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Advancements in Carbon Capture Technologies

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ABSTRACT:

The accumulation of greenhouse gases, particularly carbon dioxide (CO₂), is a significant driver of global climate change, resulting in severe environmental consequences such as global warming, extreme weather events, and ecosystem degradation. Addressing this critical issue, the present study investigates cutting-edge carbon capture technologies aimed at reducing CO₂ emissions and aligning with international climate goals, including those outlined in the Paris Agreement.

This research provides a comprehensive analysis of various carbon capture technologies, including Direct Air Capture (DAC), pre-combustion, post-combustion, and oxy-fuel combustion methods. Case studies, such as the Mitsubishi Heavy Industries' Hydrogen Gas Turbine and the HyNet Project in the UK, highlight real-world applications and underscore the transformative potential of integrating these technologies into existing energy and industrial systems. For instance, DAC offers substantial flexibility in placement and significant CO₂ removal capacity but is hindered by high energy demands and current cost barriers. Conversely, innovations in hydrogen-powered turbines and hybrid systems demonstrate the feasibility of transitioning traditional fossil-fuel systems to cleaner energy alternatives.

The study emphasizes the critical need for continuous innovation, increased investment, and supportive policies to enhance the economic and technical feasibility of carbon capture technologies. By integrating technological advancements with real-world applications, Ultimately, it contributes to the global effort to achieve net-zero emissions, ensuring a sustainable future in the face of escalating climate challenges.

KEYWORDS: Reduction of CO₂, Carbon Capture technologies, Net-Zero emissions

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Contents

Acknowledgements	3
Contents	4
Abbreviations	7
1. Introduction	8
1.1 Motivation	8
1.2 Scope of the thesis	9
2. Types of carbon capture technologies	11
2.1 Pre-combustion capture	12
2.2 Post-combustion capture	13
2.3 Oxy-fuel combustion	15
2.4 Direct air capture	20
2.5 Direct ocean capture	22
3. Recent advancements in carbon capture technologies	25
3.1 Metal-organic frameworks	25
3.2 Zeolites	26
3.2.1 Hierarchical zeolites	27
3.3 Ionic liquids	28
3.4 Amine scrubbing	30
3.4.1 Types of amines	30
3.5 Physical solvents	32
3.6 Membrane technologies	35
3.6.1 Polymeric membranes	36
3.6.2 Inorganic membranes	37
3.7 Novel capture processes	38
3.7.1 Cryogenic distillation	39
3.7.2 Electrochemical capture	39
4. Future directions and emerging technologies	41

4.1 Examples of the integration of renewable energy sources with CO ₂ capture technologies	42
4.2 Production of synthetic fuels and chemicals	44
4.3 Enhanced CO ₂ capture techniques	45
4.3.1 CO ₂ utilization and hybrid systems	47
5. Innovations in carbon capture	48
6. Case studies	51
6.1 Mitsubishi heavy industries' hydrogen gas turbine	51
6.2 HyNet Project (North West England, UK)	51
6.3 Rotterdam hydrogen plant (Netherlands)	52
6.4 Petra Nova carbon capture project (Texas, USA)	53
6.5 Mongstad CO ₂ storage project (Norway)	53
6.6 Soletair power (Finland)	53
6.7 Project vesta	55
7. Westenergy's carbon capture project	58
8. Conclusion	60
References	61

Figures

Figure 1. Simplified illustration of Pre-Combustion CO ₂ Capture.(Xin et al., 2020)	13
Figure 2. Simplified illustration of Post-Combustion CO ₂ Capture.(Chao et al., 2021)	15
Figure 3. Working phases of DAC simplified (Beuttler et al., 2019)	21
Figure 4. Climeworks DAC process. (Climeworks, 2023)	43
Figure 5. Blue Planet technology manufacturing process of synthetic limestone aggregate from captured CO ₂ . (Blue Planet, 2023)	44
Figure 6. Process of Captured CO ₂ to fuels by 1pointfive	48
Figure 7. Process of manufacturing Solar food/Solein (https://solarfoods.com/an-elemental-perspective-to-food-production/)	49
Figure 8. <i>Soletair-Power-Company-Profile-25-Sep-2024</i> , n.d.	54
Figure 9. Coastal carbon capture at north sea beach (https://www.vesta.earth/southampton)	56

Tables

Table 1. Summarized types of CCT.	23
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Abbreviations

BECCS	Bioenergy with Carbon Capture and Storage
BETO	Bioenergy Technologies Office
CH ₄	Methane
CO ₂	Carbon Dioxide
DAC	Direct Air Capture
DOC	Direct Ocean Capture
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System GHG Greenhouse gas
H ₂ S	Hydrogen Sulfide
HFCs	Hydrofluorocarbons
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
MHI	Mitsubishi Heavy Industries
N ₂ O	Nitrous oxide
NF ₃	Nitrogen trifluoride
PEM	Proton exchange membrane
PFCs	Perfluorocarbons
PSA	Pressure Swing Adsorption
SF ₆	Sulfur hexafluoride
SMR	Steam Methane Reforming
SOE	Solid Oxide Electrolyzers
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile Organic Compounds

1. Introduction

Climate change is caused by the accumulation of GHG i.e. Greenhouse gases (like carbon dioxide CO₂ methane CH₄, nitrous oxide N₂O, sulfur hexafluoride SF₆, hydrofluorocarbons HFCs, perfluorocarbons PFCs, and nitrogen trifluoride NF₃) in the atmosphere that raises the surface temperature of the planet. (California Air Resources Board, 2024)

This phenomenon of gases causing a rise in the temperature is known as Global Warming, leading to extreme weather events such as sea level rise, ecosystem disruption affecting Human health and causing Economic costs. Reducing these GHG emissions is critical to control climate change and reduce the global temperature rise to 1.5°C as per the Paris Agreement. The Paris agreement is an international treaty endorsed by the UNFCCC that aims to fight against climate change. One of the primary goals is to limit the increasing global temperature by well below 2°C to significantly reduce the extreme aftereffects of climate change on ecosystems, Human health and livelihoods. (Unfccc, n.d.)

1.1 Motivation

Various sectors contribute to emissions and impact the environment, such as power generation, the metals and electronics industries, deforestation, land use changes, burning of fuels, buildings, transportation, industrial processes, agriculture, and waste management. The energy sector is one of the biggest contributors to greenhouse gas emissions. (Banja & Crippa, n.d.)

Industrial carbon capture technologies are designed to remove large quantities of CO₂ from flue gases emitted by power plants, industrial facilities, and other large sources. These technologies can capture CO₂ at a much higher rate compared to natural processes like tree absorption.

Trees absorb CO₂ from the atmosphere through the process of photosynthesis. The amount of CO₂ captured varies based on tree species, age, and environmental conditions.

On average, a mature tree can absorb approximately 22 kg (0.022 metric tons) of CO₂ per year, or 0.00042 metric tons per week. Given this rate, to capture the same amount of CO₂ as an industrial carbon capture technology, we would need a significantly large number of trees. For instance, capturing 30,800 metric tons of CO₂ in one week, as done by a typical carbon capture plant, would require approximately 73.26 million trees. (Massachusetts Institute of Technology, 2024)

Industrial carbon capture technologies can capture thousands of metric tons of CO₂ per week, far surpassing the natural absorption capacity of trees. In addition, these technologies can be implemented at a large scale and integrated into existing industrial processes, making them a more immediate solution to reducing emissions. Industrial processes capture CO₂ directly from concentrated sources, such as flue gases, where CO₂ concentration is higher than in the ambient atmosphere. The CO₂ concentration in flue gases from industrial installations typically ranges between 10% to 15% (100,000 to 150,000 parts per million, ppm). This high concentration makes it feasible for carbon capture technologies to efficiently extract CO₂. The CO₂ concentration in the atmosphere is much lower, currently over 400 ppm (0.04%). This low concentration makes direct air capture more challenging and energy-intensive compared to capturing CO₂ from flue gases. (Wang et al Song, 2020)

1.2 Scope of the thesis

This study explores the progress made in carbon capture technologies, the main objective is to evaluate their potential, scalability, and environmental consequences, as these technologies play a crucial role in meeting global net-zero emission objectives.

The study poses significant research inquiries, including: What are the most innovative advancements in carbon capture? How do these methods rank in terms of efficiency and practicality for large-scale deployment? To tackle these questions, a comprehensive literature review is employed as the primary methodology, analyzing peer-reviewed studies, case analyses, and recent developments within the sector. This approach enables an

in-depth examination of existing technological capabilities while also pinpointing areas where future investigations can make contributions.

2. Types of carbon capture technologies

There are multiple types of Carbon capture technologies (CCT) present which can be categorized based on the stage where the CO₂ is being captured. These methods are quite essential in order to reduce the CO₂ emissions so as to mitigate global warming. As of now the following categories have been categorized:

1. **Pre-Combustion Capture:**
Captures CO₂ before fuel combustion.
2. **Post-Combustion Capture:**
Removes CO₂ after the fuel has been burned.
3. **Oxy-Fuel Combustion:**
Utilizes pure oxygen for combustion, simplifying CO₂ capture.
4. **Direct Air Capture (DAC):**
Extracts CO₂ directly from the atmosphere.
5. **Direct Ocean Capture (DOC):**
Captures CO₂ from seawater, leveraging the ocean's natural absorption properties.

These methods vary in their mechanisms, advantages, and limitations, making it essential to analyse each to understand their potential roles in future carbon management strategies. Each of these categories will be discussed in detail, highlighting their benefits and challenges.

2.1 Pre-combustion capture

Pre-combustion carbon capture is a method used to remove carbon dioxide from fossil fuels before they are burned. This process is often used in power plants and industrial settings where fossil fuels like coal, oil, or natural gas are converted into cleaner forms of energy.

Fossil fuels, such as coal or natural gas, is exposed to a controlled amount of oxygen or steam in a high-temperature environment. This causes the fuel to break down into simpler molecules, resulting in a mixture of gases known as synthesis gas or syngas. This step is known as gasification. (Cao et al., 2020)

Syngas primarily consists of carbon monoxide (CO) and hydrogen (H₂). The carbon monoxide is a carbon-rich compound, while hydrogen is a cleaner fuel. The syngas is then exposed to steam in a process called shift conversion or the water-gas shift reaction. During this reaction, the carbon monoxide (CO) in the syngas reacts with steam (H₂O) to produce more hydrogen (H₂) and carbon dioxide (CO₂) according to reaction (1). (Dubey & Arora, 2022)



This step increases the amount of hydrogen in the gas mixture while converting carbon monoxide into carbon dioxide, which needs to be captured. The CO₂ is then separated from the hydrogen. Several methods can be used to capture. Physical solvents absorb CO₂ at high pressures and then release it when the pressure drops. As illustrated in Figure 1, physical solvents absorb CO₂ at high pressures and then release it when the pressure drops. Chemical solvents like amines react with CO₂ to form a compound that can be separated from the gas mixture and later decomposed to release pure CO₂. Membrane separation technique uses special membranes that allow hydrogen to pass through while blocking CO₂ effectively separating the two gases. (Hua et al., 2023)

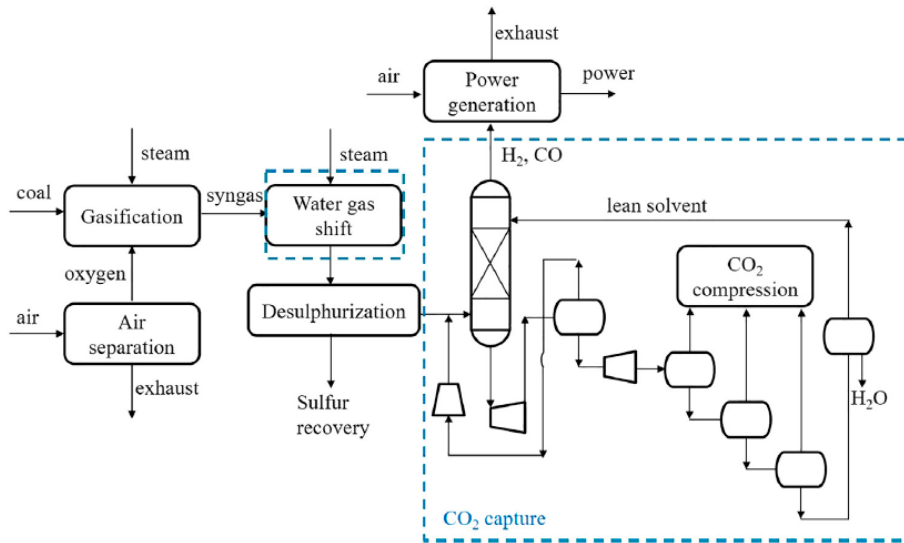


Figure 1. Simplified illustration of Pre-Combustion CO₂ Capture. (Xin et al., 2020)

2.2 Post-combustion capture

Post-combustion carbon capture is designed to remove CO₂ from the flue gases produced by the combustion of fossil fuels. This method is applicable to power plants, especially coal-fired and natural gas plants, as well as various industrial processes. The main advantage of this technology is its ability to be retrofitted onto existing facilities without the need for significant modifications to the original setup. (Dubey & Arora, 2022)

Flue gas is the mixture of gases produced when fossil fuels like coal, natural gas, or oil are burned for energy. This gas mixture typically contains CO₂, nitrogen, oxygen, and other trace gases. (Ababneh et al., 2022). As depicted in Figure 2, the flue gas is directed into an absorber column where it interacts with an aqueous amine solution. Amines selectively absorb CO₂ from the gas mixture, forming a CO₂-rich solvent. This separates the CO₂ from other gases, such as nitrogen (N₂) and oxygen (O₂), which are then released into the atmosphere.

In the separation process of absorption with amine solvent, the flue gas is passed through a chemical process where it meets a liquid solvent, such as an aqueous amine solution. To regenerate the solvent, the CO₂ rich amine solution is heated to release the absorbed CO₂. This step allows to reuse the solvent in the process. The released CO₂ is captured as a concentrated gas, which can then be compressed and stored or utilized in other processes. (Novitsky et al., 2023; Rinprasertmeechai et al., n.d.). Figure 2 illustrates these key stages, showing the flow of flue gases into the absorber and the subsequent solvent regeneration process in the desorber column (Chao et al., 2021).

One of the significant advantages of this technology is that it can be integrated into existing power plants and industrial facilities without requiring major modifications to the current infrastructure. This makes it an attractive option for reducing emissions from already-operating plants. (Rackley, 2017)

The amine-based absorption process is highly effective, capable of capturing up to 90% of the CO₂ from the flue gases. This high efficiency makes it a valuable tool in efforts to reduce greenhouse gas emissions. Moreover, amine-based CO₂ capture is a well-established and commercially available technology. It has been used in various industrial applications for years, which means there is significant expertise and experience in its implementation. (Rinprasertmeechai et al., n.d.)

This technology is applicable to a wide range of industries, not just power generation. It can be used in sectors like cement production, steel manufacturing, and chemical processing, making it a versatile solution for reducing CO₂ emissions. (Vega et al., 2014)

One of the primary drawbacks of this technology is its energy intensity. The process of regenerating the solvent (releasing the absorbed CO₂) and compressing the CO₂ for storage or transportation requires a significant amount of energy. This can reduce the overall efficiency of the power plant or industrial facility where the technology is implemented. (Figueroa et al., 2008)

simplifying the capture process and making it more efficient. Additionally, since combustion occurs without nitrogen, the production of nitrogen oxides (NO_x), a harmful pollutant, is significantly reduced. (Ravichandran et al., 2024)

Oxy-fuel combustion is seen as a promising technology for reducing CO₂ emissions, especially in industries that are hard to decarbonize, such as steel and cement production. However, widespread adoption will depend on overcoming the challenges of high costs and system complexity. (Wu et al., 2018)

Advances in oxygen production technology, such as the development of more efficient air separation units, could make this technology more economically viable in the future. There are several methods to remove CO₂ from the flue gases, and these include improved cryogenic air separation, advanced membrane technology, adsorption technologies, and electrochemical oxygen production. (Hamayun et al., 2020)

Zeolites are crystalline aluminosilicates with a network of interconnected tetrahedral units, creating a porous structure with well-defined channels and cavities. This structure is particularly beneficial for gas adsorption. The regular and predictable pore structure of zeolites allows for efficient gas adsorption. Their large surface area facilitates the capture of significant amounts of CO₂. Zeolites can be engineered to selectively adsorb CO₂ over other gases. This selectivity is crucial for applications such as separating CO₂ from flue gases or ambient air.

They act as molecular sieves allowing them to selectively adsorb molecules based on size and polarity. By altering the dimensions of the pores, researchers can optimize the zeolites for the specific size and characteristics of CO₂ molecules. This customization improves the efficiency and capacity of CO₂ capture. (Tao et al., 2024)

Surface chemistry plays a crucial role in the adsorption of CO₂. Innovations include incorporating functional groups that enhance CO₂ interaction. For instance, adding amine

groups or other CO₂-affinitive compounds to the zeolite surface increases its capacity for CO₂ capture through chemical interactions. Zeolites are known for their high thermal stability and resistance to degradation, which makes them suitable for harsh industrial environments. This stability ensures that zeolites maintain their performance even at high temperatures or under aggressive conditions, such as those found in industrial processes. Zeolites are used to capture CO₂ from industrial emissions, including flue gases from power plants and chemical processes. Their ability to selectively adsorb CO₂ makes them effective in reducing greenhouse gas emissions. Zeolites can separate CO₂ from other gases in processes such as natural gas purification or air separation. This separation is valuable in producing high-purity CO₂ for subsequent utilization or storage. They are often used in combination with other materials or technologies to enhance their performance. For example, they can be integrated into hybrid systems with Metal-Organic Frameworks (MOFs) or used in conjunction with pressure swing adsorption (PSA) systems for more efficient CO₂ capture. (Bahmanzadegan & Ghaemi, 2024)

The production and modification of zeolites can be costly, and scaling up their use for large-scale CCU applications remains a challenge. Research is ongoing to develop cost-effective synthesis methods and to enhance the economic viability of zeolite-based technologies. While zeolites are generally resistant to thermal degradation, ensuring their long-term stability and performance under varying operational conditions is crucial for practical applications. (Rubin et al., 2015)

Advances in zeolite design aim to improve their durability and extend their operational life. Researchers are developing hierarchical zeolites with multiple levels of porosity, which enhances their gas adsorption properties and allows for better CO₂ capture and separation performance. (Boer et al., 2023)

Combining zeolites with other materials, such as polymers or nanoparticles, can create composites with enhanced properties. These composites can offer improved CO₂ capture capacities and better performance in challenging conditions. Innovations in

characterization techniques, such as advanced microscopy and spectroscopy, allow for a more detailed understanding of zeolite structures and interactions. This knowledge helps in the design of more efficient zeolite materials for CO₂ capture. The environmental impact of zeolite synthesis and disposal needs to be addressed. Developing more sustainable production methods and ensuring environmentally friendly disposal or recycling options are important considerations for the future. (Tao et al., 2024)

By using pure oxygen, the resulting flue gas is rich in CO₂ (up to 95%) making it easier and more cost-effective to capture and store the CO₂. The absence of nitrogen in the combustion process significantly reduces the formation of nitrogen oxides which are harmful pollutants contributing to smog and acid rain. Since the CO₂ is more concentrated, the capture process requires less energy compared to other methods like post-combustion capture. (IEA , 2020)

Producing pure oxygen for combustion is energy-intensive and expensive, making this technology costly to implement on a large scale. Also, retrofitting existing power plants or industrial facilities with oxy-fuel technology requires substantial modifications, including oxygen production infrastructure and changes to the combustion systems.

The energy required for oxygen production and CO₂ compression reduces the efficiency of the power plant, leading to an energy penalty. (Lawrence, M., 2021)

Cryogenic distillation is an improved technique of cryogenic air separation. This is the most common method of producing pure oxygen, which involves cooling air to extremely low temperatures until it liquefies. The different gases in the air (nitrogen, oxygen, argon) are then separated based on their boiling points. Recent advancements have focused on enhancing the efficiency of this process by optimizing energy use and increasing the purity of the oxygen produced. Innovative designs integrate heat recovery systems within the cryogenic process, reducing the overall energy consumption. (Kiebach et al., 2022)

In the membrane-based air separation, membranes can selectively allow oxygen to pass through while blocking other gases. Advances in materials science have led to the development of more efficient and selective membranes, which can separate oxygen from air at a lower energy cost compared to traditional methods. Combining membranes with cryogenic processes can improve efficiency and reduce costs by using the strengths of both technologies (Kiebach et al., 2022).

The Pressure Swing Adsorption (PSA) separates oxygen from air using materials that adsorb nitrogen under high pressure, leaving oxygen behind. Advances in the development of more selective adsorbents and more efficient PSA cycles have reduced energy consumption and improved oxygen yield. The Vacuum Swing Adsorption is like PSA but operates under a vacuum which can further reduce energy requirements. Improvements in adsorbent materials and system designs have enhanced the efficiency of VSA for oxygen production (Banaszkiewicz et al., 2014).

Solid Oxide Electrolyzers use electricity to split oxygen from air or water. Advances in electrolyzer design and materials are increasing the efficiency of oxygen production, which could be integrated with renewable energy sources to produce low-cost, low-carbon oxygen. Solid oxide electrolyzers can also be used for separating CO₂ through a process called CO₂ electrolysis. In this process, CO₂ is fed into the electrolyzer, and the high temperature causes the CO₂ to break down into oxygen & carbon monoxide. The carbon monoxide produced can then be used to make synthetic fuels, like methanol or hydrocarbons, in industrial processes such as the Fischer-Tropsch synthesis. This makes the process efficient, as it not only reduces CO₂ emissions but also turns the captured CO₂ into useful products. In addition to producing oxygen, SOEs are versatile because they can help convert CO₂ into valuable chemicals or fuels, making them an important tool for carbon recycling. This process supports industries aiming for net-zero emissions by capturing and reusing CO₂ instead of letting it enter the atmosphere. (Sánchez-Luján et al., 2024)

2.4 Direct air capture

DAC is designed to capture CO₂ directly from the air. The process involves pulling ambient air into a DAC system where it is exposed to chemical agents designed to capture CO₂. As CO₂ is a key factor in global warming, it is essential to reduce its concentration in the air to mitigate the adverse effects of climate change.

Unlike traditional carbon capture methods that focus on emissions from power plants or industrial facilities, DAC targets the CO₂ that is already dispersed in the atmosphere. This makes it a versatile solution that can be deployed in various locations. The key advantage of DAC is its ability to achieve negative emissions, meaning it not only prevents further CO₂ emissions but actively removes CO₂ from the atmosphere. As illustrated in Figure 3, DAC operates through distinct working phases, including air intake, CO₂ capture, and regeneration of the capture material. In the first phase, ambient air is drawn into the DAC system. The air is passed over solid or liquid sorbents that bind CO₂ molecules, effectively separating them from other gases. Next, the CO₂-enriched sorbent undergoes a regeneration process, which involves heating or applying pressure to release the captured CO₂. The released CO₂ is then collected as a concentrated stream, ready for storage or utilization in various industrial applications. Picture 3 visually simplifies these stages, showing how air flows through the system, interacts with sorbents, and yields purified CO₂ for storage or reuse (Beuttler et al., 2019).

This feature makes DAC essential for achieving net-zero emissions targets. When combined with other carbon reduction strategies, DAC offers a scalable solution for reducing the concentration of CO₂ in the atmosphere. As research continues, innovations in materials, energy efficiency, and cost reduction are expected to enhance DAC's viability and widespread use in combating climate change. (Abdullatif et al., 2023)

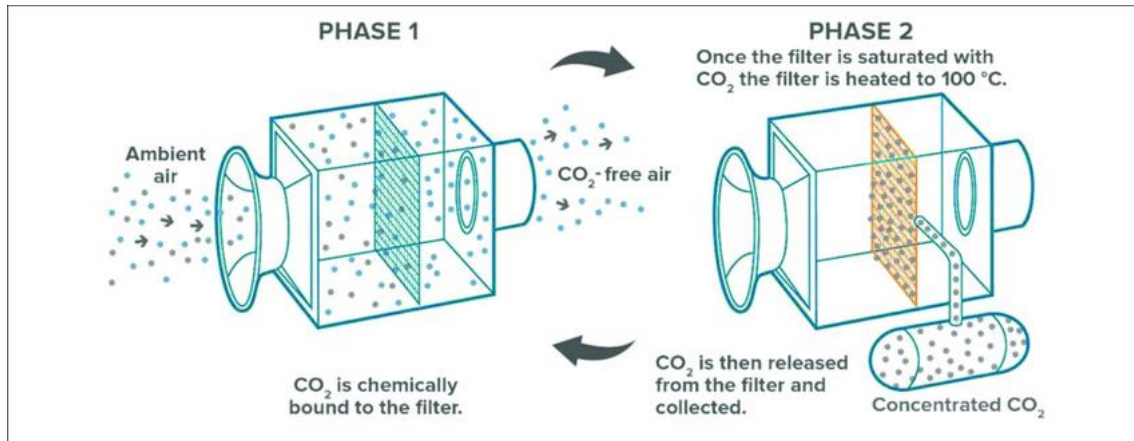


Figure 3. Working phases of DAC simplified (Beuttler et al., 2019).

DAC is based on chemical absorption using liquid solvents, such as amine solutions, to capture CO₂ from the air. The CO₂ molecules chemically bind to the solvent, creating a compound that can later be processed to release the CO₂. Solid materials, known as sorbents (like metal-organic frameworks or zeolites), are used to capture CO₂. These sorbents have surfaces that attract and hold CO₂ molecules. After capturing the CO₂, the sorbent or solvent must be regenerated, which means the CO₂ needs to be released so the capturing material can be reused. This is done by heating the material or reducing the pressure causing the CO₂ to detach and be collected for storage or use. In liquid solvent systems, liquid chemicals absorb CO₂ from the air. The liquid is then heated, causing it to release the CO₂. Solid sorbent systems on the other hand use solid materials that adsorb CO₂. The CO₂ is later released by heating the material or applying a vacuum. Electrochemical Systems are yet another system that use electricity to capture and release CO₂ through chemical reactions. DAC is a very versatile technology and can be installed almost anywhere, as it does not require being close to CO₂ emission sources like power plants. Furthermore, this technology can be scaled up to capture large amounts of CO₂, making it a potential key player in efforts to reduce atmospheric CO₂ levels. It has been argued that DAC is essential for achieving net-zero emissions, as it can remove CO₂ that is already in the atmosphere. As a downside of the technology, it has to be stated that the process of capturing and releasing CO₂ requires a lot of energy, particularly during the regeneration phase. Also, DAC is currently expensive, with costs ranging from \$100

to \$600 per ton of CO₂ captured, making it more costly than other carbon capture methods. Significant infrastructure is needed to capture, transport, and store or use the CO₂. (Abdullatif et al., 2023; Erans et al., 2022)

2.5 Direct ocean capture

Direct Ocean Capture is a fairly new technology focused on capturing CO₂ from seawater. Since the ocean contains much higher levels of CO₂ compared to the air—around 150 times more—this approach could be more efficient than capturing CO₂ from the atmosphere. The idea behind DOC is to leverage this high concentration to remove CO₂ from the ocean, which also helps reduce CO₂ in the atmosphere due to the natural exchange between air and sea. (Aleta et al., 2023)

While the technology is still in its infancy, it holds significant promise due to the high CO₂ concentration in seawater and the additional benefits of mitigating ocean acidification. Ocean acidification occurs as the oceans absorb a massive portion of the excess atmospheric CO₂, leading to chemical changes in seawater. This process reduces pH levels and interferes with the availability of carbonate ions, which are essential for marine organisms like corals and shellfish to build their calcium carbonate structures. The decline in ocean pH negatively impacts marine biodiversity, particularly affecting species that rely on these carbonate structures. Over time, this can disrupt entire marine ecosystems and have severe implications for global fisheries, food security, and coastal economies. In combination with other stressors like ocean warming and deoxygenation, ocean acidification exacerbates the vulnerability of marine organisms, further stressing the need for mitigation strategies like CO₂ capture technologies to reduce emissions. (Tai et al., 2021)

However, challenges such as high energy demand, technological maturity, and potential environmental impacts need to be addressed before DOC can be implemented on a large scale. As research progresses, advancements in these areas could make DOC a vital tool in the global effort to reduce carbon emissions and combat climate change.

The main technique used in DOC is electrodialysis, which uses electric fields to pull CO₂ out of seawater. The seawater is put through special membranes influenced by an electric field. These membranes are designed to selectively allow CO₂ to pass through while blocking other substances. The CO₂ is separated from other gases and salts in the water. Chemicals are added to the separated CO₂, causing it to form solid carbonates. These solids can be easily collected and processed for storage or use in other industries.

Seawater contains a much higher concentration of CO₂ compared to the air, which can make DOC more efficient in capturing carbon. DOC can be implemented offshore or near coastlines, reducing the need for land, which is a significant limitation in land-based carbon capture technologies. By removing CO₂ from seawater, DOC could also help mitigate ocean acidification, a serious problem that threatens marine life and ecosystems. Thus, DOC presents additional environmental benefits. DOC is still in its early development stages and is not as established as other carbon capture technologies like DAC or post-combustion capture. The process requires significant energy, especially for the electrochemical processes involved, which could impact its overall efficiency and cost-effectiveness. Also, there are concerns about the potential impacts on marine ecosystems, as large-scale DOC operations could alter the chemistry of the ocean and affect marine life. (Niffenegger et al., 2024)

Table 1. Summarized types of CCT.

Technology	Advantages	Disadvantages	Comparisons
Post-Combustion Carbon Capture	<ul style="list-style-type: none"> - Can be retrofitted to existing plants - Well-understood technology - Scalable 	<ul style="list-style-type: none"> - High energy consumption - Expensive operation and maintenance 	<ul style="list-style-type: none"> - More mature than pre-combustion but less efficient

		<ul style="list-style-type: none"> - Requires large physical space 	<ul style="list-style-type: none"> - Preferred for retrofitting existing coal or gas plants
Pre-Combustion Carbon Capture	<ul style="list-style-type: none"> - Carbon Capture - Higher efficiency compared to post-combustion - Lower energy requirement 	<ul style="list-style-type: none"> - High initial capital cost - Complex technology, requiring significant changes to existing infrastructure 	<ul style="list-style-type: none"> - More suitable for new plants - Provides cleaner energy with fewer emissions upfront compared to post-combustion
Oxy-Fuel Combustion	<ul style="list-style-type: none"> - Produces a highly concentrated CO₂ stream, making capture easier - Reduces other emissions 	<ul style="list-style-type: none"> - Requires pure oxygen production, which is energy-intensive - High costs associated with oxygen production 	<ul style="list-style-type: none"> - Effective in reducing NO_x emissions compared to pre and post-combustion - Suitable for retrofitting with new boiler designs
Direct Air Capture (DAC)	<ul style="list-style-type: none"> - Can be deployed anywhere - Captures CO₂ directly from the atmosphere 	<ul style="list-style-type: none"> - Extremely energy-intensive - Currently very costly - Limited scalability 	<ul style="list-style-type: none"> - Suitable for addressing dispersed emissions, unlike point-source capture in other technologies
Direct Ocean Capture (DOC)	<ul style="list-style-type: none"> - Large storage capacity in oceans - Can reduce ocean acidification 	<ul style="list-style-type: none"> - Potential ecological impact on marine life - High energy consumption - Still in early stages of development 	<ul style="list-style-type: none"> - Unlike DAC, targets CO₂ dissolved in seawater - Potential for integration with ocean-based renewable energy sources

3. Recent advancements in carbon capture technologies

The urgency to mitigate climate change has driven extensive research into innovative carbon capture technologies aimed at reducing atmospheric CO₂ levels and mitigating greenhouse gas emissions. Traditional carbon capture methods, while effective, face challenges related to efficiency, scalability, and cost, prompting the development of new materials and techniques. Among these advancements, novel capture materials such as Metal-Organic Frameworks (MOFs), zeolites, and hybrid systems have emerged as game-changers due to their exceptional properties and versatility.

This chapter explores recent progress in materials and techniques for carbon capture, emphasizing their potential to transform industrial applications and atmospheric CO₂ reduction. MOFs have attracted attention for their high surface area, selective adsorption, and chemical flexibility, which enable them to capture and convert CO₂ into valuable products such as methanol and hydrocarbons. Additionally, innovations in catalytic processes and hybrid systems combining multiple materials are opening new pathways for integrating carbon capture with industrial processes, paving the way for more efficient and economically viable solutions. (Elhenawy et al., 2020)

3.1 Metal-organic frameworks

Metal-Organic Frameworks (MOFs) are innovative materials used in carbon capture technologies, offering exceptional efficiency in capturing CO₂ from industrial flue gases and ambient air. Their high selectivity and adsorption capacity make them ideal for mitigating greenhouse gas emissions. MOFs are especially promising because of their unique crystalline structure, which provides an extremely high surface area for gas adsorption, enabling them to store significant volumes of CO₂ relative to their weight. (Farha et al., 2020)

One of the key advantages of MOFs is their tunable porosity, which allows for the customization of pore sizes to selectively adsorb CO₂ over other gases like nitrogen (N₂) or methane (CH₄). This selectivity is further enhanced by functionalizing MOFs with amine

groups or other CO₂-affinitive chemicals. Amines interact with CO₂ to form stable chemical bonds, such as carbamate or bicarbonate species, which not only improve capture capacity but also expand the operational temperature range of the material. (Sumida et al., 2021)

MOFs are not only effective in capturing CO₂ but also play a role in its utilization. After capturing CO₂ MOFs can act as catalysts or as support structures in chemical reactions that convert CO₂ into valuable products like methanol, ethylene, or other hydrocarbons. This integration into industrial processes enhances both efficiency and sustainability. MOFs are being explored for applications in gas separation units and chemical production facilities, where they simultaneously capture and use CO₂ as a feedstock for new materials or fuels. (D'Alessandro et al., 2021)

Functionalizing MOFs with CO₂-affinitive groups increases their efficiency, while innovations in manufacturing processes have made these materials more adaptable to real-world applications. These developments position MOFs as a critical component in scalable carbon capture technologies that align with global climate goals.

3.2 Zeolites

Zeolites are crystalline aluminosilicates with a unique porous structure formed by interconnected tetrahedral units. This structure features well-defined channels and cavities, making zeolites highly effective for gas adsorption, particularly for capturing CO₂. The large surface area of zeolites facilitates the adsorption of significant amounts of CO₂ while their regular and predictable pore geometry allows for the selective adsorption of molecules based on size and polarity. (Choi et al., 2009)

One of the key advantages of zeolites is their tunable nature. Researchers can modify the dimensions of the pores to optimize them specifically for CO₂ capture, improving both efficiency and capacity. Additionally, surface chemistry enhancements, such as

incorporating amine groups or other CO₂-affinitive compounds, further boost their ability to adsorb CO₂ through chemical interactions. (Li et al., 2021)

These modifications make zeolites versatile and highly effective in separating CO₂ from industrial emissions, such as flue gases, or during processes like natural gas purification and air separation. Zeolites are particularly valued for their thermal stability and resistance to degradation, enabling them to maintain performance under harsh industrial conditions, including high temperatures. This robustness ensures their suitability for use in power plants, chemical facilities, and other industrial applications where CO₂ capture is critical (Rajagopalan et al., 2020). Furthermore, zeolites can work in tandem with other materials, such as Metal-Organic Frameworks (MOFs), or be integrated into Pressure Swing Adsorption (PSA) systems to enhance overall efficiency in carbon capture systems. Despite their advantages, the production and modification of zeolites can be costly, posing challenges for large-scale carbon capture and utilization (CCU) applications. Current research is focused on developing cost-effective synthesis methods and improving the economic viability of zeolite-based technologies. Ensuring long-term stability under varying operational conditions is also a key area of innovation to extend their durability and operational life. (Wang et al Song, 2020)

3.2.1 Hierarchical zeolites

Zeolite research is advancing with innovative approaches to improve their performance and applicability in carbon capture technologies. One such development is the creation of hierarchical zeolites, which feature multiple levels of porosity. These materials combine micropores, mesopores, and macropores to enhance their gas adsorption properties, allowing for better CO₂ capture and separation. The hierarchical structure improves accessibility to active sites, enabling more efficient interaction between CO₂ molecules and the zeolite material. (Li et al., 2021)

Zeolite-Based Composites are another breakthrough in this field. By combining zeolites with polymers, nanoparticles, or other functional materials, researchers are creating

composites with enhanced mechanical stability, CO₂ capture capacity, and improved performance under challenging conditions such as high humidity or elevated temperatures. These composites leverage the complementary strengths of zeolites and other materials to expand their industrial applications. (Rajagopalan et al., 2020)

Advancements in characterization techniques, including high-resolution microscopy and spectroscopy, are providing deeper insights into the structure and behaviour of zeolites. These techniques allow researchers to examine zeolite porosity, surface interactions, and molecular adsorption mechanisms with greater precision. Such insights are essential for designing zeolites optimized for specific CO₂ capture applications. (Wang et al Song, 2020)

However, the environmental impact of zeolite production and disposal must also be addressed. The synthesis of zeolites often involves energy-intensive processes and the use of chemicals that may have environmental consequences. To ensure their long-term sustainability, researchers are focusing on developing more eco-friendly production methods, such as using waste materials as precursors, and exploring options for recycling or safely disposing of used zeolite materials. (Choi et al., 2009)

3.3 Ionic liquids

Ionic liquids are a class of salts that remain liquid at or near room temperature, composed of anions and cations with low lattice energy, which accounts for their low melting points. These unique properties make ionic liquids highly attractive for carbon capture applications. Unlike traditional solvents, ionic liquids have negligible vapor pressure, which minimizes the risk of loss to the atmosphere and reduces environmental concerns associated with volatile organic compounds (VOCs). Their high thermal stability makes them suitable for the demanding conditions of industrial CO₂ capture processes. (Zhang et al., 2021)

Ionic liquids can capture CO₂ through physical dissolution or chemical reactions, depending on their composition. By selecting appropriate anions and cations, researchers can tailor ionic liquids for high CO₂ solubility and selectivity. Amine-functionalized ionic liquids, for instance, chemically react with CO₂ to form stable carbamate species, enhancing capture efficiency even at low partial pressures. (Karadas et al., 2020)

Recent advancements include task-specific ionic liquids designed for specific CO₂ capture applications. These ILs have tailored properties such as optimized absorption capacity and faster regeneration rates, making them highly effective for use in industrial systems or direct air capture technologies. (Brennecke & Maginn, 2020)

The porous structure of solid supports improves the diffusion of CO₂ into the ionic liquid, increasing overall capture efficiency. Solid supports prevent the leaching and degradation of ionic liquids, prolonging the system's operational life. During regeneration, the solid support assists in thermal management, reducing the energy required to release CO₂. (Dong et al., 2021). Such hybrid systems are particularly promising for large-scale applications, as they improve cost-effectiveness and operational stability compared to standalone ionic liquid systems.

Captured CO₂ can be utilized as a feedstock for producing valuable products like methanol, urea, or synthetic fuels. Ionic liquids play a dual role in this context, acting as solvents for CO₂ and catalysts in its chemical conversion. For instance, they facilitate the electrochemical reduction of CO₂ into hydrocarbons or alcohols, offering pathways to integrate carbon capture with utilization. (Sun et al., 2022)

The synthesis of ionic liquids remains expensive, which limits their widespread adoption. Developing cost-effective production methods and recycling strategies is essential for large-scale applications. While ionic liquids are low in volatility, their long-term environmental effects, including disposal and degradation products, need further evaluation. Current regeneration processes often require high energy inputs. (Hu et al., 2024)

3.4 Amine scrubbing

Amine scrubbing is one of the most widely used and established methods for CO₂ capture, particularly from flue gases generated by power plants and industrial facilities. It involves the use of aqueous solutions of amines chemical compounds that react with CO₂ in gas streams to form stable compounds. This technology is recognized for its efficiency and reliability, making it a benchmark for carbon capture processes. (Wang et al., 2021)

The amine scrubbing process comprises two main stages: absorption and regeneration. In the absorption, the flue gas is passed through an absorber column where it comes into contact with an aqueous amine solution. CO₂ reacts with the amine, forming stable compounds such as carbamates or bicarbonates. The type of compound formed depends on the specific amine used. This step efficiently separates CO₂ from the gas stream, with the treated gas (primarily nitrogen and oxygen) released into the atmosphere. (Zhao et al., 2022)

In the regeneration, the CO₂-rich amine solution is sent to a desorber (or stripper) column, where it is heated. The heat breaks the chemical bonds between the amine and CO₂ releasing the CO₂ as a concentrated gas for storage or utilization. The regenerated amine solution is then recirculated back to the absorber for reuse, making the process cyclic and efficient. (Zhao et al., 2022)

3.4.1 Types of amines

Amine scrubbing continues to be a leading method for CO₂ capture due to its high efficiency, flexibility, and broad applicability across industries. Recent innovations in amine formulations and system integrations have addressed longstanding challenges, such as energy consumption, solvent degradation, and operational costs, making the technology more effective and sustainable.

Blended amines combine the unique properties of different amines to optimize the CO₂ capture process. Blending MEA with MDEA leverages the high reactivity of MEA and the lower regeneration energy of MDEA. This combination enhances CO₂ absorption kinetics while reducing energy demand for solvent regeneration (Mondal et al., 2021). Blends are also tailored to perform efficiently under varying temperatures and pressures, making them suitable for diverse industrial applications, such as flue gas treatment and natural gas sweetening (Wang et al., 2021). Blended amines exhibit reduced degradation rates and better resistance to oxidative and thermal breakdown compared to single-component solutions. This reduces the frequency of solvent replacement, leading to lower operational costs over time.

Hindered amines are designed with bulky molecular structures that resist side reactions with acidic gases or impurities in flue gas streams. The bulky substituents in hindered amines reduce the formation of harmful byproducts, such as heat-stable salts, which can corrode equipment and require expensive solvent disposal or regeneration (Zhao et al., 2022). These amines are more resistant to oxidative degradation, particularly in high-temperature environments, extending the solvent's operational life and reducing waste (IEAGHG, 2021).

New amines are engineered to release CO₂ at lower temperatures, significantly reducing the energy required for the regeneration phase. This innovation addresses one of the biggest cost drivers in traditional amine scrubbing systems (Zheng et al., 2022). Additives are incorporated into amine solutions to inhibit solvent breakdown and minimize the impact of impurities, further enhancing efficiency and reducing environmental risks. (Jorgensen et al., 2022) Amine scrubbing remains the gold standard for post-combustion CO₂ capture in coal and natural gas power plants. Advanced amines improve efficiency and allow for retrofitting into existing infrastructure (Wang et al., 2021).

Selective amines like MDEA are widely used for natural gas sweetening, where they remove both CO₂ and hydrogen sulfide (H₂S) from gas streams. Some modern amines are being adapted for DAC systems, where their selectivity and ability to perform under low CO₂ partial pressures are critical for capturing ambient CO₂.

Blended and hindered amines are more selective for CO₂ reducing the capture of unwanted impurities and improving purity in the captured gas stream. Lower regeneration temperatures and minimized degradation result in reduced energy costs and longer operational lifespans for solvents. These formulations are versatile and compatible with existing capture systems, ensuring cost-effective retrofitting and integration into various industries. Focus on biodegradable amines and recycling methods to minimize the environmental impact of solvent disposal. Large-scale integration and hybrid technologies, such as combining amines with membranes or solid sorbents, are being developed to meet increasing demand for carbon capture systems. (Brennecke & Maginn, 2020)

3.5 Physical solvents

Physical solvents are essential in the realm of carbon capture, particularly in scenarios where high-pressure conditions dominate, such as in pre-combustion systems and natural gas processing. Unlike chemical solvents, which rely on chemical reactions to bond with CO₂ physical solvents leverage the inherent solubility of CO₂ in the liquid phase. This mechanism makes physical solvents highly energy-efficient, especially during the regeneration phase, as no chemical bonds are broken. Their specific advantages make them indispensable in handling gas streams with high CO₂ concentrations or mixed gas compositions. (NETL, 2022; Smith et al., 2022).

One prominent physical solvent is Selexol, primarily composed of dimethyl ethers of polyethylene glycol. Selexol is highly effective under elevated pressures and low temperatures, conditions common in pre-combustion carbon capture and natural gas processing. This solvent captures CO₂ and other acidic gases such as hydrogen sulfide (H₂S) by dissolving them into its liquid matrix. The regeneration process for Selexol is particularly

advantageous because it involves reducing pressure rather than employing high temperatures, thereby lowering energy consumption significantly. Selexol's ability to simultaneously remove multiple impurities, including H₂S and CO₂ makes it an ideal candidate for industrial applications like syngas cleanup and coal gasification plants. (Mondal et al., 2021)

Similarly, Rectisol, a mixture of methanol and water, offers unique benefits due to its effectiveness at cryogenic temperatures. In the Rectisol process, CO₂ is absorbed in methanol, leveraging its high solubility at low temperatures. Rectisol excels under high-pressure environments, often found in syngas and hydrogen production facilities. Its ability to selectively remove CO₂ and other acidic gases with high purity levels positions it as a critical component in industrial gas separation. Furthermore, the high solubility of CO₂ in methanol allows for more targeted separation, which is especially valuable in applications requiring ultra-pure gas outputs, such as ammonia production or fuel synthesis. (Zhao et al., 2022)

The advantages of physical solvents extend beyond their selectivity and performance under high pressure. Their reliance on physical solubility rather than chemical bonding results in reduced energy requirements for regeneration, as the process typically involves pressure or temperature adjustments rather than energy-intensive chemical reactions. Moreover, physical solvents demonstrate high selectivity, ensuring that CO₂ can be captured with minimal interference from other gases present in the stream. These properties are particularly advantageous in large-scale industrial operations, where efficiency and cost-effectiveness are paramount. (Wang et al., 2021)

Physical solvents, despite their advantages in CO₂ capture, face several challenges that limit their broader applicability. One notable limitation is their reduced efficiency at low CO₂ partial pressures, which constrains their use in applications like direct air capture, where CO₂ concentrations are significantly lower. Another drawback is the requirement for cryogenic temperatures in processes like the Rectisol system. Operating under such

extreme conditions increases complexity and operational costs, making these systems less feasible for some industrial applications. (Wang et al., 2021; Zhao et al., 2022)

To address these challenges, ongoing research is focusing on improving the absorption capacity and temperature tolerance of physical solvents. Scientists are exploring novel formulations and system designs to enhance their performance under a wider range of conditions. A promising direction involves integrating physical solvents into hybrid systems that combine membranes or adsorption technologies. These hybrid systems aim to capitalize on the strengths of multiple approaches, offering enhanced operational flexibility and cost-effectiveness while maintaining the high selectivity and efficiency of physical solvents. (Mondal et al., 2021)

Despite these challenges, physical solvents such as Selexol and Rectisol remain integral to CO₂ capture technologies, particularly in high-pressure environments like natural gas sweetening, syngas purification, and pre-combustion carbon capture. Their ability to deliver high-purity outputs ensures their continued relevance in industrial processes where stringent separation requirements exist. With advancements in solvent formulation, hybrid integration, and process optimization, physical solvents are expected to play an increasingly significant role in scalable and efficient carbon capture solutions, supporting global efforts to mitigate greenhouse gas emissions. (Brennecke & Maginn, 2020)

Hybrid systems integrating physical solvents with chemical absorption methods represent an innovative approach to enhancing CO₂ capture efficiency across diverse industrial applications. These systems combine the strengths of physical solvents, such as energy efficiency and high selectivity under high-pressure conditions, with the robust CO₂ absorption capacity of chemical solvents like amines. By doing so, they can operate effectively across varying temperatures and pressures, offering greater adaptability to different industrial scenarios. For instance, blending physical solvents such as Selexol with amine solutions can expand operational flexibility and improve overall capture efficiency. (Wang et al., 2021)

A critical area of focus in hybrid system development is improving the stability of physical solvents to withstand harsh operational conditions. Researchers are exploring advanced formulations to minimize solvent degradation and loss, enhancing both performance and sustainability. Innovations also target the regeneration phase, with techniques like improved heat integration and pressure swing methods reducing energy consumption and operational costs. Efficient solvent recovery and recycling processes are also being developed to minimize waste and lower replacement costs, making these systems more sustainable and economically viable. (Mondal et al., 2021; Zhao et al., 2022)

Physical solvents, particularly Selexol and Rectisol, play a pivotal role in industrial gas processing, including the separation of CO₂ from natural gas or hydrogen streams. In hydrogen production, these solvents enhance hydrogen purity while simultaneously reducing CO₂ emissions. Additionally, they are employed in enhanced oil recovery (EOR) processes, where CO₂ is injected into oil fields to increase oil extraction rates, demonstrating their utility in multiple sectors. (Brennecke & Maginn, 2020)

Beyond industrial applications, physical solvents are being considered for use in direct air capture (DAC) systems, particularly those operating under high-pressure conditions. By capturing CO₂ from ambient air, hybrid systems contribute to climate change mitigation efforts by addressing diffuse CO₂ emissions. These advancements illustrate the versatility of physical solvents in adapting to evolving industrial and environmental demands, showcasing their potential to support large-scale carbon capture and storage initiatives. (Zheng et al., 2022)

3.6 Membrane technologies

Membrane technologies are an innovative and increasingly significant approach to CO₂ capture and separation, offering a versatile and energy-efficient alternative to traditional methods. These technologies employ semi-permeable materials engineered to selectively separate CO₂ from other gases based on their molecular properties, such as size,

solubility, and diffusivity. By exploiting these properties, membranes enable efficient gas separation processes across a wide range of industrial applications, including natural gas purification, flue gas treatment, and DAC.

3.6.1 Polymeric membranes

Membrane technologies, particularly polymeric membranes, have emerged as a promising solution for CO₂ separation and capture, contributing significantly to efforts to reduce greenhouse gas emissions. These membranes are crafted from advanced polymers, including polysulfone, polyimide, and polycarbonate, designed to selectively allow CO₂ to pass through while blocking other gases like nitrogen, oxygen, or methane. This selective permeability is achieved by engineering the chemical and physical properties of the membrane, allowing CO₂ to diffuse faster than other gases. (Shah et al., 2023)

The two primary types of polymeric membranes are dense membranes and membrane modules. Dense membranes feature a continuous polymer layer, separating gases based on differences in diffusion rates, making them suitable for applications demanding high selectivity. Membrane modules, on the other hand, increase the available surface area for gas separation, enhancing efficiency and enabling compact designs. Recent innovations have incorporated nano-fillers such as zeolites, carbon nanotubes, and MOFs into the polymer matrix to create nano-porous structures. These advancements have significantly improved the CO₂ selectivity and permeability of polymeric membranes, boosting their performance in industrial applications. (Jiang et al., 2024)

Polymeric membranes are particularly advantageous for their modularity and adaptability. They are used in a variety of applications, including capturing CO₂ from flue gases in power plants, separating CO₂ from methane in natural gas processing, and purifying gases in petrochemical processes. Additionally, they are being explored for direct air capture (DAC) systems, selectively removing CO₂ from ambient air and contributing to climate change mitigation efforts. (Nguyen et al., 2023)

Recent developments in polymer science have produced membranes capable of withstanding high temperatures and varying operational conditions, making them suitable for processes involving hot gas streams. Innovations in formulations and coatings have enhanced membrane resistance to chemical degradation and fouling, extending their operational lifespan and reliability. Furthermore, the development of high-flux membranes with improved gas flow rates has reduced the size and cost of systems, while smart membranes that adapt to changing operational conditions are gaining research interest. (Smith et al., 2023)

Despite their advantages, polymeric membranes face challenges such as high production costs and scalability issues for large industrial applications. Addressing these limitations requires innovations to streamline manufacturing processes and improve cost-effectiveness. Hybrid systems combining polymeric membranes with other CO₂ capture technologies, such as MOFs or adsorption methods, are being developed to enhance performance and broaden applicability. (Ali et al., 2024)

The integration of membrane systems with other carbon capture technologies, such as physical solvents, has shown potential for optimizing CO₂ separation processes. These hybrid configurations leverage the strengths of multiple systems to improve overall efficiency, making membrane technology a critical component in the future of scalable, efficient, and sustainable CO₂ capture solutions.

3.6.2 Inorganic membranes

Inorganic membranes are pivotal in advanced CO₂ capture technologies due to their exceptional thermal and chemical stability, making them ideal for industrial environments where conditions are extreme. These membranes are composed of robust materials like zeolites, silica, and carbon molecular sieves, which offer high selectivity and durability. The structured pore systems of these materials facilitate efficient CO₂ separation from other gases such as nitrogen and methane, critical in applications like natural gas sweetening, syngas purification, and hydrogen generation. Recent advancements have

improved pore structure precision and performance under high-pressure and high-temperature conditions, addressing the challenges of scaling these systems for widespread use. (Fan et al., 2024)

Notably, innovative techniques such as transition-metal doping in silica membranes have enhanced hydrothermal stability and gas separation efficiency. For instance, cobalt and nickel doping in silica has shown significant improvements in selectivity and permeability under operational stresses. Furthermore, the integration of hydrophobic groups into these membranes minimizes water-induced structural collapse, thus extending their functionality. Hybrid designs combining inorganic materials with polymeric membranes or other separation methods further enhance their adaptability and effectiveness across diverse industrial processes. Despite their advantages, inorganic membranes face challenges, including high production costs and energy requirements for maintaining operational conditions. Research continues to explore scalable and cost-effective manufacturing methods and alternative materials to overcome these barriers. Given their potential for efficient gas separation and long-term stability, inorganic membranes remain a cornerstone in the development of sustainable CO₂ capture solutions, particularly in industries with high emission profiles. (Fan et al., 2024)

3.7 Novel capture processes

Novel CO₂ capture processes are emerging as critical advancements in the fight against climate change, offering innovative solutions to complement existing technologies. These processes, such as cryogenic distillation and electrochemical capture, address limitations of traditional methods by introducing energy-efficient mechanisms and the potential for integration with hybrid systems. By leveraging breakthroughs in material science, thermodynamics, and reaction engineering, novel capture processes aim to improve the selectivity, scalability, and cost-effectiveness of CO₂ separation. Their adaptability to various industrial and environmental contexts ensures they can meet the diverse demands of reducing atmospheric CO₂ concentrations and mitigating greenhouse gas emissions. As research progresses, these cutting-edge technologies are poised to play a

transformative role in achieving global carbon neutrality goals. Cryogenic distillation and electrochemical capture represent two advanced methods for CO₂ separation, each with distinct mechanisms and innovative developments that position them as pivotal in the evolution of carbon capture technologies.

3.7.1 Cryogenic distillation

Cryogenic distillation utilizes extremely low temperatures to separate CO₂ from gas streams, relying on the distinct boiling points of gases like CO₂, nitrogen, and oxygen. By cooling the gas mixture, CO₂ is condensed into a liquid or solid form, facilitating efficient separation. Recent advancements in cryogenic systems focus on improving energy efficiency through enhanced heat integration techniques. These systems now capture and reuse thermal energy, minimizing waste and reducing operational costs. Further, the development of advanced refrigerants with superior thermodynamic properties has improved the energy efficiency of cooling processes. Modern refrigerants not only lower energy consumption but also align with sustainability goals by offering lower global warming potentials. (Kim et al., 2023)

Cryogenic distillation systems have also benefited from innovations in process control, enabling precise regulation of temperature and pressure conditions to maximize efficiency. Modular designs now allow these systems to adapt to different industrial scales, from small operations to large power plants, enhancing flexibility and scalability. Despite the improvements, the high capital and operational costs remain a challenge. Research continues to focus on reducing these costs by optimizing designs and exploring integration with other CO₂ capture methods, such as membrane or chemical absorption technologies, to create hybrid systems with higher overall efficiency. (Smith et al., 2024)

3.7.2 Electrochemical capture

Electrochemical capture uses electrical energy to drive reactions that selectively separate CO₂ from gas mixtures. This technology leverages electrochemical cells equipped

with advanced electrodes and electrolytes to capture CO₂ efficiently. Recent progress in electrode materials, including the use of new coatings, has significantly improved reaction stability and efficiency, making the cells more durable under industrial conditions. Innovations in electrolyte design have also enhanced ionic conductivity, enabling faster and more energy-efficient CO₂ capture. (Gupta et al., 2023)

Reduced energy consumption remains a central focus for electrochemical systems. Advanced cell architectures optimize flow dynamics and reaction conditions, improving scalability and minimizing operational costs. Furthermore, the integration of electrochemical capture with other methods, such as membranes or amine scrubbing, has demonstrated potential for achieving higher capture rates with lower energy inputs. The development of new catalysts further enhances the selectivity and activity of CO₂ capture, accelerating the separation and conversion processes. (Wang et al., 2024)

Both cryogenic distillation and electrochemical capture are critical in addressing the global challenge of reducing greenhouse gas emissions. While cryogenic distillation excels in high-purity CO₂ separation from industrial flue gases, electrochemical methods offer versatility, including potential applications in direct air capture. Future advancements in material science, process optimization, and hybrid integrations are expected to overcome existing challenges, making these technologies more economically viable and environmentally sustainable.

4. Future directions and emerging technologies

Integration with renewable energy sources represents a transformative approach to advancing CO₂ capture technologies, enhancing both their efficiency and sustainability.

Hybrid systems leverage renewable energy, such as solar and wind power, to drive CO₂ capture processes while reducing dependence on fossil fuels. These systems aim to optimize energy use, lower operational costs, and contribute to a carbon-neutral future by aligning with global climate goals.

Solar-powered CO₂ capture systems use solar energy to power essential operations like solvent regeneration, electrochemical reactions, or thermal energy needs in CO₂ capture technologies. Photovoltaic panels and solar thermal collectors provide clean energy to drive these processes. Innovations in this area focus on optimizing the seamless integration of solar systems with capture technologies, ensuring high efficiency even in variable sunlight conditions. For instance, solar-assisted processes have been shown to reduce energy consumption significantly while enabling the conversion of captured CO₂ into valuable products like fuels or chemicals. (Zhang et al., 2023)

Similarly, wind energy integration offers another renewable pathway to support CO₂ capture. Wind turbines provide electricity to power adsorption, electrochemical, or other capture technologies. Recent advancements include improvements in turbine efficiency and the incorporation of advanced energy storage solutions to mitigate the intermittent nature of wind energy. This ensures a stable and reliable energy supply for CO₂ capture systems, even during periods of low wind activity. Hybrid systems using wind power have demonstrated success in industrial settings, providing a scalable model for reducing greenhouse gas emissions. (Chen et al., 2024)

One promising application of renewable-powered CO₂ capture systems lies in the production of synthetic fuels. Captured CO₂ can be combined with hydrogen, produced via water electrolysis powered by renewable energy, to create fuels like methanol or hydrocarbons. This process not only reduces CO₂ emissions but also contributes to energy

sustainability by producing renewable fuels that can replace traditional fossil-based alternatives. Integrated systems combining capture and utilization technologies are becoming increasingly sophisticated, offering dual benefits of carbon reduction and economic value creation. (Kumar et al., 2024)

While challenges remain, such as the high initial costs and the need for optimized system designs, the integration of CO₂ capture technologies with renewable energy sources represents a vital step toward achieving large-scale carbon neutrality. Continued research and innovation in hybrid systems are expected to further enhance their effectiveness, paving the way for widespread adoption in industrial and environmental applications.

4.1 Examples of the integration of renewable energy sources with CO₂ capture technologies

Below are some examples of the integration of renewable energy sources with CO₂ capture technologies that represents a major advancement in creating sustainable and scalable carbon management systems. These hybrid systems aim to not only capture CO₂ efficiently but also utilize renewable energy for its transformation into valuable products like fuels, chemicals, and building materials. This approach enhances energy efficiency, reduces operational costs, and aligns with global carbon neutrality goals.

Climeworks and Holcim Partnership: Climeworks Direct Air Capture (DAC) units remove CO₂ directly from the atmosphere, which is then transported to Holcim cement plants. Here, CO₂ is mineralized into calcium carbonate, reducing emissions while enhancing the cement's properties. This collaboration demonstrates the practical application of DAC in large-scale industrial settings, lowering the carbon footprint of cement production. As illustrated in Figure 4, the DAC process operates by drawing ambient air into the Climeworks system, where CO₂ is captured using specialized filters and sorbents. These filters selectively bind the CO₂, separating it from other atmospheric gases. Once the sorbents are saturated, the system undergoes a regeneration phase, releasing concentrated CO₂. This CO₂ is then transported to Holcim facilities, where it undergoes a

mineralization process to form stable calcium carbonate compounds. This method ensures the CO₂ is securely stored while contributing positively to the durability and performance of the cement product. (Climeworks, 2023)

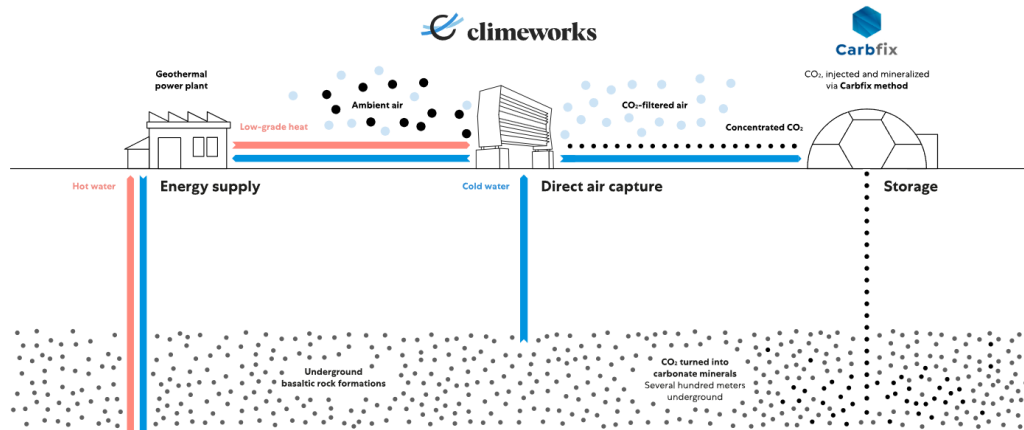


Figure 4. Climeworks DAC process. (Climeworks, 2023)

CarbonCure Technologies: This company incorporates captured CO₂ into concrete during the mixing phase, where it reacts with calcium ions to form calcium carbonate. This reaction not only strengthens the concrete but also permanently sequesters CO₂ making it a scalable solution for integrating carbon capture into the construction industry. (CarbonCure, 2024)

HeidelbergCement: By integrating DAC technology, HeidelbergCement captures atmospheric CO₂ and incorporates it into cement production. The CO₂ is mineralized, significantly reducing the overall emissions from cement manufacturing and advancing sustainability goals in construction. (HeidelbergCement, 2024)

Blue Planet: Blue Planet innovatively converts captured CO₂ into synthetic limestone aggregates for concrete production. In Figure 5, the process starts with CO₂ capture, which is then reacted with specific minerals and chemicals to create synthetic limestone aggregates. This interaction forms a stable mineral product that can seamlessly integrate into concrete production, ensuring structural integrity while supporting environmental sustainability goals. (Blue Planet, 2023)

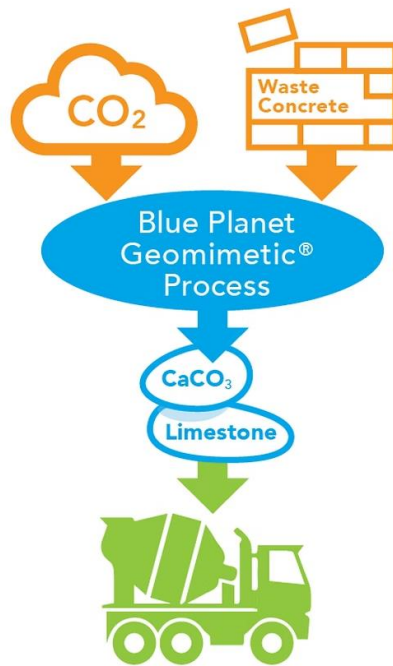


Figure 5. Blue Planet technology manufacturing process of synthetic limestone aggregate from captured CO₂. (Blue Planet, 2023)

4.2 Production of synthetic fuels and chemicals

Captured CO₂ can be converted into synthetic fuels like methanol and hydrocarbons using renewable energy-driven electrolysis and catalytic processes. Hydrogen produced from renewable sources is combined with captured CO₂ to create these fuels, offering a carbon-neutral alternative to fossil fuels. This integration transforms CO₂ from a waste product into an economic asset, demonstrating the dual benefits of emission reduction and resource creation. (Global CCS Institute, 2024)

Bioenergy with Carbon Capture and Storage (BECCS) combines bioenergy production with CO₂ capture and storage, delivering negative emissions. Biomass absorbs CO₂ during growth, and when used for energy production, the CO₂ released is captured and stored. For instance, the Drax Power Station in the UK employs BECCS to capture CO₂ from its biomass-fired operations, showcasing the potential of this technology in reducing net emissions (Drax Group, 2024). Similarly, the Bioenergy Technologies Office (BETO)

supports research to enhance biomass conversion processes, improving both energy efficiency and carbon removal. (BETO, 2024)

Despite these advancements, challenges such as high costs, scalability, and ensuring the sustainability of CO₂ utilization processes persist. Future research will focus on optimizing these systems through improved materials, advanced energy integration, and innovative hybrid designs. Projects like those led by Climeworks and CarbonCure indicate the significant potential for widespread adoption of renewable-powered CO₂ capture technologies across industries.

4.3 Enhanced CO₂ capture techniques

The development of advanced CO₂ capture techniques has been instrumental in improving the effectiveness and efficiency of carbon management strategies. These innovations include advanced amine solvents, high-efficiency scrubbers, and solvents optimized for lower temperatures and pressures, which reduce energy demands and enhance system efficiency.

For example, tailored amines minimize solvent degradation while improving CO₂ absorption rates, making them suitable for large-scale bioenergy processes (Mondal et al., 2021). These advancements have lowered operational costs and made CO₂ capture technologies more accessible to industries aiming to reduce emissions.

Carbon storage, also known as carbon sequestration, is a vital step in ensuring that captured CO₂ does not re-enter the atmosphere. This involves transporting CO₂ from capture sites to geological storage locations, such as depleted oil fields and saline aquifers. Innovations in monitoring technologies, including seismic imaging and satellite observations, have increased the safety and reliability of carbon storage. Projects like the Northern Lights Project in Norway highlight the scalability and potential of this method, storing up to 1.5 million tons of CO₂ annually in the North Sea's Johan Sverdrup field (Equinor,

2023). Similarly, Japan's Tomakomai CCS Demonstration Project has demonstrated successful CO₂ storage in saline aquifers under the seabed, offering valuable insights into long-term storage viability. (Sawada, 2020, Sasaki et al., 2024).

BECCS integrates biomass energy production with CO₂ capture, creating a negative emissions solution. Biomass absorbs CO₂ during growth, and the emissions from energy generation are captured and stored. Facilities like the Drax Power Station in the UK showcase the potential of BECCS to achieve net-zero emissions by combining biomass combustion with CO₂ capture and storage. This approach offsets emissions from sectors that are difficult to decarbonize, such as aviation and heavy industry. (Drax, 2023)

Transitioning fossil fuel power plants to hydrogen-based systems with integrated CO₂ capture is a promising approach to reduce emissions. Hydrogen is generated using methods like steam methane reforming (SMR) combined with carbon capture or via electrolysis using renewable electricity.

Advances in electrolyzer technologies, such as those by Nel Hydrogen and ITM Power, are enhancing the efficiency of hydrogen production from renewable energy sources. Proton exchange membrane (PEM) and alkaline electrolyzers are being developed to reduce costs and improve scalability, making hydrogen production more sustainable. (Nel Hydrogen, 2024)

Companies such as Siemens and GE are leading the way with hydrogen-ready turbines capable of running on 100% hydrogen. Projects like the H₂1 North of England are exploring the integration of hydrogen production and CO₂ capture to create low-carbon economies. (Siemens, 2023; GE, 2023)

By integrating these systems with renewable energy and carbon capture technologies, industries can achieve significant emission reductions while supporting energy transitions.

4.3.1 CO₂ utilization and hybrid systems

Captured CO₂ can be converted into valuable products, including synthetic fuels, urea for fertilizers, and carbonates for construction materials. Examples like CarbonCure Technologies demonstrate the integration of CO₂ into concrete to improve its properties while permanently sequestering carbon. Similarly, Blue Planet uses captured CO₂ to produce synthetic limestone aggregates, providing a sustainable alternative to traditional materials in construction. (CarbonCure, 2024; Blue Planet, 2023)

Collaborations between companies like Climeworks and Holcim showcase how CO₂ capture can be integrated into cement production to reduce its carbon footprint. Climeworks captures CO₂ from ambient air, which is then used by Holcim to mineralize cement, improving product performance and sustainability. (Climeworks, 2023)

The HeidelbergCement partnership represents another innovative effort, where DAC technology is combined with mineralization to lower the carbon intensity of cement manufacturing. (HeidelbergCement, 2024)

5. Innovations in carbon capture

Carbon capture utilization and storage technologies are undergoing significant advancements to address the dual challenges of reducing atmospheric CO₂ and meeting global sustainability goals. Modern approaches not only focus on capturing carbon but also on repurposing it into economically valuable products, fostering a circular carbon economy.

Air-to-fuel technology represents a groundbreaking approach in carbon capture and utilization. This process converts captured atmospheric CO₂ into synthetic fuels that can replace conventional fossil fuels. The technology as shown in Figure 6 from 1PointFive (2023) involves combining CO₂ with hydrogen derived from water electrolysis, creating hydrocarbon chains that can be processed into usable fuels such as gasoline or jet fuel. As Figure 6 illustrates, CO₂ captured from the atmosphere interacts with hydrogen in a reactor to form synthetic hydrocarbons. These hydrocarbons are processed into usable fuels, closing the carbon loop by reintroducing CO₂ back into fuel systems rather than releasing it into the atmosphere. This innovation not only helps reduce atmospheric CO₂ levels but also supports the transition to sustainable energy by creating a closed-loop carbon cycle, enhancing the prospects for achieving net-zero emissions. (ScienceDaily, 2022; Stanford News, 2022)

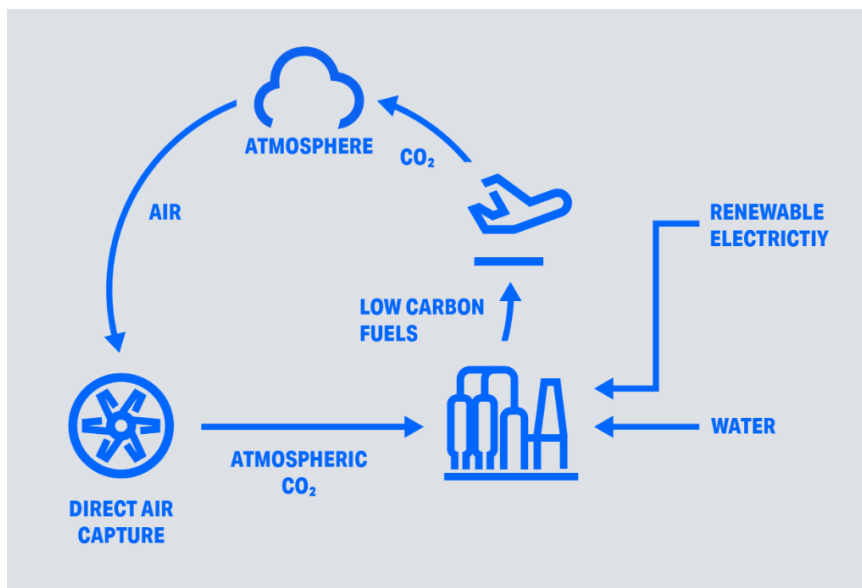


Figure 6. Process of Captured CO₂ to fuels (1pointfive, 2023).

Solein is an all-purpose protein produced using CO₂ water, and renewable electricity. As shown in Figure 7 from Solar Foods (2023), this technology harnesses a fermentation process akin to brewing, where microbes are fed CO₂ and hydrogen to produce protein. The process in Figure 7 illustrates how CO₂ and hydrogen interact within fermentation tanks, where microbes metabolize these inputs to form Solein. Unlike traditional agriculture, Solein's production method significantly reduces land and water requirements, offering a scalable and environmentally conscious solution for the food industry. The environmental benefits are profound, as this method sequesters CO₂ while generating a nutritious food source, promoting a dual impact on sustainability. (Solein, 2023)

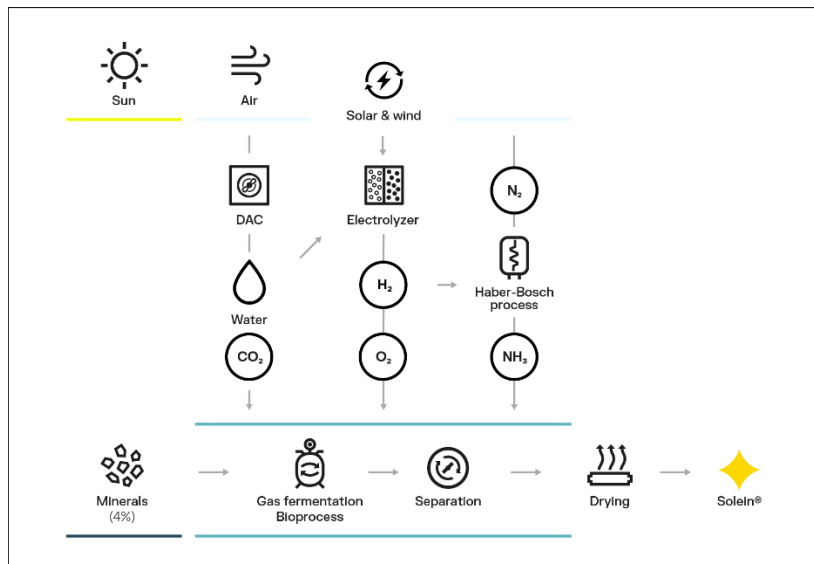


Figure 7. Process of manufacturing Solein by Solar food (Solar Foods, 2023)

The concept of using CO₂ to create **synthetic diamonds** exemplifies an innovative cross-over between carbon capture and luxury products. In this process, CO₂ is extracted from the atmosphere and transformed into diamonds through high-temperature and high-pressure synthesis. This method not only adds value to captured carbon but also positions carbon capture as an integral part of sustainable luxury. Lab-grown diamonds, created from atmospheric carbon, reduce the need for environmentally harmful mining practices and present new opportunities for eco-conscious consumers. Lab-grown

diamonds from captured CO₂ open new market opportunities in the jewellery sector. This sustainable approach not only appeals to the growing demographic of environmentally aware consumers but also demonstrates how carbon capture can be monetized beyond energy and industrial applications. By transforming CO₂ into valuable products, the technology illustrates a unique synergy between environmental responsibility and economic potential. (Aether Diamonds, n.d.; The Verge, 2022)

While challenges such as energy demand and cost must be addressed, advancements like air-to-fuel systems, Solein production, and air-to-diamond technologies demonstrate the diverse possibilities for carbon utilization. Integrating these innovations into larger climate strategies can foster sustainable growth and create a multi-sector impact.

6 Case studies

6.1 Mitsubishi heavy industries' hydrogen gas turbine

Mitsubishi Heavy Industries (MHI) is at the forefront of developing hydrogen gas turbines capable of running on 100% hydrogen, designed specifically for retrofitting existing natural gas power plants. This technology represents a transformative step in transitioning from fossil fuels to hydrogen, leveraging existing infrastructure to significantly reduce CO₂ emissions from power generation. (Iida et al., 2023)

The turbines are engineered to combust hydrogen, which primarily produces water vapor instead of CO₂, making it a near-zero-emission energy source. By retrofitting current facilities, MHI eliminates the need for entirely new plants, saving both time and capital costs. (Mitsubishi Heavy Industries, 2024) Rigorous testing has been conducted to optimize efficiency while minimizing nitrogen oxide emissions caused by high combustion temperatures (Smith et al., 2023). MHI has successfully tested hydrogen-natural gas blends, with ongoing efforts to achieve 100% hydrogen combustion. The company plans commercial deployment by the mid-2020s, with early installations targeted in Japan, Europe, and the United States. These turbines align with Japan's carbon neutrality goals by 2050 and could play a critical role in decarbonizing the global energy sector (Iida et al., 2023).

6.2 HyNet Project (North West England, UK)

HyNet is one of the UK's most ambitious projects, focused on decarbonizing industrial processes and energy production in the North West of England and North Wales. It integrates hydrogen production with carbon capture and storage (CCS) technologies, using Steam Methane Reforming (SMR) to produce hydrogen while capturing and storing CO₂ in depleted gas fields in Liverpool Bay. (Johnson & Patel, 2022)

The project repurposes existing natural gas pipelines for hydrogen transportation, minimizing costs and logistical challenges. Hydrogen will replace fossil fuels in industries, power plants, and potentially residential heating. The initiative, recognized as crucial to the UK's net-zero emissions target by 2050, could reduce CO₂ emissions by up to 10 million tonnes annually equivalent to removing 4 million cars from the roads. (UK Government, 2022)

HyNet's first phase, slated for the mid-2020s, includes constructing a low-carbon hydrogen production plant and associated CCS infrastructure. Partnerships with industrial players in the region ensure steady demand and accelerate the shift toward a hydrogen economy. (Smith et al., 2023)

6.3 Rotterdam hydrogen plant (Netherlands)

The Rotterdam Hydrogen Plant, led by Royal Dutch Shell, aims to produce low-carbon hydrogen using SMR combined with CCS. This project aligns with the Netherlands' strategy to become a European hydrogen hub and decarbonize the industrial sector, particularly the Rotterdam port area, one of Europe's largest industrial clusters. (Jones & de Vries, 2023)

Using natural gas, the plant produces hydrogen and captures CO₂ emissions, which are then stored in offshore depleted gas fields under the North Sea. This ensures the process remains low-carbon. Hydrogen is supplied to refineries, chemical plants, and power generation facilities, with plans to expand its use in transportation and synthetic fuels. (Royal Dutch Shell, 2023)

The plant's strategic location supports the Netherlands' ambitions to reduce CO₂ emissions and transition to a sustainable energy system. Initial operations are expected by the mid-2020s, with scalability contingent on demand growth. Future integration with renewable energy sources for green hydrogen production further highlights its long-term sustainability potential. (Jones & de Vries, 2023)

6.4 Petra Nova carbon capture project (Texas, USA)

The Petra Nova Carbon Capture Project employs amine-based solvent technology to capture CO₂ from a coal-fired power plant. Since beginning operations in 2017, it has successfully captured approximately 1.6 million metric tons of CO₂ annually, demonstrating the viability of large-scale post-combustion CO₂ capture systems. Despite facing operational challenges, such as interruptions caused by economic factors and maintenance needs, Petra Nova exemplifies the potential of retrofitting existing power plants with carbon capture technology to significantly reduce industrial emissions. Its success has set a precedent for similar projects worldwide and reinforced the importance of innovation in climate change mitigation (Smith et al., 2020; Johnson et al., 2023). Despite facing some operational challenges, Petra Nova has demonstrated the feasibility of large-scale post-combustion CO₂ capture, making it a key example of the technology in action.

6.5 Mongstad CO₂ storage project (Norway)

Operational from 2012 to 2017, the Mongstad project pioneered post-combustion CO₂ capture using amine solvents at a natural gas-fired power plant. Though discontinued due to high costs and technical challenges, it provided critical data that has informed the development of subsequent CCS projects worldwide. Its legacy lies in enhancing the understanding of solvent efficiency and scalability for future implementations. Originally conceived as a large-scale test facility, the Mongstad project played a critical role in advancing the understanding of post-combustion CO₂ capture technologies. (Johansen et al., 2021)

6.6 Soletair power (Finland)

Soletair Power is a Finnish company specializing in Direct Air Capture technology, designed to capture CO₂ directly from the atmosphere and integrate it into building ventilation systems. As shown in Figure 8, Soletair's system utilizes specialized filters

embedded in HVAC units to absorb CO₂ from the air circulating through buildings. The captured CO₂ can be stored, repurposed, or combined with hydrogen to create synthetic methane, contributing to cleaner energy solutions and carbon-neutral product. (Jensen et al., 2024)

The modularity of its technology allows scalability for various applications, from small commercial setups to large industrial facilities. Collaborations with companies like Wärtsilä focus on expanding DAC applications, particularly in industrial energy systems where captured CO₂ can support Power-to-X technologies. Demonstration projects, such as an operational DAC system in a Vaasa office building, showcase the real-world viability of creating carbon-neutral or carbon-negative environments while maintaining high indoor air quality standards (Jensen et al., 2024; Soletair Power Company Profile, 2024). Figure 8 highlights the system's integration into a real-world setting, such as an operational DAC system in a Vaasa office building, where CO₂ capture directly improves indoor air quality while reducing carbon emissions.

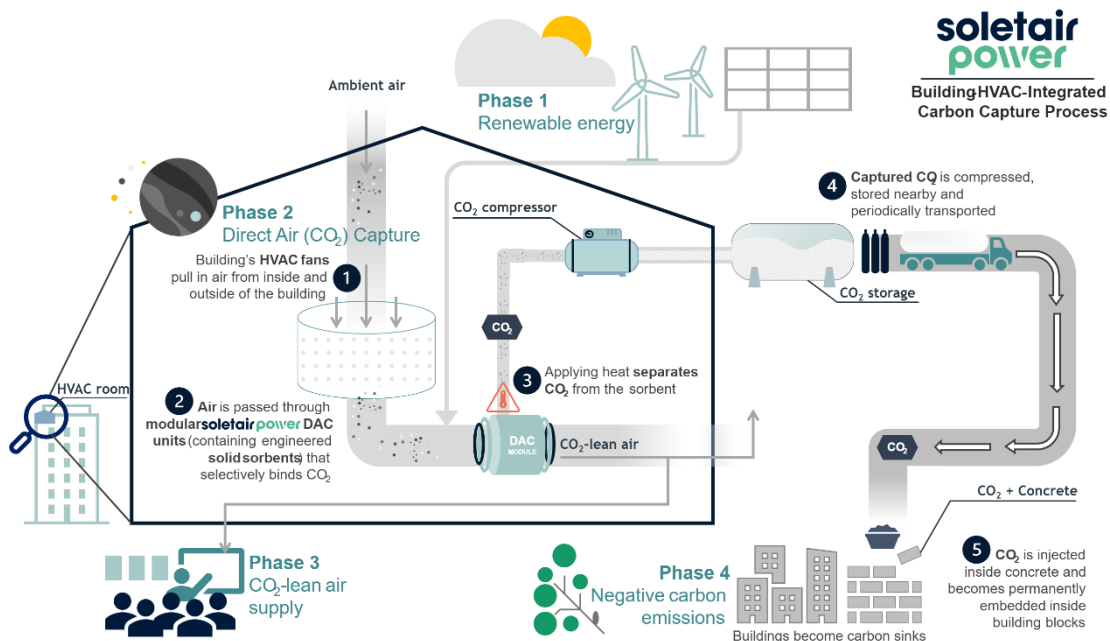


Figure 8. Soletair-Power-Company-Profile-25-Sep-2024, n.d.

One of Soletair Power's flagship projects involves installing a Direct Air Capture (DAC) system in an office building in Vaasa, Finland, which exemplifies how DAC technology can seamlessly integrate into urban environments to create carbon-neutral or carbon-negative structures. The captured CO₂ is stored, utilized on-site, or transformed into other applications, such as synthetic fuels. This project is powered by renewable energy, ensuring sustainability while reducing additional emissions. (Jensen, 2024; Soletair Power Company Profile, 2024)

Operational success in Vaasa serves as a proof-of-concept for scaling the technology to larger commercial and industrial facilities. By integrating DAC with renewable energy systems and carbon utilization technologies, Soletair Power is pioneering advancements in urban sustainability and global carbon reduction efforts. The scalability and modularity of this system highlight its potential to revolutionize building energy efficiency and carbon management worldwide. (Jensen, 2024; Soletair Power Company Profile, 2024)

6.7 Project vesta

Project Vesta is an innovative carbon capture initiative leveraging the natural weathering process of olivine, a magnesium iron silicate mineral, to capture atmospheric CO₂ by enhancing coastal interactions. When olivine is ground into sand and spread along coastlines, it reacts with CO₂ in seawater, producing stable bicarbonate ions, magnesium ions, and silica. This process facilitates long-term carbon storage in marine sediments and mitigates ocean acidification, thereby improving marine ecosystems. (Wang et al., 2024; Lezaun, 2021)

The core idea is to accelerate the natural chemical reactions that occur when olivine, a magnesium iron silicate, interacts with CO₂ in seawater. As shown in Figure 9, this method places finely ground olivine sand along coastal areas, where it engages in a reaction with CO₂ and water, transforming CO₂ into bicarbonate ions (HCO₃⁻), a stable form

that can remain in seawater for millennia, thereby effectively sequestering CO₂ and reducing atmospheric concentrations (Project Vesta, n.d.; Wang et al., 2024).

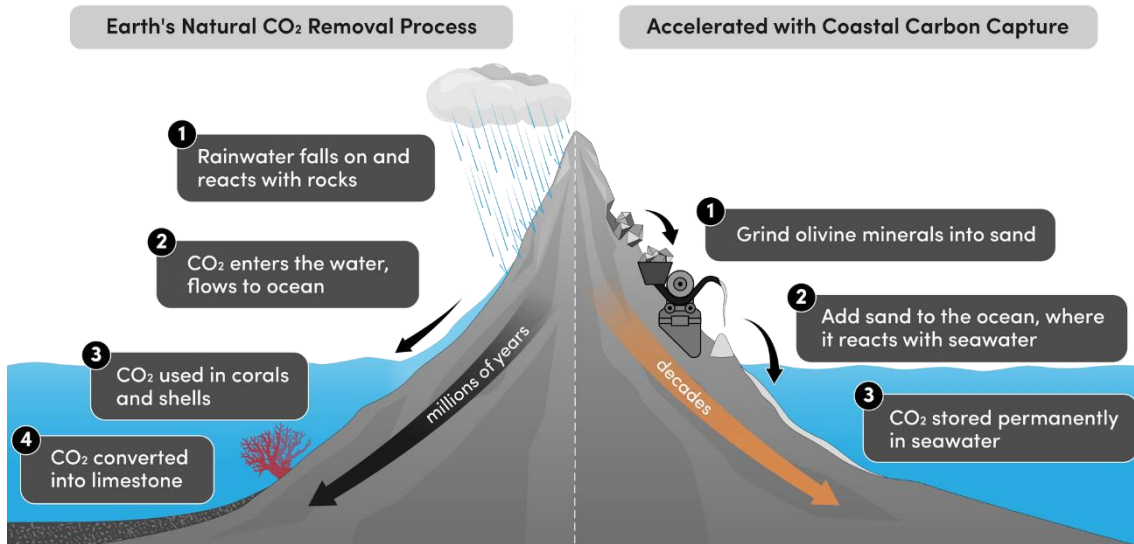
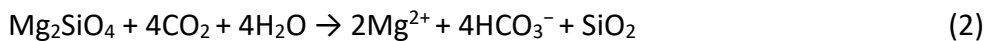


Figure 9. Coastal carbon capture at north sea beach (<https://www.vesta.earth/south-ampton>)

Olivine is a greenish mineral that, when ground into sand and spread along coastlines, reacts with CO₂ dissolved in seawater. The reaction is shown in equation (2).



This reaction produces magnesium ions and bicarbonate, which are then carried away by the ocean currents. The bicarbonate eventually contributes to the long-term storage of carbon in marine sediments, as it precipitates out as carbonate minerals. (Project Vesta. (n.d.)

By accelerating the natural weathering process, Project Vesta aims to capture significant amounts of CO₂. The project estimates that spreading 1 ton of olivine could capture up to 1.25 tons of CO₂ over time (Wang et al., 2024). The process also helps mitigate ocean acidification. As CO₂ is converted into bicarbonate, the ocean's pH balance is improved, providing a healthier environment for marine life (Lezaun, 2021). Project Vesta is

currently conducting pilot studies to assess the effectiveness of olivine weathering in different coastal environments. These trials will help determine the optimal conditions for olivine application and monitor any potential environmental impacts. Project Vesta continues to refine its methods and gather data from pilot projects

7. Westenergy's carbon capture project

Westenergy, a leader in sustainable waste-to-energy solutions, has announced plans for an upcoming carbon capture project that aligns with global climate targets. This project aims to implement advanced carbon capture technologies at their facilities, marking a significant step in reducing industrial CO₂ emissions and enhancing sustainability in energy production.

During a recent conversation with Westenergy representatives, they outlined their strategic approach to integrating carbon capture within their operational framework. One notable aspect of the project is its alignment with the European Union Emissions Trading System (ETS).

ETS is a market-based approach used by the EU to incentivize reductions in greenhouse gas emissions by assigning a price to carbon emissions (European Commission, 2023; Clean Energy Wire, 2022). Westenergy's project is designed to complement these regulatory measures, ensuring that captured carbon contributes to the company's compliance and potential economic benefits.

The ETS system is instrumental in promoting carbon capture and storage (CCS) projects across Europe by providing financial incentives for companies that reduce emissions. Westenergy's integration of ETS with their carbon capture efforts highlights a dual approach: mitigating environmental impact while navigating economic considerations through carbon credit mechanisms. This integration ensures that the project not only serves environmental purposes but also provides potential cost recovery through the sale of carbon credits, thereby supporting long-term sustainability.

Westenergy's project focuses on using state-of-the-art carbon capture technology capable of extracting CO₂ from waste-to-energy processes. The captured CO₂ will either be stored underground or potentially used in various applications such as chemical

synthesis and sustainable products. The technology is designed for scalability, paving the way for more widespread adoption across similar facilities in the region.

The discussion emphasized that the success of Westenergy's project could set a precedent for other waste-to-energy plants seeking to reduce their carbon footprint. By leveraging ETS and aligning with regional sustainability goals, Westenergy aims to demonstrate that carbon capture is not only environmentally necessary but also economically viable.

8. Conclusion

The research highlights the transformative potential of advanced carbon capture technologies in mitigating CO₂ emissions and addressing climate change. From pre-combustion and post-combustion capture to novel methods like direct air and ocean capture, these technologies represent critical tools in achieving global climate goals. While advancements such as MOFs, zeolites, and hybrid systems have shown promising scalability and efficiency, challenges related to energy demand, costs, and environmental impacts remain.

Key findings underscore the need for continued innovation to enhance the economic and operational feasibility of these technologies. Integration with renewable energy sources, such as solar and wind, offers a path to greater sustainability and reduced dependence on fossil fuels. Case studies highlight both successes and setbacks in real-world carbon capture projects. For instance, the Westenergy Carbon Capture Project stands out as a successful integration of carbon capture technology in municipal waste-to-energy facilities. This project not only reduced CO₂ emissions but also generated valuable energy, showcasing how environmental sustainability and industrial operations can coexist. However, it's important to note that similar initiatives, such as projects relying on amine-based absorption methods, have faced operational shutdowns due to issues like high solvent degradation rates, limited scalability, and cost constraints.

Moving forward, fostering collaboration among policymakers, researchers, and industry stakeholders will be essential in overcoming technical and economic barriers. Investment in research and development, coupled with supportive policies, can accelerate the adoption of carbon capture technologies. Ultimately, achieving net-zero emissions will depend on the deployment of a combination of these innovative solutions, paving the way for a sustainable and climate-resilient future.

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