

Cryogenic Carbon Capture (CCC) Innovations and Potential Applications

Abdualhadi Ahmed M. Alzahrani
Jeddah, Saudi Arabia

Bachelor of Science in Chemistry, Arizona State University, 2020

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List of Abbreviations

As	Arsenic
CAPEX	Capital Expenditure
CCC	Cryogenic Carbon Capture
CCC-PR	Cryogenic Carbon Capture Pollutant Removal
CCC-ES	Cryogenic Carbon Capture Energy Storage
CCC-Ret	Cryogenic Carbon Capture Retrofit
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CO	Carbon Monoxide
CO₂	Carbon Dioxide
COE	Cost of Electricity
DOE	Department of Energy (United States)
EOR	Enhanced Oil Recovery
EPA	Energy Protection Agency (United States)
FGD	Fuel Gas Desulfurization
GHG	Greenhouse Gases
GtC	Gigaton of Carbon
H₂	Hydrogen
HTS	High-temperature Shift
Hg	Mercury
IPCC	Intergovernmental Panel on Climate Change
IGCC	Integrated Gasification Combined Cycle
IEA	International Energy Agency
LNG	Liquified Natural Gas
LTS	Low-temperature Shift
NETL	National Energy Technology Laboratory (United States)
KAUST	King Abdullah University of Science and Technology (Saudi Arabia)
OPEX	Operating Expenditure
PPM	Parts Per Million
Pb	Lead metal
PSA	Pressure swing adsorption
SCR	Selective Catalytic Reducer
MW	Megawatts
SC-PC	Supercritical Pulverized Coal
SES	Sustainable Energy Solutions
WHO	World Health Organization
TS&M	Transportation, Storage, and Monitoring
NO_x	Nitrogen Oxides
SO_x	Sulfur Oxides

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Abstract

Our constant drive for economic growth is responsible for the degradation of the environment, poor air quality, and accelerated climate change. To mitigate carbon dioxide emissions from industrial emitters, one potential method is to use carbon capture and storage (CCS). Cryogenic carbon capture (CCC), one of the most promising CO₂ separation technologies, achieves high rates of CO₂ recovery and purity. This thesis discusses the various CCC methods that are currently under development, their advantages, and the obstacles that prevent their commercialization. The research evaluates the current state of technology, proposes recommendations for CCC deployment, acknowledges rival technologies, and concludes by outlining potential future directions for the CCC system.

A promising technology for lowering greenhouse gas emissions from industrial processes is cryogenic carbon capture. Using cryogenic temperatures, which are typically below -100°C, CO₂ is captured from industrial gas streams using this process. The CO₂ is then compressed and purified in preparation for use or storage. Compared to conventional solvent-based carbon capture, cryogenic carbon capture has several benefits, including greater efficiency and less energy usage. Additionally, cryogenic carbon capture has the potential to capture CO₂ from flue gas streams that have high impurity concentrations and are challenging to capture with other technologies. Before it can be widely used, however, cryogenic carbon capture's high capital costs and technical difficulties must be overcome. Cryogenic carbon capture is a technology with a lot of potential for lowering greenhouse gas emissions and reducing the effects of climate change.

Cryogenic carbon capture (CCC) is a potential method for removing CO₂ after combustion. This approach is relatively new compared to established practices, but it has significant technological and economic advantages. Despite its benefits, CCC is not yet commercially available, so a model-based design approach can provide valuable insights. The paper will begin by explaining the CCC process, followed by an extensive literature review that emphasizes various techniques for component-level modeling. The most efficient modeling methods for each system component are thoroughly presented. The authors suggest using the least complex modeling methods that are still able to accurately model specific CCC process components after comparing their complexity and accuracy levels. Additionally, possible directions for CCC process modeling and simulation study are discussed.

Depending on the specific application, the effectiveness of the technology, and the facility size, the precise removal rate of carbon dioxide (CO₂) in gigatons of carbon (GtC) can change. Cryogenic carbon capture is thought to potentially remove CO₂ from the atmosphere on a global scale of 1-2 GtC (0.5-1 ppm) annually. This estimate is based on the power plants' and industrial facilities' projected and actual global emissions, as well as the possibility that a significant portion of these emissions could be captured using cryogenic carbon capture.

Introduction

Carbon Capture and Storage (CCS) is a potential solution to reduce greenhouse gas emissions and mitigate the impacts of climate change. The concept of CCS involves capturing carbon dioxide (CO₂) emissions from industrial processes or power plants, transporting them to a designated storage location, and then storing them underground, often in geological formations. Various techniques, such as pre-combustion capture, post-combustion capture, and oxy-fuel combustion, can be used to capture CO₂ emissions. Once captured, the CO₂ can be transported via pipeline, ship, or truck to the storage site. Typically, CO₂ is stored in deep geological formations, saline aquifers, or depleted oil and gas reservoirs. (IPCC, 2022)

Carbon Capture and Storage has the potential to reduce greenhouse gas emissions from industrial processes and power generation facilities, which are responsible for a significant proportion of global CO₂ emissions. It could also help to facilitate the transition to a low-carbon economy by allowing the continued use of fossil fuels while reducing their carbon footprint. However, CCS is not without its challenges. (Parkinson, 2021) The capture, transportation, and storage of CO₂ require significant infrastructure and can be costly. Additionally, there are concerns about the potential for CO₂ leakage from storage sites, which could have environmental and health impacts. Therefore, the development and deployment of CCS technology will need to be accompanied by strong regulations and monitoring to ensure its safety and effectiveness.

Despite the obstacles, CCS is still regarded as a promising technology in mitigating greenhouse gas emissions and addressing the impacts of climate change. Its potential to facilitate the transition to a low-carbon economy makes it a crucial component of a comprehensive approach to tackling climate change. Cryogenic carbon capture (CCC) is a novel technology currently being developed for the capture of carbon dioxide (CO₂) emissions, and it is considered

a significant research area due to its potential to reduce costs and energy requirements associated with traditional carbon capture technologies, according to Maqsood (2022). The CCC process entails cooling the flue gas from industrial processes or power plants to extremely low temperatures (-100°C to -160°C), causing CO_2 to condense into a liquid. The liquid CO_2 can then be isolated from other gases in the flue gas and transported or stored.

Compared to traditional carbon capture technologies, cryogenic carbon capture has several advantages. First, it requires less energy to capture CO_2 , as the cooling process is less energy-intensive than traditional chemical absorption processes. Second, it produces a more concentrated stream of CO_2 , which can reduce the size and cost of downstream processing and storage infrastructure. Finally, it can capture CO_2 from flue gases that are too dilute for other carbon capture technologies to be effective. (NETL, 2023) However, cryogenic carbon capture is still in the early stages of development and several challenges need to be overcome. These include the development of materials that can withstand the extremely cold temperatures required for the process, the need for specialized equipment and infrastructure, and the need for further research to fully understand the potential environmental impacts of the process. (NETL, 2023)

CCC represents a promising avenue of research that can contribute to the global effort to reduce greenhouse gas emissions and mitigate climate change, despite the challenges involved in its development. Climate change refers to long-term changes in the Earth's climate, primarily caused by human activities that release greenhouse gases such as carbon dioxide, methane, and nitrous oxide. The impacts of climate change are diverse and extensive, including rising sea levels caused by the melting of glaciers and ice caps as temperatures rise. This can result in flooding and erosion that threaten coastal communities and ecosystems, as well as more frequent

and severe extreme weather events. Climate change can also lead to droughts, floods, heat waves, and storms, which can cause significant damage to homes, infrastructure, and communities, as well as disrupt agriculture and food security, leading to higher food prices, food shortages, and malnutrition. Finally, the loss of biodiversity can cause the extinction of plant and animal species, disrupting ecosystems and reducing biodiversity. (Neumann et al., 2020)

Public health impacts can lead to increased air pollution, water contamination, and the spread of vector-borne diseases such as malaria and dengue fever. Economic impacts can lead to significant economic losses, including damage to infrastructure, property, and crops, as well as disruptions to trade and transportation. Migration and displacement can lead to the displacement of people from their homes, either due to environmental factors such as sea level rise or due to economic or social pressures caused by the impacts of climate change. (WHO, 2021)

Taking a global approach is necessary to address climate change and reduce greenhouse gas emissions. This can involve implementing a variety of strategies, such as promoting the use of renewable energy, enhancing energy efficiency, supporting public and active transportation, minimizing food waste, and adopting sustainable land use practices. By implementing these actions, we can mitigate the negative effects of climate change and build a more sustainable future for present and future generations. (EPA, 2022)

Cryogenic carbon capture is an innovative technology that has gained significant attention in recent years as a potential solution to mitigate greenhouse gas emissions. It involves the use of cryogenic fluids such as liquid nitrogen to capture carbon dioxide (CO₂) from industrial flue gases. This process has been extensively studied and evaluated through numerous scientific sources, including feasibility studies, thermodynamic analysis, and performance evaluations. These studies provide valuable insights into the potential of cryogenic carbon

capture as a carbon capture and storage (CCS) solution, its efficiency, and its potential applications in power plants. In this context, this technology has the potential to play a critical role in reducing CO₂ emissions and addressing the issue of climate change. (Font-Palma et al., 2021)

In the late 19th and early 20th centuries, the field of cryogenics saw significant advancements with the development of new techniques for cooling and liquefying gases. One of the most important breakthroughs in cryogenics was the discovery of the Joule-Thomson effect in 1852, which provided a method for cooling gases by expanding them through a porous plug. (Radebaugh, 2007) In thermodynamics, the Joule-Thomson effect describes the temperature change of a real gas or liquid (as opposed to an ideal gas) when forced through a valve or porous plug while remaining insulated so that no heat is exchanged with the environment.

During the mid-20th century, cryogenics saw significant advancements with the development of new techniques for producing and storing liquid helium and other cryogenic fluids. This led to the development of new technologies that rely on cryogenics, such as superconducting magnets used in medical imaging and particle accelerators, and cryogenic rocket engines used in space exploration. (Jouhara et al., 2023)

Today, cryogenics is a rapidly growing field with a wide range of applications in science, engineering, and industry. The development of CCC, which involves the use of cryogenic fluids to capture carbon dioxide from industrial flue gases, is just one example of ongoing innovation in the field of

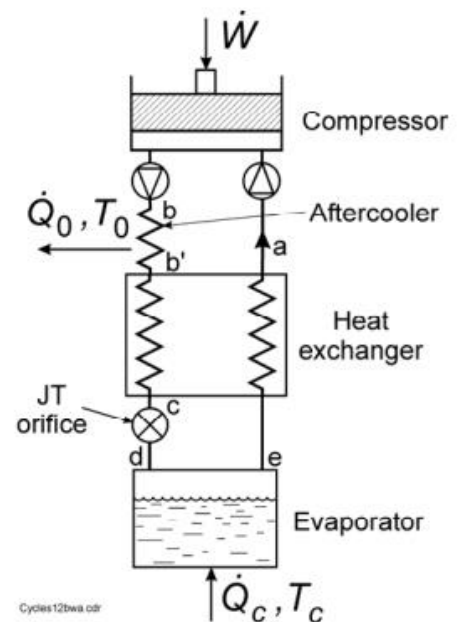


Figure 1: Schematic of the Joule-Thomson cycle (Radebaugh, 2007)

cryogenics (University of Brighton, 2019). Cryogenic carbon capture is a relatively new technology that has emerged as a potential solution to mitigate greenhouse gas emissions from industrial processes. The origin of CCC can be traced back to the early 21st century when researchers began to investigate the use of cryogenic fluids for carbon capture and storage (CCS) applications. (Frankman et al., 2021)

The first experiments on cryogenic carbon capture were conducted in the mid-2000s by researchers at the University of Oslo in Norway. They investigated the use of liquid nitrogen to capture CO₂ from flue gases and demonstrated the feasibility of the process in laboratory-scale experiments. Since then, numerous studies have been conducted on cryogenic carbon capture, with a focus on optimizing the process for industrial-scale applications. One of the key advantages of CCC is its ability to capture CO₂ from flue gases at high concentrations and temperatures, which can reduce the energy required for the capture process and lower the cost of CCS. (Font-Palma, 2021)

In recent years, cryogenic carbon capture has gained significant attention as a potential CCS solution for power plants and other industrial processes. Research has focused on improving the efficiency and scalability of the technology, as well as its economic viability. Overall, research into the use of cryogenic fluids for carbon capture and storage applications dates to the early 21st century, which is when cryogenic carbon capture first emerged. Since then, the technology has advanced significantly, with ongoing research and development aimed at improving its efficiency, scalability, and economic viability (Hoeger, 2021).

Three main types of carbon capture technologies are currently being developed and deployed: (Maqsood, 2022)

Post-combustion capture: This technology captures carbon dioxide (CO₂) from the flue gases produced by the combustion of fossil fuels in power plants and industrial facilities. Post-combustion capture typically involves the use of chemical solvents, adsorbents, or membranes to separate the CO₂ from other gases in the flue stream.

Pre-combustion capture: This technology captures carbon dioxide (CO₂) before it is released during the combustion of fossil fuels. In pre-combustion capture, the fuel is converted into a gas (syngas) through a process called gasification, and the CO₂ is then separated from the syngas using a shift reaction and other separation techniques.

Oxyfuel combustion: This technology involves burning fossil fuels in an environment of pure oxygen, rather than air. The resulting flue gas is primarily composed of carbon dioxide and water vapor, which can then be separated and captured using post-combustion capture technologies.

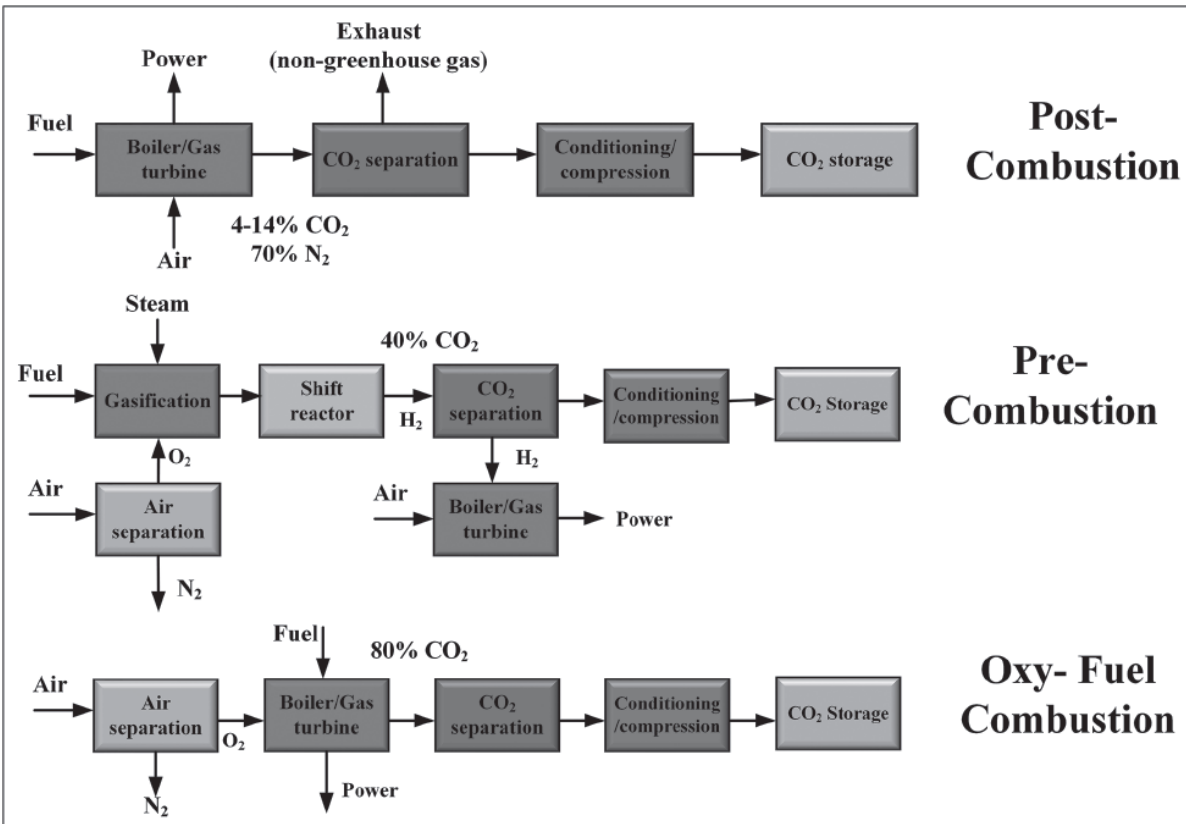


Figure 2: Main types of carbon capture technologies (Maqsood, 2022)

Each of these carbon capture technologies has its advantages and disadvantages, and the most appropriate technology will depend on factors such as the type of facility, the fuel source, and the required level of CO₂ capture. Cryogenic carbon capture is a type of post-combustion capture technology. It involves cooling the flue gas from a power plant or industrial facility to very low temperatures (-100°C to -160°C) using a refrigeration system. This cooling process condenses the CO₂ in the flue gas while the other gases remain in their gaseous form due to their freezing points, allowing it to be separated from other gases such as nitrogen and oxygen. The separated CO₂ can then be stored or used in other applications. (Folger, 2013)

Cryogenic carbon capture is a relatively new technology that is still being developed and tested on a commercial scale. However, it has several advantages over other post-combustion capture technologies, including a higher efficiency in capturing CO₂, lower energy requirements,

and the ability to capture impurities such as sulfur dioxide and nitrogen oxides along with the CO₂.

In addition to its advantages, cryogenic carbon capture also has some limitations and challenges that need to be addressed. These include High capital costs, the refrigeration system required for cryogenic carbon capture can be expensive to install and maintain, making it a more expensive option compared to other post-combustion capture technologies. (IEA, 2021)

While cryogenic carbon capture has lower energy requirements than some other post-combustion capture technologies, it still requires a significant amount of energy to operate the refrigeration system. Cryogenic carbon capture involves handling very low temperatures, which can create technical challenges such as ice formation and equipment corrosion. These challenges must be addressed to ensure the safe and efficient operation of the system. (Hoeger, 2021)

Despite these challenges, CCC has the potential to play an important role in reducing greenhouse gas emissions from power plants and industrial facilities. Ongoing research and development efforts are focused on improving the efficiency and reliability of cryogenic carbon capture, as well as reducing its costs, to make it a more practical and widely adopted technology. (IPCC, 2022)

*Latest CO₂ reading: **421.33 ppm**

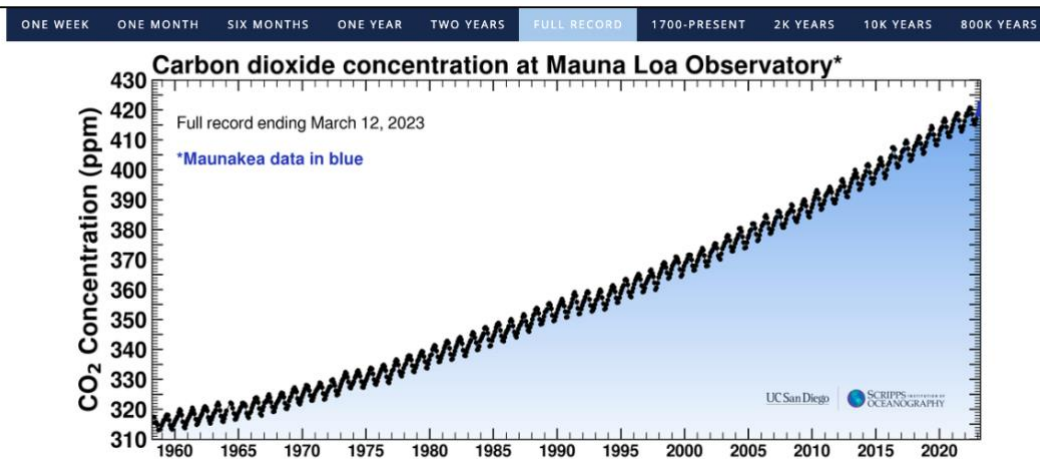


Figure 3: The Keeling Curve (Monroe, 2023)

Research Question

- **How effective is Cryogenic Carbon Capture in CO₂ removal rate?**

Cryogenic carbon capture is a highly effective technology for the removal of carbon dioxide (CO₂) from flue gas emissions. The technology has been shown to have a CO₂ removal rate of up to 95%, which is higher than many other post-combustion capture technologies. The high efficiency of cryogenic carbon capture is because the process involves cooling the flue gas to very low temperatures, which causes the CO₂ to condense and separate from other gases such as nitrogen and oxygen. This allows for more efficient separation of CO₂ from the flue gas stream. In addition to its high CO₂ removal rate, cryogenic carbon capture also has the potential to capture other greenhouse gases and air pollutants such as sulfur oxides (SO_x) and nitrogen oxides (NO_x). This can help to reduce the overall environmental impact of power plants and industrial facilities. (Baxter et al., 2021)

Hence, cryogenic carbon capture is a promising technology for reducing greenhouse gas emissions, it is still in the early stages of development and some challenges need to be addressed. These include high capital costs, energy requirements, and technical challenges such as ice

formation and equipment corrosion. Ongoing research and development efforts are focused on improving the efficiency, reliability, and cost-effectiveness of cryogenic carbon capture to make it a more practical and widely adopted technology for carbon capture and storage.

The exact removal rate of carbon dioxide (CO₂) in gigatons of carbon (GtC) using cryogenic carbon capture technology can vary depending on the specific application, efficiency of the technology, and the size of the facility. However, it is estimated that the global potential for CO₂ removal using cryogenic carbon capture is in the range of 1-2 GtC (~0.5-1 ppm) per year. This estimate is based on current and projected global emissions from power plants and industrial facilities, as well as the potential for cryogenic carbon capture to capture a high percentage of these emissions. (Font-Palma et al., 2021)

The need for a significant amount of energy to cool the flue gas to the cryogenic temperatures necessary for the CO₂ to condense into a liquid is a significant drawback of CCC. The amount of energy required to cool the flue gas to a low enough temperature to capture all the CO₂ can become prohibitively expensive or energy-intensive, which can reduce the rate at which CCC is removed. The fact that CCC can only capture CO₂ from specific point sources, such as industrial processes, power plants, or other sources with high concentrations of CO₂ emissions, is another limitation. Where CO₂ concentrations are much lower and the cost and viability of capturing and storing the CO₂ become more difficult, diffuse sources like the atmosphere are not good candidates for CCC. (Naddaf, 2023)

While CCC is a useful technology for capturing carbon dioxide, it has drawbacks that make it ineffective for eliminating CO₂ emissions from industrial processes or other sources. It might be necessary to combine CCC with other carbon capture technologies, like absorption-

based or solid sorbent capture, or to pursue other mitigation strategies, like the use of renewable energy and energy efficiency, to overcome these restrictions.

It is important to note that cryogenic carbon capture is still a developing technology, and many factors can influence its effectiveness and cost-effectiveness in real-world applications. As research and development continue, it is possible that the removal rate and potential impact of cryogenic carbon capture could increase.

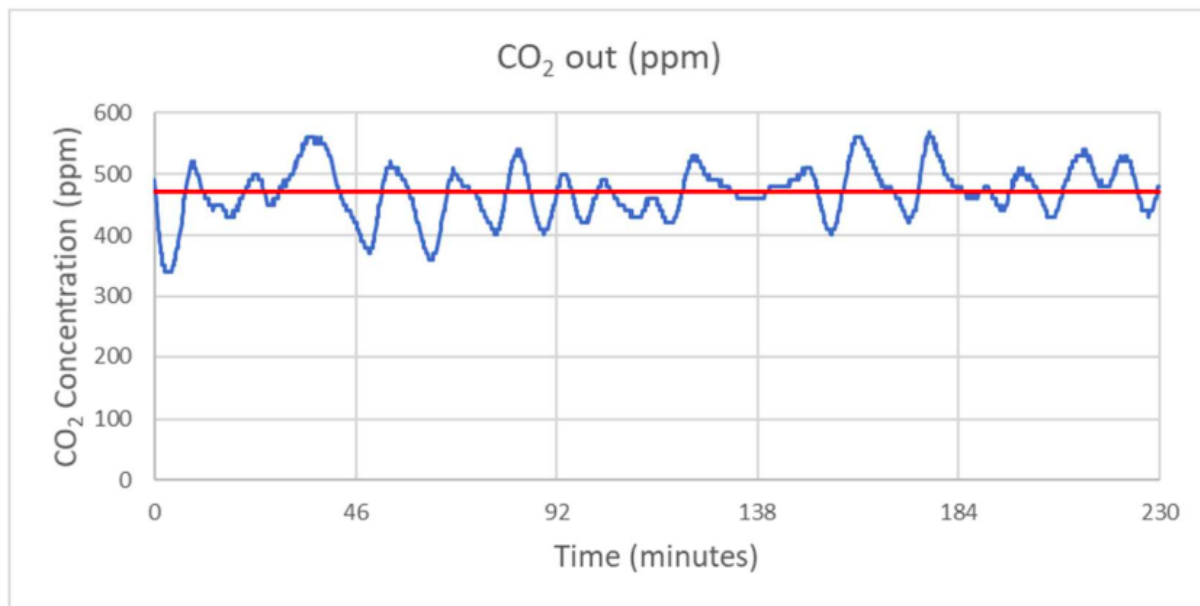


Figure 4: Results of a test showing how the CCC process directly captures air. The outlet CO₂ concentration from the CCC process is depicted in this plot. The CO₂ captured comes from the air, not the fuel, once the outlet CO₂ concentration falls below 470 ppm (red line), which accounts for the O₂ consumed during combustion. (Baxter et al., 2021)

Literature Review

Each of these carbon capture technologies has its advantages and disadvantages in terms of their technical feasibility, cost-effectiveness, and environmental impact. The choice of technology will depend on factors such as the type of industrial process or power generation, the scale of the operation, and the availability of infrastructure for CO₂ storage and transportation.

Carbon capture technologies are designed to capture carbon dioxide (CO₂) emissions from various industrial processes and power plants, preventing them from entering the atmosphere and contributing to climate change. There are three primary types of carbon capture technologies: pre-combustion capture, post-combustion capture, and oxy-fuel combustion.

Post-Combustion Carbon Capture

This technology involves capturing CO₂ after the fuel has been burned. The flue gas is passed through a chemical solvent that absorbs the CO₂, which is then separated and stored. This technology can be retrofitted to existing power plants, making it a viable option for reducing emissions from existing facilities. (IEA, 2021) This analysis predicted a post-combustion regeneration heat rate of 2.0 GtC CO₂ and an overall capture cost of \$50.6/ton CO₂. Post-combustion capture is a carbon capture technology that involves removing carbon dioxide (CO₂) from the flue gas produced by the combustion of fossil fuels. This technology can be retrofitted onto existing power plants, making it an attractive option for reducing emissions from older facilities. Here are the key steps involved in post-combustion capture: (Maqsood, 2022)

The first step in post-combustion capture involves separating the flue gas into its constituent parts, which typically includes nitrogen, water vapor, and carbon dioxide. This is typically achieved using a process called gas scrubbing, which involves passing the flue gas through a liquid solvent that selectively absorbs CO₂. (See figure 5)

Once the flue gas has been separated, the next step is to capture the CO₂ from the liquid solvent. This is typically achieved through a process called regeneration, which involves heating the solvent to release the CO₂. The released CO₂ can then be captured and stored for later use. After the CO₂ has been captured, it must be compressed to a high pressure to transport it for

storage. This is typically done using large compressors that require a significant amount of energy. Once the CO₂ has been compressed, it is transported to a storage site, which could be an underground geological formation, an oil field, or another suitable location. The CO₂ is then injected into the storage site and monitored to ensure that it remains securely stored over the long term. (Maqsood, 2022)

Post-combustion capture is a mature technology, and there are a variety of solvents that can be used for the gas scrubbing step. Some of the most used solvents include amines, ammonia, and chilled ammonia. However, the process is energy-intensive, and the cost of capturing and storing CO₂ remains a significant barrier to widespread deployment. Additionally, post-combustion capture systems can be expensive to retrofit onto existing power plants, and they can reduce the overall efficiency of the plant, which can impact profitability. Nevertheless, post-combustion capture remains an important tool for reducing emissions from existing power plants, and ongoing research and development efforts are focused on improving the efficiency and cost-effectiveness of this technology. (Maqsood, 2022)

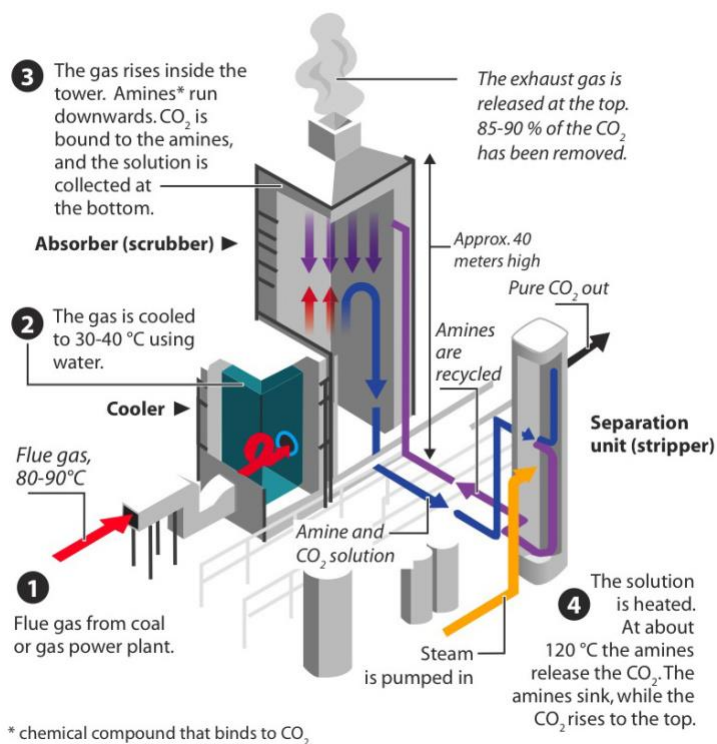


Figure 5: Simplified model of a post-combustion capture unit (Zero Emission Resource Organization, 2023)

Pre-combustion Carbon Capture

This technology involves capturing CO₂ before the fuel is burned. In this process, the fuel is first gasified, and the resulting gas is then cleaned and separated into hydrogen and CO₂. The CO₂ is then captured and stored, while the hydrogen is used as a fuel. Other carbon capture technologies in development include chemical looping combustion and membrane separation. Chemical looping combustion uses a solid material to transport oxygen to the fuel, producing a concentrated stream of CO₂ that can be captured. (Maqsood, 2022)

Membrane separation uses a membrane to selectively separate CO₂ from other gases in the flue gas. Overall, carbon capture technologies have the potential to significantly reduce greenhouse gas emissions from industrial processes and power generation. However, the cost of implementing these technologies remains a major barrier to their widespread adoption. (Chen et al., 2022) Pre-combustion carbon capture technologies that are currently commercially available typically employ physical or chemical adsorption techniques and will cost about \$60/ton to capture CO₂ produced by an integrated gasification combined cycle (IGCC) power plant. The DOE is working to bring this price down to \$30/ton of CO₂. To achieve this, research focuses on three essential separation technologies: advanced solvents, sorbents, and membranes. (DOE, 2022)

Pre-combustion capture can generate a stream of highly pure CO₂ that can be applied in a range of industrial processes, such as enhanced oil recovery and the creation of chemicals and fuels. Since it captures CO₂ when it is concentrated and relatively pure rather than from a dilute flue gas stream, it may be more effective than post-combustion capture. However, pre-combustion capture requires significant capital investment and can increase the cost of electricity generation by up to 80%. It also requires additional energy to compress and transport the

captured CO₂, which can further increase costs. As a result, pre-combustion capture is currently only economically viable in certain niche applications, such as natural gas processing plants where the high-purity CO₂ can be sold for industrial use. (Wang, 2018)

The fuel gasification is converted into a gas in a process called gasification. This typically involves reacting the fuel with a mixture of steam and oxygen in a gasifier. The gasifier operates at high temperatures and pressures, typically between 700 and 1000°C and 20 to 30 atmospheres of pressure. The heat and pressure cause the fuel to break down into its constituent molecules, which form a gas mixture called syngas. Syngas typically consists of hydrogen (H₂), carbon monoxide (CO), and various impurities such as nitrogen, sulfur compounds, and trace metals. (Wang, 2018)

The gasification process can be carried out using different types of gasifiers, including fixed-bed gasifiers, fluidized-bed gasifiers, and entrained-flow gasifiers. Each type of gasifier has its advantages and disadvantages in terms of efficiency, scalability, and capital cost.

The syngas produced by the gasifier is then cleaned to remove impurities that could damage downstream equipment or reduce the efficiency of the carbon capture system. The cleaning process typically involves several steps. The desulfurization removes sulfur compounds, which can corrode equipment and reduce the efficiency of the carbon capture process. Desulfurization is typically carried out using a chemical solvent, such as amine or physical solvent, which selectively absorbs sulfur compounds. (NETL, 2023)

Next, particulate removal removes solid particles, such as ash or dust, which can damage equipment or clog pipelines. Particulate removal can be achieved using mechanical filters, cyclones, or electrostatic precipitators.

In the trace metal removal step, it starts to remove trace metals, such as mercury or arsenic, which can poison catalysts or harm the environment. Trace metal removal can be achieved using activated carbon, chemical sorbents, or catalytic oxidation. The cleaned syngas is then subjected to a chemical reaction called shift conversion, which converts the remaining carbon monoxide (CO) into carbon dioxide (CO₂) and hydrogen (H₂). (NETL, 2023) The shift conversion reaction is exothermic, meaning it releases heat, which can be used to generate steam for power generation.

The shift conversion reaction can be carried out using two different processes: high-temperature shift (HTS) and low-temperature shift (LTS). HTS operates at temperatures between 350 and 450°C and uses a catalyst to speed up the reaction. LTS operates at temperatures between 200 and 250°C and does not require a catalyst.

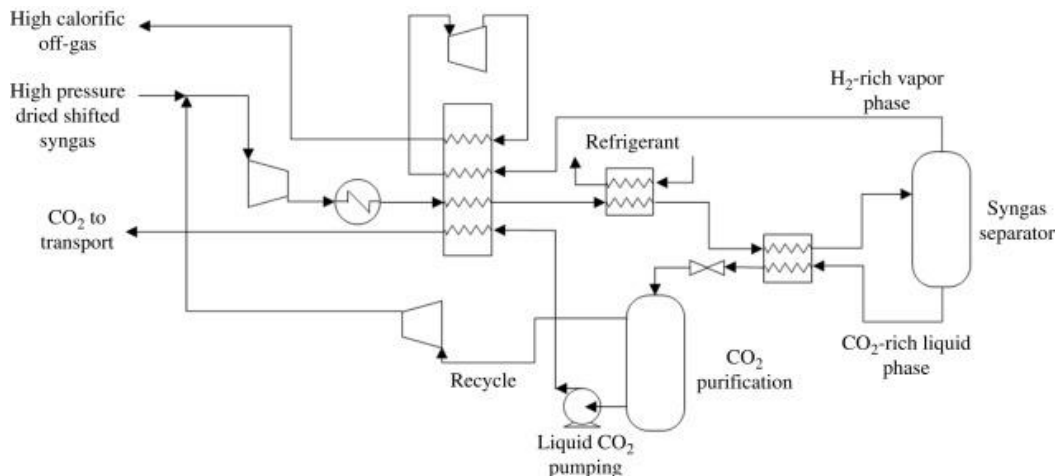


Figure 6: The schematic representation of the cryogenic CO₂ separation process. (Samipour et al., 2020)

The CO₂ is then separated from the hydrogen using a process called pressure swing adsorption (PSA) or membrane separation. PSA uses a porous material, such as zeolite or activated carbon, to selectively adsorb CO₂ from the syngas stream. The adsorbent is then regenerated by reducing the pressure, which releases the adsorbed CO₂. The separated CO₂ is

then compressed to high pressure, typically between 100 and 200 atmospheres, and stored, typically in underground geological formations such as depleted oil and gas reservoirs.

Membrane separation uses a thin, selective membrane to separate CO₂ from the syngas stream.

The membrane is typically made of polymers or ceramics and operates based on the principles of permeation and diffusion. The separated CO₂ is then compressed and stored, as with PSA.

(Samipour et al., 2020)

The shifted synthesis gas stream is rich in CO₂ and at higher pressure than post-combustion technology, which removes CO₂ from flue gas streams that is dilute (5-15% CO₂ concentration) and at low pressure. This makes it easier to remove CO₂ before the H₂ is burned. Pre-combustion capture is typically more effective due to the more concentrated CO₂, but the base gasification process's capital costs are frequently higher than those of conventional pulverized coal power plants. (NETL, 2023) Pre-combustion carbon capture technologies that

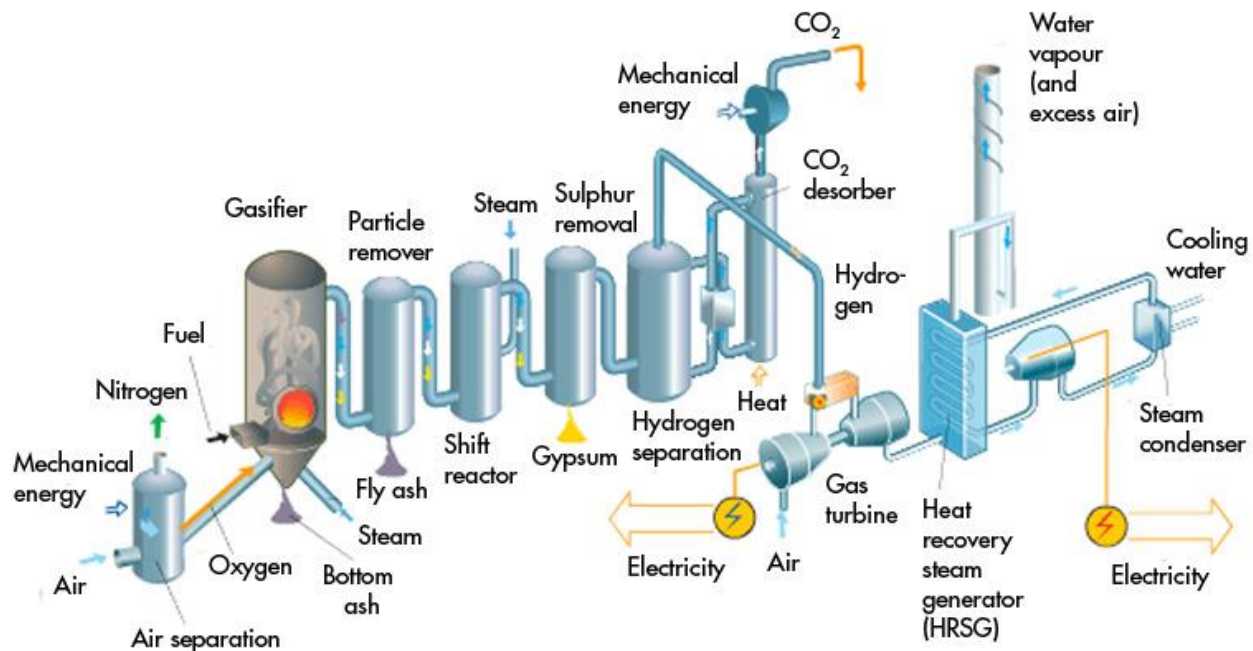


Figure 7: Simplified model of a pre-combustion capture unit. (Zero Emission Resource Organization, 2023)

are currently commercially available typically employ physical or chemical adsorption techniques and will cost about \$60 per ton to capture CO₂ produced by an integrated gasification combined cycle (IGCC) power plant. The DOE is working to bring this price down to \$30 per ton of CO₂. To achieve this, research focuses on three essential separation technologies: advanced solvents, sorbents, and membranes. (NETL, 2023)

Oxy-Fuel Combustion Carbon Capture

This technology involves burning the fuel in pure oxygen instead of air, which produces a concentrated stream of CO₂ that is easier to capture. The CO₂ is then separated and stored, while the remaining gases are used to produce steam to generate electricity. Oxy-fuel combustion is a carbon capture technology that involves burning fossil fuels in a mixture of oxygen and recycled flue gas, which is primarily made up of CO₂. The process results in a highly concentrated stream of CO₂, which can then be captured and stored for later use. Here are the key steps involved in oxy-fuel combustion. (NETL, 2023) Because the oxy-fuel process is costly and energy-intensive, the cost of electricity generated in oxy-fuel plants rises dramatically from \$66.8 per MWh in an average power plant to \$123.7 per MWh in oxy-fuel plants, resulting in a removal rate cost of \$104 per ton of CO₂.

The first step in oxy-fuel combustion involves separating oxygen from the air. This can be done using a variety of technologies, including cryogenic distillation, pressure swing adsorption, or membrane separation. Once the oxygen has been separated, it is typically cooled to a low temperature and stored in tanks for later use. The fuel is then burned in a mixture of the separated oxygen and recycled flue gas. This produces a stream of hot, CO₂-rich flue gas, which is then cooled to condense out water vapor and other impurities. (NETL, 2023)

Oxyfuel (O_2/CO_2 recycle) combustion capture

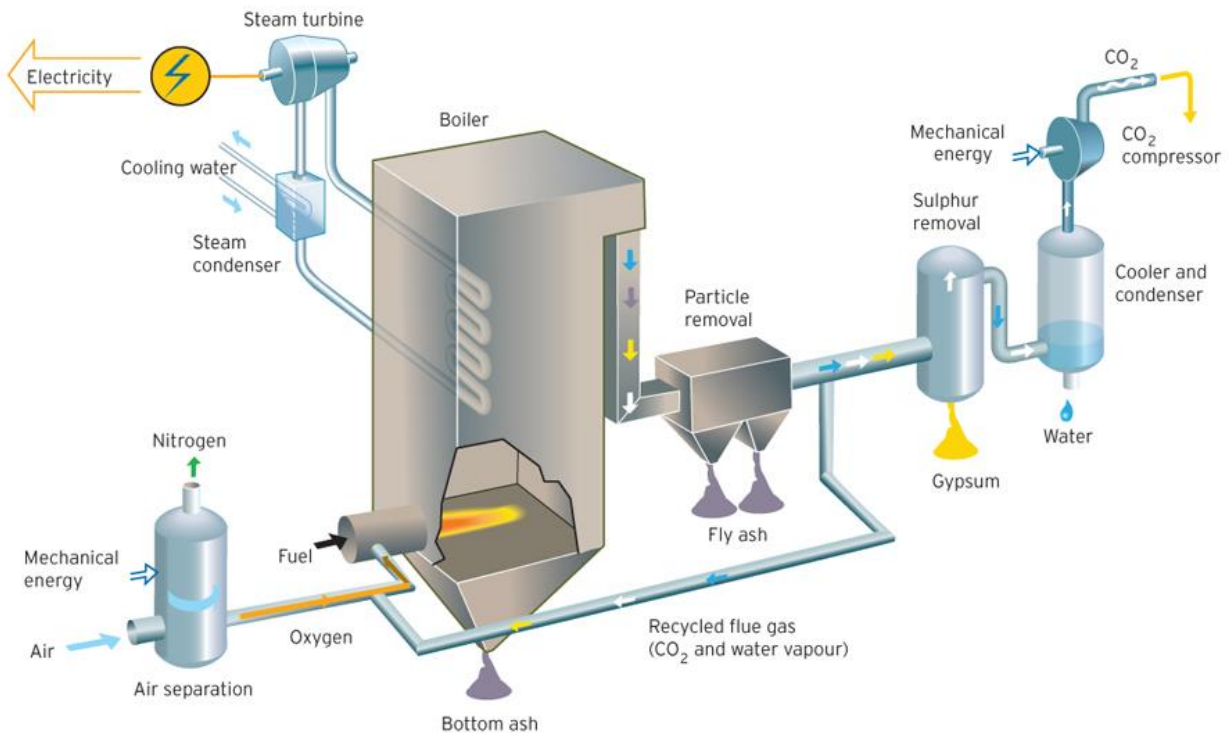


Figure 8: Simplified model of an oxyfuel capture unit. Zero Emission Resource Organization, 2023)

Once the flue gas has been cooled and purified, the next step is to capture the CO₂. This is typically achieved using a process called absorption, in which the flue gas is passed through a liquid solvent that selectively absorbs CO₂. The absorbed CO₂ can then be separated from the solvent and compressed for transport and storage.

Compression, Transport, and Storage; Once the CO₂ has been captured, it must be compressed to a high pressure to transport it for storage. This is typically done using large compressors that require a significant amount of energy. The CO₂ is then transported to a storage site, which could be an underground geological formation, an oil field, or another suitable location. The CO₂ is then injected into the storage site and monitored to ensure that it remains securely stored over the long term. (IEA, 2021)

Oxy-fuel combustion is a promising technology for carbon capture, as it produces a highly concentrated stream of CO₂ that is easier to capture and store than the more dilute flue

gases produced by traditional combustion. However, the process is energy-intensive, and the cost of separating oxygen from the air can be a significant barrier to widespread deployment. (Ahmed & Zahid, 2019)

Additionally, oxy-fuel combustion systems can reduce the overall efficiency of the plant, which can impact profitability. Nevertheless, ongoing research and development efforts are focused on improving the efficiency and cost-effectiveness of this technology, as it has the potential to play a key role in reducing greenhouse gas emissions from power plants and other industrial facilities. (Ahmed & Zahid, 2019)

Comparability

In terms of efficiency, pre-combustion capture generally has the highest potential for capturing CO₂, as it involves separating carbon from the fuel before combustion. This allows for a higher concentration of CO₂ in the captured stream, which can reduce the energy required for compression and storage. However, pre-combustion capture also requires additional processing steps, which can increase the overall complexity of the system and impact overall efficiency.

Post-combustion capture, on the other hand, is a mature technology that has been widely deployed in the power industry. While it generally has a lower efficiency than pre-combustion capture, it can be retrofitted onto existing power plants, which can help to reduce emissions from older facilities. The efficiency of post-combustion capture systems can vary depending on the specific technology and operating conditions.

Oxy-fuel combustion is another carbon capture technology that has the potential to be highly efficient, as it produces a concentrated stream of CO₂. However, the process is energy-intensive, and the cost of separating oxygen from the air can be a significant barrier to

deployment. Oxy-fuel combustion also requires specialized equipment, which can increase capital costs and limit scalability.

In terms of cost, post-combustion capture is generally the most cost-effective option, as it can be retrofitted onto existing power plants and uses well-established technology. Pre-combustion capture and oxy-fuel combustion tend to be more expensive, due to the additional processing steps and specialized equipment required. However, the cost of carbon capture can vary significantly depending on the specific application, as well as regulatory and market factors. (Ahmed & Zahid, 2019)

When it comes to scalability, post-combustion capture, and pre-combustion capture are generally the most scalable options, as they can be deployed in a wide range of applications and industries. Oxy-fuel combustion, on the other hand, may be limited by the availability of oxygen and the need for specialized equipment.

Overall, each carbon capture technology has its advantages and disadvantages in terms of efficiency, cost, and scalability. The most appropriate technology will depend on the specific application and operating conditions, as well as economic and regulatory factors. Ongoing research and development efforts are focused on improving the efficiency and cost-effectiveness of these technologies, to make carbon capture a viable solution for reducing greenhouse gas emissions from a wide range of industrial sources. (Liao et al., 2019)

The choice of carbon capture technology will depend on several factors, including the type of industrial process or power generation plant, the CO₂ capture rate required, the operating conditions (e.g., temperature, pressure), the availability of infrastructure and resources (such as water and energy), and the economic and regulatory environment.

For example, in the power industry, post-combustion capture may be the preferred technology for retrofitting existing coal-fired power plants, as it is a proven technology that can be added to the existing infrastructure. In contrast, pre-combustion capture may be more suitable for gasification-based power plants or chemical processing facilities, as it can be integrated into the overall process design. (Liao et al., 2019)

In addition, the cost of carbon capture and storage will also depend on the specific application and the prevailing market conditions, including the price of carbon credits or other incentives, the availability of financing and capital, and the cost of competing technologies such as renewable energy or nuclear power. (IEA, 2021) Ultimately, the choice of carbon capture technology will depend on a careful evaluation of these factors, as well as ongoing research and development efforts aimed at improving the efficiency and cost-effectiveness of these technologies.

Cryogenic carbon capture is a relatively new and emerging technology that uses a low-temperature separation process to capture and purify CO₂. Compared to other carbon capture technologies, cryogenic carbon capture has both advantages and disadvantages. It can achieve high-purity CO₂ streams, which can reduce the energy required for compression and transportation. However, the energy required for the low-temperature separation process can be a significant drawback, which reduces the overall efficiency of the system. (Font-Palma et al., 2021)

Cryogenic carbon capture is relatively scalable and can be used in a wide range of industrial processes, such as power generation, cement production, and steel manufacturing. However, due to the need for specialized equipment and infrastructure, the scalability of the technology may be limited. (Hoeger, 2021)

When compared to the other carbon captures technologies, such as pre-combustion capture, post-combustion capture, and oxy-fuel combustion, cryogenic carbon capture is less mature and has a higher cost per ton of CO₂ captured. However, cryogenic carbon capture has the potential to achieve higher-purity CO₂ streams than other technologies and may be more suitable for applications where high-purity CO₂ is required, such as in the production of food and beverages.

In summary, cryogenic carbon capture is a promising technology that offers high-purity CO₂ streams but is currently more expensive than other carbon capture technologies. As the technology continues to develop, and deployment increases, costs are expected to decrease, making cryogenic carbon capture a more cost-effective option for industrial processes that require high-purity CO₂ streams. Cryogenic carbon capture (CCC) is a relatively new technology that has been developed over the past decade. It involves capturing CO₂ by cooling the gas to extremely low temperatures, which causes it to condense into a liquid. The liquid CO₂ can then be easily separated from other gases and stored. (Hoeger, Burt, & Baxter, 2021)

History and Development

The history of CCC dates to the early 2000s when researchers began investigating the use of cryogenics in natural gas processing. They found that by cooling natural gas to very low temperatures, they could remove impurities such as CO₂ and sulfur compounds. This led to the development of a new cryogenic process for capturing CO₂, which was first tested in a pilot plant in 2007 (Radebaugh, 2007). Since then, there has been significant progress in the development of cryogenic carbon capture technology, with a few companies and research institutions investing in the development of new processes and equipment. One of the most promising areas of research

has been the use of cryogenic distillation to separate CO₂ from other gases, which has been shown to be more energy-efficient than other separation methods.

In addition to its potential for capturing CO₂ emissions from industrial processes and power generation, cryogenic carbon capture has also been proposed to capture CO₂ directly from the atmosphere. This could potentially help to offset the emissions from sources that are difficult to decarbonize, such as aviation and shipping. Overall, the development of cryogenic carbon capture technology represents an important advance in the field of carbon capture and storage, offering a potentially more efficient and cost-effective way to capture and store CO₂ emissions. (Antohi, 2011) There has been significant progress in the development of cryogenic carbon capture technology. In 2011, researchers at the Massachusetts Institute of Technology (MIT) developed a new process for separating CO₂ from other gases using cryogenic distillation. The process, known as the "Cold Trap Process," uses a series of cryogenic distillation columns to separate CO₂ from other gases, and has been shown to be more energy-efficient than other separation methods.

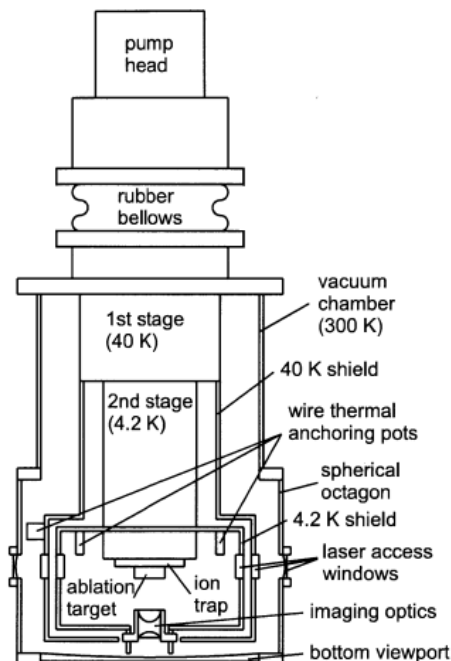


Figure 9: Diagram of a cross section through a closed cycle cryostat. The imaging optics, which are anchored to a 4 K radiation shield, are directly exposed to the 300 K radiation from the bottom viewport. (Antohi, 2011)

In 2016, the company Carbon Clean Solutions developed a new cryogenic carbon capture process that uses a proprietary solvent to capture CO₂ from industrial flue gases. The solvent is cooled to extremely low temperatures, causing the CO₂ to condense and separate from other gases. The captured CO₂ can then be stored or used for enhanced oil recovery. (CarbonClean., 2022)

Methodology

The methodology of cryogenic carbon capture involves the following steps: (Baxter et al., 2022)

Flue gas cooling: The first step in the process is to cool the flue gas emissions from power plants or industrial facilities to very low temperatures, typically around -120°C. This is done using a refrigeration system that is powered by electricity or another energy source.

Condensation: As the flue gas is cooled, the carbon dioxide (CO₂) within it begins to condense into a liquid. This liquid CO₂ can then be separated from the other gases in the flue gas stream, such as nitrogen and oxygen.

Separation: The liquid CO₂ is then separated from the other gases using a distillation process or other separation methods. This allows the CO₂ to be captured and stored separately from other gases.

Compression: The captured CO₂ is then compressed to increase its density, which makes it easier to transport and store. The compressed CO₂ can then be transported to a storage site, such as an underground geological formation or other secure storage location.

Storage: The final step is to store the captured CO₂ in a secure location where it will not be released into the atmosphere. This can involve injecting the CO₂ into underground formations, using it for enhanced oil recovery, or other forms of storage.

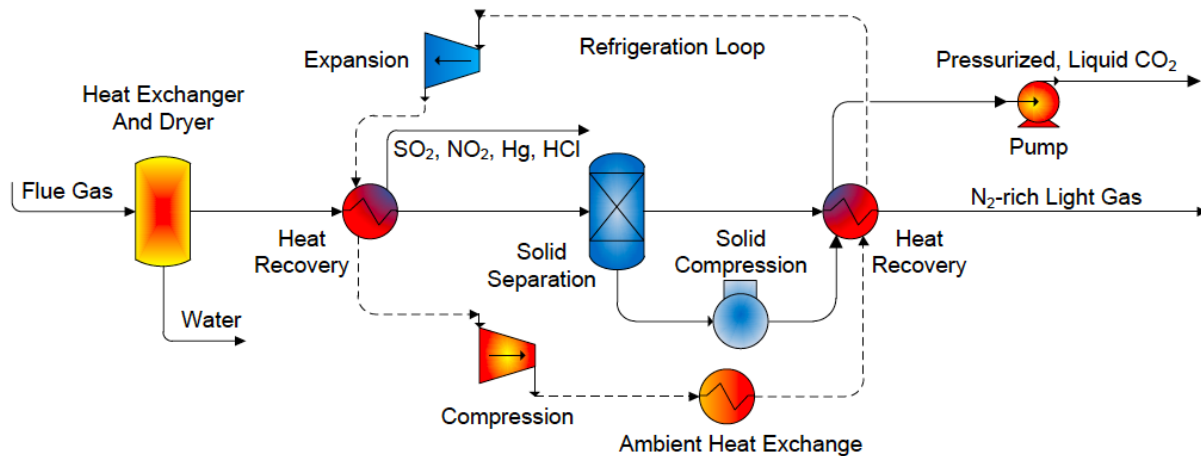


Figure 10: Simplified Flow Diagram for Cryogenic Carbon Capture process (Baxter et al., 2022)

Cryogenic carbon capture is a type of post-combustion carbon capture technology, which is used to capture carbon dioxide (CO_2) emissions from industrial facilities after the fuel has been burned. However, it is still a developing technology and there are challenges that need to be addressed, such as high capital costs and technical challenges such as ice formation and equipment corrosion. Ongoing research and development efforts are focused on improving the efficiency, reliability, and cost-effectiveness of cryogenic carbon capture to make it a more practical and widely adopted technology for carbon capture and storage. (Font-Palma et al., 2021)

Water usage is significantly reduced by the CCC process in two different ways. First, a light, bone-dry gas stream with temperatures just below ambient is produced by the process. Due to its low temperature and absence of humidity, this gas can produce cooling water. Second, the CCC process necessitates cooling the flue gas from its exit temperature to ambient temperature, condensing and recovering nearly all the moisture in the flue gas, further reducing the CCC water demand. (Hoeger et al., 2021) Any molecule with a vapor pressure greater than the vapor pressure of CO_2 will be captured with the CO_2 as the flue gas cools to nearly cryogenic temperatures. This includes criteria pollutants like SO_2 , NO_x , and particulates as well as heavy

metals like Hg, As, and Pb. These pollutants are captured by CCC so effectively that it can take the place of selective catalytic reducer (SCR) units for NO_x reduction, activated carbon beds for

Pollutant	ppm
SO ₂	32.7
SO ₃	0.002
NO ₂	0.007
Hg	4.80E-10
As	7.31E-37

Table 1: Pollutant composition in the clean flue gas exiting the CCC process when capturing 90% of the inlet CO₂. (Hoeger, Burt, & Baxter, 2021)

Hg removal, and flue gas desulfurization (FGD) units for SO₂ reduction. The CCC process will not capture carbon monoxide (CO) or any other substances lighter than CO₂. The concentration of pollutants in the effluent gas from a coal-fired boiler that was part of a CCC system that captured 90% of the CO₂ is displayed in Table 1.

Cryogenic carbon capture (CCC) has the potential to significantly reduce CO₂ emissions from a variety of industries, including the production of steel, cement, and natural gas for power. These industries use a lot of carbon and produce a lot of CO₂ emissions as a result of their industrial operations. These processes' carbon footprints can be decreased and removed using CCC, assisting in the achievement of climate goals.

Advantages of CCC and its product

With the ability to capture up to 95% of CO₂ emissions, cryogenic carbon capture (CCC) is one of the most efficient options available. As the cooling process uses the waste heat from the power plant, CCC uses less energy than other carbon capture technologies, making it a low energy consumption option. Furthermore, CCC uses no chemicals or solvents, lowering the possibility of contamination or environmental harm and making it a sustainable technology. As a

scalable technology that can be tailored to suit the requirements of various industries, CCC is a flexible option for carbon capture. Additionally, CCC is a more affordable option for businesses looking to cut their carbon emissions because its capital and operating costs are lower than those of other carbon capture technologies. (NETL, 2023)

Dry ice is the main product of CCC, and it has several environmental uses due to its unique properties. Some of the common environmental uses of dry ice is in carbon capture and sequestration (CCS) projects to capture carbon dioxide (CO₂) from industrial and power plant emissions. Dry ice is added to the emissions stream to capture and solidify CO₂, which is then transported and stored underground. (Font-Palma et al., 2021)

Dry ice is also used in air quality testing to measure the concentration of airborne particles, such as dust and pollen. Dry ice is added to a container with a known volume of air, and the resulting pressure drop is used to calculate the concentration of particles in the air. (DryIceUK, 2018). Dry ice can be used in soil remediation to remove contaminants from soil. When dry ice is added to the contaminated soil it causes the contaminants to freeze and become easier to remove. Another use is in pest control to kill insects and rodents. Dry ice is placed in a container with the pests, and the resulting CO₂ gas as the dry ice sublimates suffocates the pests. Dry ice is used in oil spill clean-up efforts to freeze and solidify the oil, making it easier to remove from water or soil (Cole, 1971). Overall, dry ice's unique properties make it a useful tool for several environmental applications. Its ability to freeze and solidify materials, as well as its low temperature and non-toxic nature, make it a popular choice for a variety of environmental applications.

One potential solution to make cryogenic carbon capture cheaper and more accessible is to invest in research and development to improve the efficiency of the technology and reduce its costs. This could involve developing new materials and processes that are more effective at capturing CO₂, as well as finding ways to reduce the energy requirements for the cryogenic process. (Beaumont, 2022)



Figure 11: Photo of CCC product from Sustainable Energy Solution (SES) (Baxter et al., 2022)

Another approach could be to increase funding for large-scale demonstration projects that could help to drive down costs and increase the adoption of cryogenic carbon capture. This could involve partnering with industry, governments, and other stakeholders to develop and implement large-scale projects that can demonstrate the feasibility and effectiveness of the technology in a real-world setting. In addition, policies and incentives could be put in place to encourage the development and adoption of cryogenic carbon capture. This could include tax credits, subsidies, or other financial incentives to support the development and deployment of the technology. (DOE, 2023) Finally, it is important to address any regulatory barriers that may be preventing the

widespread adoption of cryogenic carbon capture. This could involve working with policymakers to streamline regulations and remove any unnecessary barriers to the development and deployment of the technology.

A singular opportunity for cost-effective, large-scale, high-efficiency energy storage is provided by CCC. The temperature regime in which the CCC process runs makes it possible to use natural gas as a refrigerant. In times of low cost, high supply, or low demand for electricity, the refrigerant can be produced and stored as liquefied natural gas (LNG), which can then be used in times of high cost, low supply, or high demand for electricity. The refrigerant compressors account for most of the parasitic load, so using liquefied natural gas that has been stored will mostly offset the energy cost. (Safdarnejad et al., 2016)

The extra warm natural gas that has vaporized can either be put back into the pipeline or burned in a gas turbine that also captures CO₂ from its exhaust. According to SES, the potential for energy storage is between 7 and 12% of the total installed capacity of power plants. The process in this iteration is known as CCC with energy storage or (CCC-ES). With this process, the carbon capture system can serve as a spinning reserve for the grid, maximizing the use of renewable resources and substituting dependable, CO₂-free reserve power for the most expensive electricity produced. (Safdarnejad et al., 2016)

Even in a retrofit application, most carbon capture technologies require a sizable infrastructure to function properly. For instance, the steam cycle of the Boundary Dam power plant had to be significantly integrated with the amine carbon capture plant that was installed there. This turned out to be harder than anticipated, which contributed to the project's overruns and delays. A brand-new cogeneration combined heat and power plant had to be installed for the

Petra Nova project to supply the amine system with the electricity and steam it requires. (Craig et al., 2017)

The CCC process can be easily retrofitted onto existing power plants and industrial facilities because it only needs electricity and cooling water. Using air-cooled compressors can turn the CCC process into a net positive source of water if water is scarce. This results in the only retrofit carbon capture technology that needs only power to operate, though it slightly reduces the system's efficiency. (Craig et al., 2017)

Techno Economics Analysis

The exact cost of cryogenic carbon capture (CCC) can vary depending on several factors, including the size of the facility, the efficiency of the technology, and the specific application. Currently, the cost of CCC is generally considered to be higher than other carbon capture technologies, such as post-combustion and pre-combustion carbon capture. Estimates for the cost of CCC range from \$12 to \$27 per metric ton of CO₂ captured, compared to \$50 to \$100 per metric ton for other carbon capture technologies. (Hoeger et al., 2021)

$$\text{Avoided Cost} = \frac{(\text{COE}_{\text{CCS with TS\&M}} - \text{COE}_{\text{Non CCS}}) \frac{\$}{\text{MWh}}}{(\text{CO2 Emissions}_{\text{Non CCS}} - \text{CO2 Emissions}_{\text{CCS}}) \frac{\text{tonne}}{\text{MWh}}} \quad (1)$$

$$\text{Captured Cost} = \frac{(\text{COE}_{\text{CCS w/o TS\&M}} - \text{COE}_{\text{Non CCS}}) \frac{\$}{\text{MWh}}}{(\text{CO2 Captured}_{\text{CCS}}) \frac{\text{tonne}}{\text{MWh}}} \quad (2)$$

However, as with any emerging technology, it is expected that the cost of CCC will decrease over time as research and development efforts continue and more CCC facilities are

built. In addition, policies and regulations that incentivize or require carbon capture and storage can also help to reduce the cost of CCC. Overall, the cost of CCC is an important consideration when evaluating its potential use for reducing greenhouse gas emissions. While the cost of CCC is currently higher than other carbon capture technologies, it may still be a viable option for certain applications or in conjunction with other carbon mitigation strategies. (Hoeger, Burt, & Baxter, 2021)

The "Cost and Performance Baseline for Fossil Energy Plants" by the National Energy Technology Laboratory (NETL) contains a thorough technoeconomic analysis of carbon capture. As far as we are aware, it contains the largest and most comprehensive collection of publicly available cost and performance data for comparing various carbon capture technologies. In-depth guidelines for process assumptions and economic modeling are provided by the NETL study, enabling a thorough side-by-side comparison of carbon capture technologies. Cases 11 and 12 from the cited report serve as the baseline studies for this report. (NETL, 2023)

Case 11 is a carbon-captured, greenfield, 550 MW supercritical pulverized coal (SC-PC) power plant. Case 12 is a new 550 MW net SC-PC plant that uses an amine capture unit to capture 90% of the CO₂ emissions. To simulate a 550 MW net SC-PC plant that uses the same process and economic assumptions as stated in the NETL report, SES performed in-depth modeling of the CCC process. The system was created for 90% capture to align with the NETL study, even though CCC can easily achieve higher capture efficiencies at low marginal cost. The size and price of the base power plant must be scaled to achieve 550 MW net output for both the amine and CCC case studies. Therefore, to produce the same amount of net electricity, a carbon capture system with a higher parasitic load needs a larger base plant. (NETL, 2023)

The cost of electricity (COE) is the primary economic comparison metric used in the NETL report. The cost of the capture cases' transportation, storage, and monitoring (TS&M) as well as the capital, operating, and fuel costs all have an impact on the price of electricity. The capture cases (Case 12 and the CCC cases) have higher contingencies and a higher cost of capital than the base non-capture case because it views all capture plants as having a higher risk than a non-capture plant (Case 11). (NETL, 2023)

To enable a direct comparison of the CCC technology with the amine technology, the CCC cases have undergone the same meticulous execution as the energy studies to align with all economic assumptions made as part of the NETL study. The price of CO₂ avoided (Eq. 1) and price of CO₂ captured will also be included (Eq. 2). One common metric is the cost of CO₂ captured. The less common concept of "cost of CO₂ avoided" refers to the expenses incurred to prevent emitting one unit of CO₂. By accounting for the additional fuel and resulting CO₂ emissions needed to produce the same net 550 MW of electricity, avoided cost incorporates the parasitic load of the capture plant into the cost. (NETL, 2023)

Cost information for Cases 11 and 12 is available in the NETL report. Since there is no CO₂ capture, Case 11 has a COE of \$58.90/MWh and neither an avoided cost nor a captured cost. The overall COE for Case 12 is \$106.50/MWh. According to this study, that translates to a cost of \$42.06/ton for CO₂ captured and a cost of \$68.92/ton for CO₂ avoided. The COE of a greenfield amine capture plant is \$47.60/MWh higher than a greenfield non-capture plant, an increase of 80.8%. This considers the higher fuel costs, capital expenditures for scaling the base plant and the amine system, higher operating costs, and the costs associated with moving, storing, and monitoring CO₂. (Baxter et al., 2022) The removal rate efficiency of cryogenic carbon capture (CCC) refers to the percentage of carbon dioxide (CO₂) emissions that are

captured and stored from a power plant or industrial facility. The exact removal rate efficiency of CCC can vary depending on several factors, including the design of the CCC system, the type of facility being used, and the operating conditions. (Hoeger, Burt, & Baxter, 2021)

Vendor quotes adapted to the designs generated by the process' thermodynamic simulations are used to determine the capital cost of all major equipment. Many of the quotes have been recently revised and are valid as of the time of publication. Quotes for the priciest components, the multi-stream heat exchanger, and refrigerant compressors, are also included. Installation factors and other economic factors, such as line-by-line operating cost estimation, are like those in the NETL study. The COE for the base CCC case, using these parameters and quotes, is \$87.46/MWh, which is a 48.5% increase over Case 11. (Baxter et al., 2022)

CO₂ capture costs \$26.88 per ton, while CO₂ avoidance costs \$40.57 per ton. In comparison to Case 11, the incremental cost of CCC is \$28.56/MWh, which is 40% less than Case 12's incremental cost over Case 11. The COE for CCC-PR is \$74.54/MWh, with captured costs of \$12.36 per ton and avoided costs of \$22.19 per ton. As a result of the FGD, SCR, and baghouse being eliminated because they are no longer necessary due to significant economic savings, the CCC-PR costs are reduced. (Baxter et al., 2022)

	Case 11	Case 12	CCC	CCC-PR	CCC-ES	CCC-Ret
COE (\$/MWh)	58.90	106.50	87.46	74.54	63.46	49.43
TS&M (\$/MWh)	0.00	5.60	4.93	4.88	4.93	4.93
Fuel (\$/MWh)	14.20	19.60	17.29	17.11	17.29	17.29
Variable OPEX (\$/MWh)	5.00	8.70	7.53	4.81	7.53	7.53
Fixed OPEX (\$/MWh)	8.00	13.00	10.59	10.49	10.59	10.59
CAPEX (\$/MWh)	31.70	59.60	47.12	37.25	47.12	9.10
Energy Storage Value (\$/MWh)	0.00	0.00	0.00	0.00	-24.00	0.00
COE Increase (\$/MWh)	0.00	47.60	28.56	15.64	4.56	-9.47
Difference from Case 11	0.0%	80.8%	48.5%	26.6%	7.7%	-16.1%
Avoided Cost (\$/tonne)	0.00	68.92	40.57	22.19	6.47	n/a
Captured Cost (\$/tonne)	0.00	42.06	26.88	12.36	-0.43	n/a

Table 2: Cost breakdown for each case compared in this work. CCC-Ret does not have a reported avoided or captured cost, since it would have a different base case than the other cases in this table.

Although it was briefly mentioned above, the CCC's energy storage feature merits a second mention in this article's economic discussion. In addition to improving other less quantifiable metrics like grid stability, the ability to time-shift the process's parasitic load has significant economic advantages. Although a thorough analysis of the CCC-ES system is outside the purview of this work, earlier thorough analyses have estimated the value of utility-scale energy storage to be around \$24/MWh. This includes the slight capital cost increase for the LNG storage tank that sets CCC-ES apart from the original CCC procedure. (NETL, 2023)

As a result, the COE for CCC-ES is calculated to be \$63.46/MWh, which is just slightly higher than the COE for NETL's non-capture case. The cost of CO₂ avoided is \$6.48 per ton, and the cost of CO₂ captured is approximately \$0.42 per ton. (Baxter et al., 2022) The TS&M costs were slightly higher than the difference between the COE of Case 11 and the CCC-ES case, which is what caused the negative capture cost. The advantages of the CCC-PR case are not assumed in this scenario, and even with the advantages of pollutant removal, the COE would be lower than for a non-capture plant. (NETL, 2023)

Overall, the removal rate efficiency of CCC is an important consideration when evaluating the effectiveness of this technology for reducing greenhouse gas emissions. While the exact removal rate efficiency can vary, CCC has the potential to capture a significant portion of CO₂ emissions from power plants and industrial facilities, making it a promising option for carbon capture and storage.

Like any technology, there are trade-offs associated with using cryogenic carbon capture (CCC) to reduce greenhouse gas emissions. One major trade-off is the cost of implementing CCC. As mentioned earlier, CCC is generally considered to be more expensive than other carbon capture technologies, such as post-combustion and pre-combustion carbon capture. This is because CCC requires significant energy consumption to cool the flue gas to cryogenic temperatures and maintain those temperatures throughout the process. (University of Brighton, 2019) Another trade-off is the energy penalty associated with CCC. The energy consumption required for CCC can result in a reduction in the net energy output of the power plant or industrial facility. This can increase the cost of energy production and may make it less economically viable. In addition, there are potential safety risks associated with handling and storing cryogenic materials, which must be carefully managed to avoid accidents.

Despite these trade-offs, CCC has some advantages over other carbon capture technologies. For example, it can capture CO₂ from flue gas at higher concentrations and in a more concentrated form, which can result in a higher capture efficiency. CCC may also be more suitable for certain industrial applications where high purity CO₂ is required. Overall, the trade-offs associated with CCC must be carefully weighed against the potential benefits of reducing greenhouse gas emissions. Further research and development efforts are needed to improve the

efficiency and cost-effectiveness of CCC, as well as to mitigate potential safety risks. (University of Brighton, 2019)

Removal Rate

The expected removal rate fluctuations for cryogenic carbon capture are likely to depend on a variety of factors, including the availability and demand for CO₂ capture technologies, the cost of implementing the technology, and changes in government policies and regulations. (Cann et al., 2021) In the short term, removal rates may be affected by fluctuations in energy prices and demand for CO₂ capture technologies. If energy prices rise or demand for CO₂ capture technologies increases, then we may see an increase in the deployment of cryogenic carbon capture and an associated increase in removal rates. Conversely, if energy prices fall or demand for CO₂ capture technologies decreases, then we may see a decrease in removal rates.

In the longer term, removal rates may be affected by changes in government policies and regulations, as well as advances in technology that could improve the efficiency and cost-effectiveness of cryogenic carbon capture. If governments continue to support the development and deployment of CO₂ capture technologies, and if research and development efforts continue to yield improvements in cryogenic carbon capture technology, then we may see an increase in removal rates over time. Overall, the expected removal rate fluctuations for cryogenic carbon capture will likely depend on a complex interplay of technological, economic, and policy factors, and it is difficult to predict with certainty how removal rates will change in the coming years (Cann et al., 2021).

All the case studies presented up to this point presuppose a coal-fired power plant's greenfield installation. This is useful for comparisons and instructive, but it does not accurately reflect the current situation. In the current market climate, it is extremely unlikely that any such

plants would be constructed. Most opportunities in the current market would be plant upgrades. As was previously mentioned, CCC is perfect for retrofitting existing utilities and industrial facilities because only electricity and water, and occasionally just electricity, are needed (Hoeger et al., 2021).

Contrarily, amine systems would require more water in addition to a very large steam source, necessitating either significant plant integration or the construction of a new plant to supply the necessary steam and electricity. Additionally, instead of replacing existing plants, retrofitting enables businesses to take advantage of their current infrastructure and capital resources. For instance, most coal-fired power plants in the United States have already recovered their initial capital expenditures, so their COE is primarily determined by operating and fuel costs (Hoeger et al., 2021).

One more CCC retrofit case (CCC-Ret) has been added to demonstrate the financial benefit of retrofitting existing plants. This case assumes that a 670 MW plant exists with the same per-MW operating and fuel costs as the 550 MW plant in Case 11. The capital costs for the current power plant have already been recovered by this 670 MW plant. Then, this plant is retrofitted with CCC, derating it to 550 MW, and 90% of the CO₂ emissions are captured. The cost estimates include the new capital expenditures for the CCC plant and the slightly expanded cooling water system, but due to the technology bolt-on nature, there are no additional capital expenditures for the existing plant (Hoeger et al., 2021).

The COE of this retrofitted plant is \$49.43/MWh, which is less expensive than Case 11's COE of \$58.90/MWh, which is new but non-capture. Even with the capital costs and additional operating costs of the recently installed CCC system, and even though the operating and fuel costs for this plant are higher than those for a new 550 MW plant, the overall cost to the utility is

still lower than Case 11. This demonstrates a crucial point: upgrading an existing plant frequently results in a power plant with CO₂ capture at a lower cost to the utility than developing a new plant without capture. (Hoeger et al., 2021)

The Sharm el-Sheikh Implementation Plan, adopted at COP 27, recognizes that limiting global warming to 1.5 degrees Celsius requires rapid, deep, and sustained reductions in global greenhouse gas emissions of 43% by 2030 compared to 2019. The most recent Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Working Group III Report, as well as an increase in the number of national determined contributions that include CCS, have demonstrated the science and policy behind CCS's role in our transition to low-carbon emissions pathways (IPCC, 2022).

As we continue our full-scale system transition, the Saudi Green Initiative (SGI) announced the deployment of one of the world's largest CCUS hubs at COP 27. The Sharm el-Sheikh Implementation Plan also emphasizes the complex and difficult global geopolitical situation, as well as its impact on the energy, food, and economic dimensions. In this critical decade for implementation, all climate action solutions, including CCS technologies, must be integrated within the broader context of the Sustainable Development Goals (SDGs) (IPCC, 2022).

The IPCC includes CCS as a key mitigation technology and its illustrative mitigation scenarios and the IEA demonstrates CCS accounts for 15-20% of emission reductions towards net zero scenario. Along with other methods of reducing CO₂ emission, the figure below indicates the removal rate of the total CO₂ emission scenario in GtC/yr in the next 50 years.

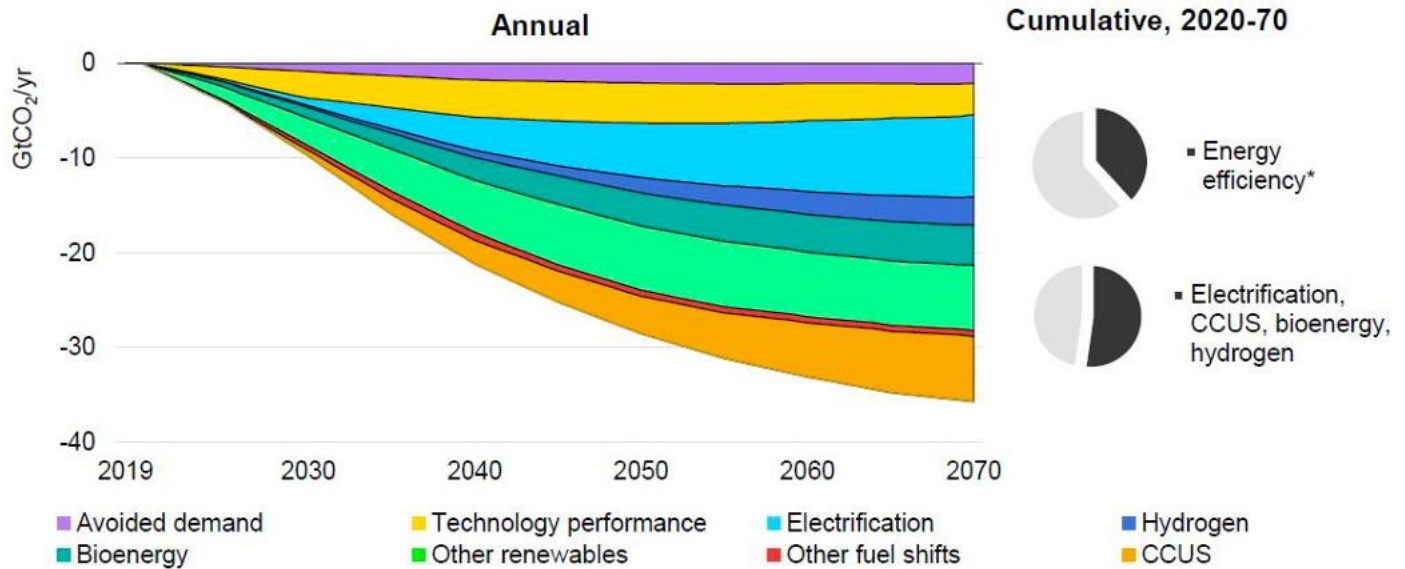


Figure 12: Global energy sector, CO₂ emissions reductions by measure in the sustainable development goals relative to the stated policies scenario, 2020 to 2070 (IEA, 2021)

Conclusion

A promising post-combustion CO₂ removal technique is cryogenic carbon capture (CCC). Comparing this method to established and conventional ones reveal how novel it is. Cryogenic carbon capture has technological and economic advantages, but it is not yet commercially available. So, for this process, a model-based design approach can offer useful information. (Asgharian et al., 2023)

The cryogenic carbon capture process will be discussed in detail in this paper first. The next step is a thorough literature review that concentrates on various approaches for modeling the process at the component level. For each of the significant system components, a more thorough presentation of the modeling techniques thought to be most effective is made. The least complex methods with a tolerable degree of precision for modeling a particular component in the CCC process are advised after these methods' complexity and accuracy levels have been compared.

Potential areas for CCC process modeling and simulation research are also highlighted (Asgharian et al., 2023).

Even though the CCC process is a new technology for reducing CO₂ emissions, various aspects of this process have been modeled and simulated using numerical methods. However, more research is still needed in the following areas: Finding the ideal size for tubes and heat exchangers to reduce the pressure drop without creating a maldistribution phenomenon may be helped by a numerical model that can accurately predict the pressure drop in the process (Asgharian et al., 2023).

Even if the heat exchangers are modeled using the integral method, a dynamic model of the power plant and the CCC process would be beneficial for understanding the transient behavior of the process. Using the computational fluid dynamics method to model the desublimation heat exchanger system can be a very useful way to learn more about the solid-vapor equilibrium of CO₂ mixtures. CCC performs better than competing carbon capture technologies in terms of cost and energy. It is a potential paradigm-shifting technology that provides an answer to the current issues the energy sector is dealing with.

Cryogenic Carbon Capture (CCC) has the potential to be a critical component of a low-cost approach to climate change mitigation. According to economic modeling, using CCS would significantly reduce the cost of meeting the goal of limiting CO₂ concentrations in the atmosphere to less than 2°C. Without CCS, the costs of climate change mitigation would increase by 138%.

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