbon dioxide removal, which captures carbon already in the atmosphere, contributing to negative emissions. This essay will review the advantages and disadvantages of each stage in carbon capture and storage (CCS).

These technologies are being proposed as a green method, because they reduce industrial carbon emissions. However, the vast amount of energy needed for capture would most likely be derived from fossil fuels, thus counteracting its sustainable objective. There is a view within the energy sector that CCS should be implemented as a short-term method to help reduce emissions (Andrew Bostock, personal communication, August 2024). There are also public queries about whether carbon capture is being used to mitigate climate action; a strategy to continue polluting the planet without decreasing our reliance on fossil fuels.

Three stages involved in CCS will be analysed: (1) capture, (2) transport, and (3) storage. Each stage will be evaluated by its pros and cons, highlighting its energy usage and environmental impact. Lastly, a conclusion will be made on the use of carbon capture to achieve climate goals. I have interviewed three industry professionals for their own knowledge and opinions on this topic. David King, an environmental manager from an energy company called Orsted. He gave insight into the company's new carbon capture plants in Denmark, which will serve as a primary case study for this essay. Daopu Somoni, a PHD student at the University of Aberdeen researching carbon capture usage and storage (CCUS) from a "Just Transition" perspective. Just Transition emerged to provide equity in the global energy transition, so countries in the global South could move towards net-zero without impacting their economic development (Daopu Somoni, personal communication, July 2024). His background is in law, and therefore his responses focused on the regulations involved in carbon capture. Finally, I interviewed Andrew Bostock, a subsurface manager and reservoir engineer for the Chinese National Oil Offshore Corporation. Their responses will be interwoven into this essay where relevant.

Capture

Pre-combustion

Carbon capture begins with the separation of the carbon dioxide from the flue gas stream. The three methods of capture I will examine are pre-combustion, post-combustion and oxyfuel combustion. Pre-combustion removes the carbon dioxide before the fossil fuel is burned (Office of Fossil Energy and Carbon Management, no date). In a gasification process, the fuel is converted into a synthesis gas of mainly carbon monoxide and hydrogen. This is done either by adding steam to the feedstock in a process termed 'steam reforming', or adding oxygen to achieve partial oxidation (Jansen *et al.*, 2015). Next, a water-gas shift reaction converts the carbon monoxide and water vapour into carbon dioxide and hydrogen, increasing the mole concentrations of the carbon dioxide and the hydrogen in the synthesis gas stream (National Energy Technology Laboratory, no date).

$$\mathrm{CO\,(g) + H_2O\,(g) \rightarrow CO_2\,(g) + H_2\,(g)}$$

Figure 1. The water gas shift equation. (Dincer, Rosen and Al-Zareer, 2018)

Thus, the carbon dioxide captured is of a high concentration, meaning separation will be more favourable and energy efficient (Bandilla, 2020), although separation equipment is still expensive. Moreover, the hydrogen produced is also a useful product (UK Carbon Capture and Storage Research Community, no date). The largest problem is that existing industrial plants cannot easily convert to pre-combustion technology, and there are high investment costs for the new infrastructure. (MIT, no date). Mr Bostock was not entirely convinced we should be building new plants designed for pre-combustion technology, questioning if the benefits of its installation would outweigh its high investment costs (Andrew Bostock, personal communication, August 2024). Evidently, pre-combustion technology is less useful in our goals towards net-zero. Our main aim is to reduce emissions from our *current* infrastructure, but this technology cannot be easily retrofitted to existing industrial plants.

Post-combustion

Post-combustion carbon capture involves carbon dioxide being removed from the flue gas stream before it is released into the atmosphere. The carbon dioxide can be separated from the flue gas using multiple methods, such as membranes, sorbents or solvents. Herzog, Meldon and Hatton (2009) said that all commercial post-combustion technologies used a chemical absorption method with monoethanolamine-based solvents. Unlike pre-combustion technology, this can be retrofitted to existing power plants. On the other hand, due to the dilute concentrations and low pressure of carbon dioxide in the flue gas stream, a large volume of gas has to be treated. This is unlike pre-combustion technology, where the carbon dioxide is present at a high concentration. Because of its low pressure, compressing it to pipeline pressure for transportation would require large quantities of energy. (National Energy Technology Laboratory, no date). Herzog, Meldon and Hatton (2009) compared two industrial plants: A post-combustion carbon capture plant, and a regular industrial plant. They concluded that a surplus of carbon dioxide was being emitted from the carbon capture plant, suggesting this post-combustion capture plant was unsustainable. This is because of a parasitic energy loss introduced by the carbon capture equipment, meaning more fossil fuels had to be burned to produce the same amount of power. Also, the cost of equipment was found to increase the total capital cost of the plant by 22%. (Herzog, Meldon and Hatton, 2009)

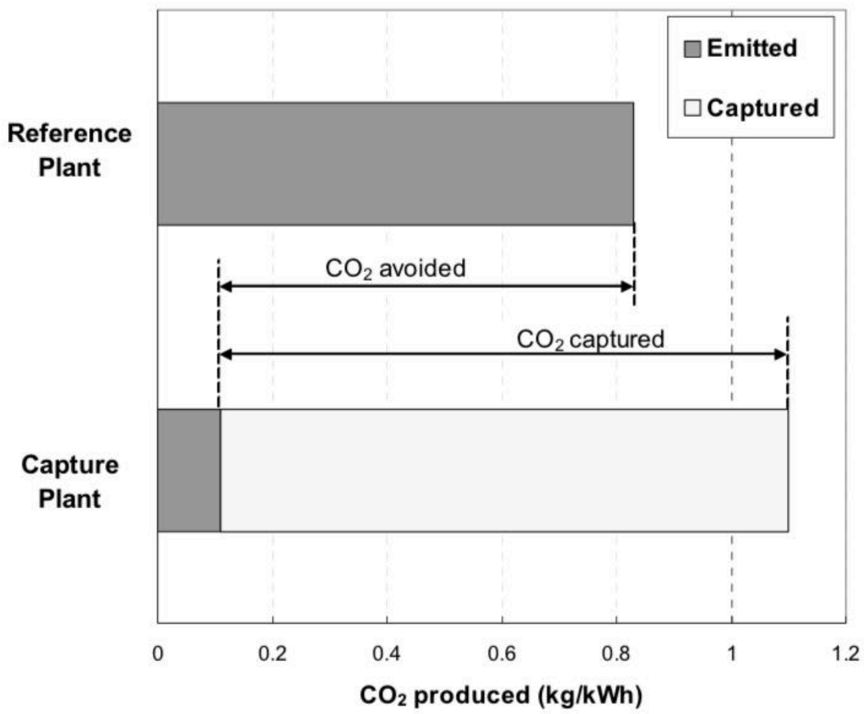

Figure 2. Graphical representation of avoided CO2. The avoided emissions are simply the difference between the actual emissions per kWh of the two plants. (Herzog, Meldon and Hatton, 2009)

Despite its energy intensity and high costs, current research is focused on making post-combustion technology more efficient, and it seems easier to integrate with our current industrial processes.

Post-combustion: A case study

Mr King informed me of Orsted's current bio-energy, carbon capture and storage (BECCS) facilities (David King, personal communication, July 2024). The company has one for their wood-chip fired power station in Kalundborg, and another for their straw-fired power station in Greater Copenhagen. Amine post-combustion technology is being used (Danish Energy Agency, 2021), as outlined below:

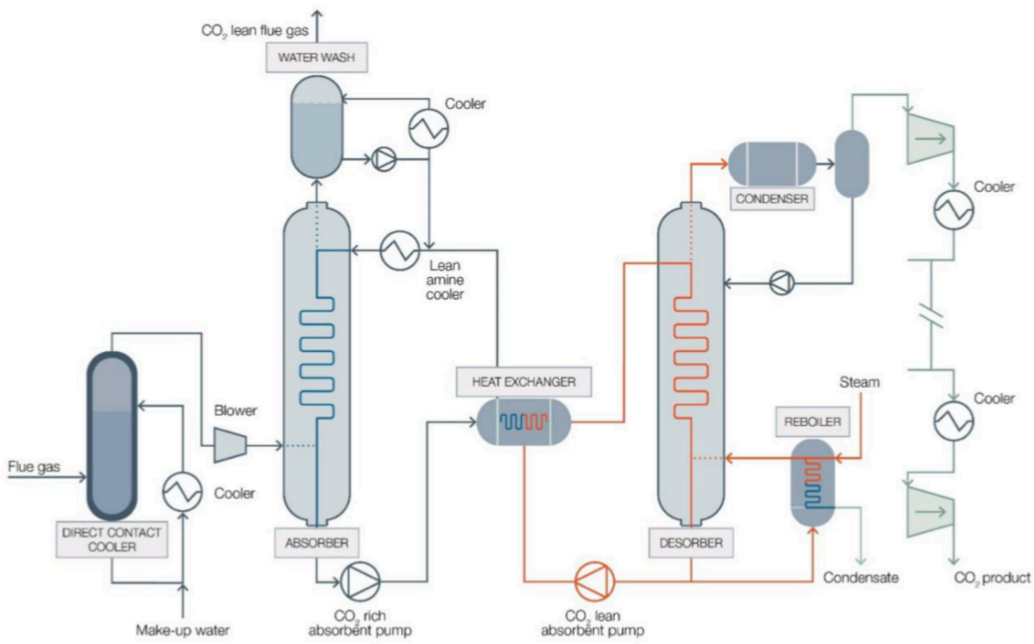

Figure 3. Schematic illustration of amine-based carbon dioxide capture process. Flue gas is cooled in a pre-treatment unit prior to entering the carbon dioxide capture unit where carbon dioxide is washed out of the stream by an amine solution. The carbon dioxide gas is stripped from the amine solution, whereby it is regenerated by applying heat in a stripper (desorber). The recovered carbon dioxide may be compressed and dehydrated for pipe-line transportation or liquefied for export by ship or truck (Danish Energy Agency, 2021).

The project's report outlines that, 'the energy consumption for amine CC processes is significant', mainly caused by thermal energy required to regenerate the solvent (Danish Energy Agency, 2021). This lowers the system's thermal energy efficiency; a symptom of the aforementioned parasitic energy load. There are several methods to reduce thermal energy consumption that would need to be considered by Orsted in their process design. For flue gas of low concentrations, there could be an energy penalty of about 10-15%. An energy penalty is the amount of energy spent on capture compared to the power generated by the power plant (Vasudevan *et al.*, 2016). This poses a serious challenge to CC implementation, because the CC equipment significantly reduces the power efficiency of existing power plants.

Bioenergy can be considered carbon neutral as plants absorb carbon dioxide during their lifetime, which is then released when the biomass is burned. When used in conjunction with carbon capture, this would lower emissions into the atmosphere, making BECCS a viable solution to reduce carbon emissions. Orsted claims their BECCS facility will store 430,000 tonnes of carbon dioxide per year (Orsted, no date). This value would need to be compared to the carbon footprint of the carbon capture equipment to see if the carbon dioxide stored offsets the carbon dioxide emitted during capture. Considering the project has been deemed feasible and is currently running, there is most likely a net negative of carbon emissions.

Although Orsted's project is being fueled by renewable energy, it is uncertain if the majority of CCS plants are. The carbon emitted from these post-combustion plants is a crucial factor in determining their environmental impact. Mr King assumed companies in the UK are either using the National Grid or carbon credits to fuel their CCS projects (David King, personal communication, July 2024). I believe there needs to be greater transparency on how commercial CCS projects' are being powered, because it is clear their energy usage is high.

Oxyfuel combustion

Oxyfuel carbon-capture involves burning fossil fuels in nearly pure oxygen to produce flue gas with a high concentration of carbon dioxide and water vapour. Firstly, nitrogen is stripped from the oxygen in an air separation unit which produces a stream that is approximately 95 percent oxygen. The flue gas produced after burning the pure oxygen with the fuel is approximately 70 percent carbon dioxide by volume (National Energy Technology Laboratory, no date). Next, carbon dioxide is separated and compressed. Similar to pre-combustion and post-combustion technology, there are high capital costs for the separation equipment. However, the carbon dioxide is at a higher concentration in the flue gas stream compared to post-combustion capture. Therefore, it is easier to remove impurities from the carbon dioxide. The largest energy expenditure in this process comes from the air separation stage. The most efficient method is cryogenic air separation, which involves compressing and purifying the air to prepare it for cooling and separation (Cryospain, 2023). Afterwards, the air is cooled to very low temperatures and then distilled to remove the nitrogen from the air (Griffin, 2018). According to Fu, C. and Gundersen, T. (2011), the power consumption of a cryogenic air separation unit could be approximately 4.7 times the theoretical minimum. Research is focused on reducing energy consumption during air separation, whilst lowering investment costs. The cryogenic air separation process presents the most energy intensive part of oxyfuel combustion.

Mr Somoni decided that no method stood out to him as better, but rather a method should be used depending on which phase of the energy transition a country is in (Daopu Somoni, personal communication, July 2024). For instance, pre-combustion technology could be considered in China, where coal gasification is still a primary method of power generation (Andrew Bostock personal communication, August 2024). All three carbon capture methods involve huge energy penalties, which must be reduced if they are truly to be considered a green process.

Transport

Vehicle

Once the carbon dioxide has been compressed into either a liquid or supercritical fluid, it needs to be transported to the storage site. Orsted is currently using trucks to transport the carbon captured from their power station in Greater Copenhagen to their power station in Kalundborg. The trucks serve as a temporary transport method before installing pipelines (Orsted, no date). Next, the carbon is shipped to an onshore terminal in Norway. The carbon dioxide is then shipped by their partner company to an onshore terminal. Marine fuel is a significant emitter of greenhouse gases (David King, personal communication, July 2024). However, Orsted claims the carbon emissions from transportation and handling account for only 2.7% of the carbon captured.

In ship transportation, carbon is typically stored in a temporary storage tank, before loaded onto the ship. A conceptual design created by Suzuki et al. (2013), displays the use of steel tanks at -50 degrees Celsius and a gauge pressure of 1.0 MPa. Steel manufacture is energy intensive, however the material is used to help control the stored carbon's low temperature and high pressures. Evidently, an environmental impact analysis accounting for the fuel burned during a journey, and cost of equipment would have to be conducted to substantiate ship transport use for a company.

Pipeline

Pipeline networks appear to be the most viable transport solution. However, there are risks of pipeline corrosion and carbon dioxide leakage. The pipes are typically manufactured from manganese steel, and when water is carried into these pipes, combined with the carbon dioxide, it is extremely corrosive (GreenFacts, no date). Corrosion-resistant alloys or a continuous polymer coating can be used, but these materials often cost several times more than manganese steel. Mr Somoni mentioned this in his interview, commenting that pipeline infrastructure is capital intensive (Daopu Somoi, personal communication, July 2024). Leakage due to infrastructure damage or component failure could pose a human and environmental risk, depending on the volume of carbon released. Thus, a quantitative risk assessment must be conducted by companies when transporting carbon dioxide. Computational fluid dynamics can be used to do so, determining the dispersion of the leaked carbon dioxide in case of failure (Mazzoldi, Hill and Colls, 2011).

Interestingly, there are also problems with pipelines from a legal perspective. Mr Somoni stated that there can be property issues when transporting carbon dioxide onland.

> ‘The pipeline has to go through land, and sometimes the pipeline right of way interferes with property rights of landowners. This can lead to litigation, which delays or even suspends projects.’ (Daopu Somoni, personal communication, July 2024)

He further explained that if the land is private property, then the company has to negotiate with the property owner for the pipeline’s right of way. This is likely a main factor that has delayed the expansion of pipeline networks for emerging CCS technologies. It is clear that transportation poses significant obstacles regarding vehicle carbon emissions, potential leakage and legal conflict.

Storage

Aquifers

Finally, the transported carbon dioxide must be stored. Any company must first obtain a licence to use a storage site, and have screening conducted for its safety (Daopu Somoni, personal communication, July 2024). For Orsted's project, they are pumping their carbon dioxide via a subsea pipeline into a storage complex: a 2.6km deep saline aquifer (Orsted, no date). Saline aquifers are deep rock formations containing concentrated brine; their large storage capacity and prevalent occurrence proposing a viable method of storage (British Geological Survey, no date). However, little is known about aquifers, and there is uncertainty of the percentage pore volume that can be safely occupied by sequestrated carbon dioxide (Heddle *et al.*, 2003). Moreover, aquifer storage proposes no useful by-product to offset the cost of storage. (British Geological Survey, no date).

Ocean

Another method of carbon storage, though currently considered unreliable, is ocean storage. This is when carbon dioxide is pumped deep into the ocean where the high pressures allow the carbon dioxide to remain liquefied. The largest concern is that injecting carbon dioxide into the sea will cause ocean acidification, having disastrous consequences on the marine ecosystem (Haugan, 1998).

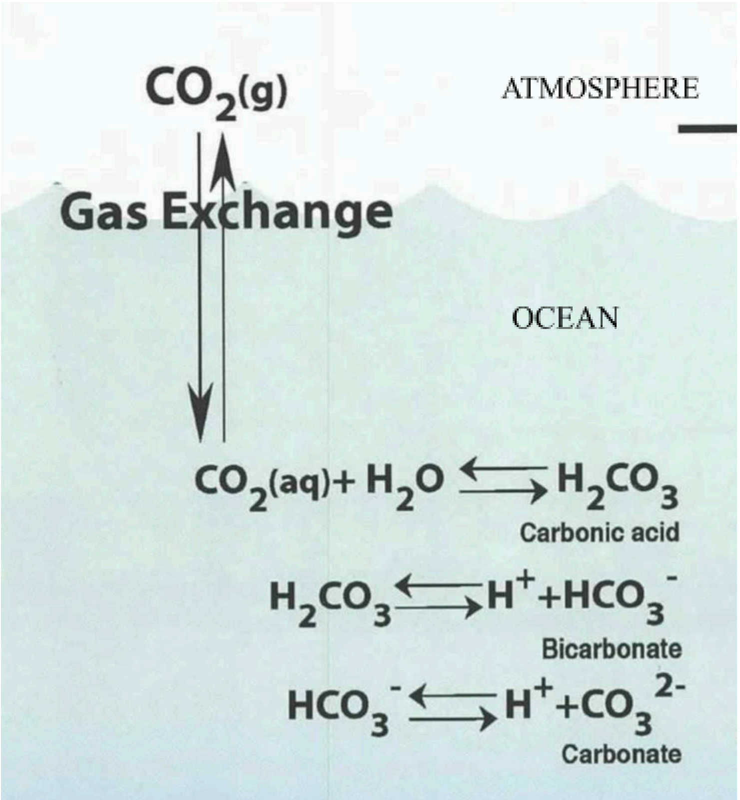

Figure 4. [Edited] (Feely *et al.*, 2001)

This represents the equilibrium of carbon dioxide in the atmosphere and seawater. The injection of carbon dioxide would have to be heavily monitored, as an increase in carbon dioxide concentration in the sea could alter the equilibrium position of these reactions, thereby increasing carbon dioxide concentration in the atmosphere.

Despite the oceans' ability to absorb carbon dioxide, it seems an environmentally hazardous storage method, although some research is being done to see if carbon dioxide could be stored without the consequence of ocean acidification (Goldthorpe, 2017).

Oil and gas fields

The final method of storage I will investigate are depleted oil and gas fields. Mr Bostock believes this area best suits carbon sequestration because engineers understand their behaviour. It can trap carbon and, '...You know what pressure that trap can contain, so you can inject carbon dioxide up to that pressure level and stop.' (Andrew Bostock, personal communication, August 2024). This is a technique that was used in the pilot plant Lacq, the first industrial CCS project in Europe. A report from Lescanne et al. (2011) outlines the several monitoring equipment set up to check groundwater quality, carbon dioxide flow rate, pressure, temperature, biodiversity and more. This equipment would have contributed to the project's high capital costs and energy requirements, a problem outlined in the report's conclusion. Solutions were still needed to make an, 'optimal long term monitoring program economically and technically viable.'

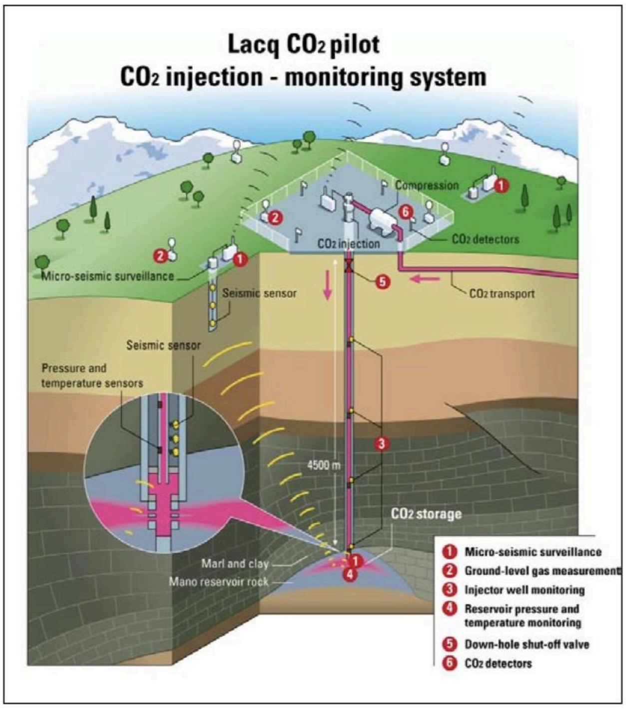

Figure 5. General scheme of the Rousse monitoring system (Lescanne *et al.*, 2011)

Another concern of using depleted oil and gas fields is well integrity, as old oil and gas reservoirs are likely in poor condition (Andrew Bostock, personal communication, August 2024). Injection of carbon dioxide could result in the degradation of the wellbore seal interfaces (Hannis *et al.*, 2017), increasing the chances of carbon dioxide leakage. Therefore, the potential for reusing these wells are very limited. Even if the well is in good condition, it might not be a suitable material for carbon dioxide injection.

Enhanced oil recovery

Alternatively, there is a way to profitably use the carbon captured. This is called enhanced oil recovery. Carbon dioxide is injected into oil wells to help release carbon dioxide from depleted reservoirs, and some of the carbon dioxide is retained in the oil field. The carbon dioxide is miscible with the oil and reduces its viscosity, allowing for a single-phase drainage (Bui *et al.*, 2018). The objective is for the oil profits to offset the cost of the CCS process, making it attractive to oil companies for investment. There are ethical queries within the energy sector regarding this process, as the goal is to eventually move away from using oil and gas (Andrew Bostock, personal communication, August 2024). Nevertheless, there is a general consensus that several industries still require oil and gas, so perhaps it should be used to help supply our current demand.

Conclusion

Carbon capture is certainly an energy intensive process, and this is hindering its sustainable efforts. With 37 large scale projects globally (Bui *et al*. (2018), mostly in the US and Europe, the deployment of carbon capture has been rather slow. The reasons for this are evident: the continued problems relating to cost and energy intensity, particularly in the capture process. All three of my interviewees agreed that CC should be used to aid transition towards net-zero. Even developing countries that still rely on fossil fuels for economic development are looking towards CCS as part of their energy transition programme (Beck, Surridge and Hietkamp, 2013). CCS can be used to attain our sustainability goals, but it is clear that research must focus on reducing its energy consumption and capital costs. Reviewing the several problems involved in each step of the CCS process, I do question whether our efforts should be redirected towards further development and implementation of renewable energy, as opposed to retrofitting existing fossil-fuel based industries with CCS equipment. Nonetheless, I accept that reducing carbon emissions will need several methods rather than a single solution, and Orsted's BECCS project demonstrates that CCS can be used in conjunction with bioenergy. If renewable energy could be used to power CC, I believe it has great potential for the future. Several innovative techniques will be needed to reach net-zero, and CC has the potential to be one of them, so long as companies thoroughly evaluate their project's risk towards human and environmental health. I believe if the energy usage of these technologies can be significantly reduced, CCS would certainly become a powerful transition tool towards a more sustainable future.

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