



Carbon Capture Technologies in Energy Conversion: Emphasis on Membrane and Hybrid Systems

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Abstract: Carbon dioxide emissions from power plants and industrial producers are a major driver of global warming, leading to rising temperatures and numerous adverse impacts on ecosystems and human life. In response, various strategies have been developed to mitigate greenhouse gas emissions. This review paper examines the three main stages of energy conversion for carbon dioxide capture: pre-combustion, oxy-fuel combustion, and post-combustion, with particular emphasis on the latter. Several capture techniques have been explored, including chemical and physical absorption, membranes, adsorption on porous materials, and cryogenic freezing. Among these, membrane-based methods have attracted significant attention due to their advantages in energy efficiency, operational simplicity, and potential integration with hybrid systems. Comparing the efficiency of different capture technologies, membranes achieve 85–90% efficiency at a lower cost (\$25–45/ton CO₂), while deep cooling technology boasts high purity (>99%) but comes at the cost of high energy consumption (>3.5 GJ/ton CO₂). Absorption technology, on the other hand, ranges between 90–95% efficiency at a cost of \$40–60/ton CO₂. Membranes have been successfully combined with absorption, desorption, and cryogenic processes to achieve higher purity in CO₂ capture. This study reviews twenty research papers on membrane technology, focusing on hybrid membrane systems and their performance. Carbon capture and storage (CCS) is widely recognized as a key strategy for achieving climate goals by reducing carbon emissions from thermal energy production and industrial processes, while also enabling the net removal of CO₂ from the atmosphere.

Keywords: CO₂ capture; Gas permeation; Membrane separation; Process integration

1 Introduction

The impact of carbon dioxide emissions on human health and the environment is becoming increasingly evident. These emissions, driven primarily by human industrial activity and fossil fuel-based energy production, pose significant environmental challenges [1, 2].

Table 1 provides an overview of the key factors contributing to this issue [3–10].

Table 1. Primary sources of CO₂ for carbon capture techniques

Source	CO ₂ in Flue Gas (%)	Emissions (kg CO ₂ /MWh)	Capture Technology	Cost (\$/ton CO ₂)	Region	Ref.
Coal	2–15	850–1200	Post-combustion	50–100	Global	[3]
Gas	4–5	350–600	Post-combustion	30–70	United States	[4]
Steel	5–20	1500–3000	Oxy-fuel combustion	40–90	China	[5]
Cement	20–30	600–1200	Post-combustion	30–60	Global	[6]
Petrochemicals	10–30	100–500	Pre-combustion	20–50	Middle East	[7]
Waste Incineration	5–15	400–1000	Post-combustion	30–60	European Union	[8]
Biomass Boilers	5–15	200–500	Post-combustion	20–40	Europe	[9]
Biogas	40–60	150–300	Chemical scrubbing	10–30	Southeast Asia	[10]

It is widely recognized that discussions about global warming often focus on carbon dioxide emissions. Therefore, all countries—not just industrialized nations with large economies—should contribute to achieving a

cleaner environment by reducing emissions [11].

This commitment is stipulated in the Paris Climate Agreement, signed by 197 countries in Paris, France, during the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change on December 12, 2015, and entered into force in November 2016. The agreement's central goal is to stabilize greenhouse gas concentrations in the atmosphere at levels considered safe for the climate system and human well-being [12].

Thus, researchers across multiple fields have been seeking ways to reduce its concentration in the atmosphere, as its average monthly concentration is expected to peak at approximately 429.64 Parts Per Million (PPM) in April 2025, as shown in Figure 1.

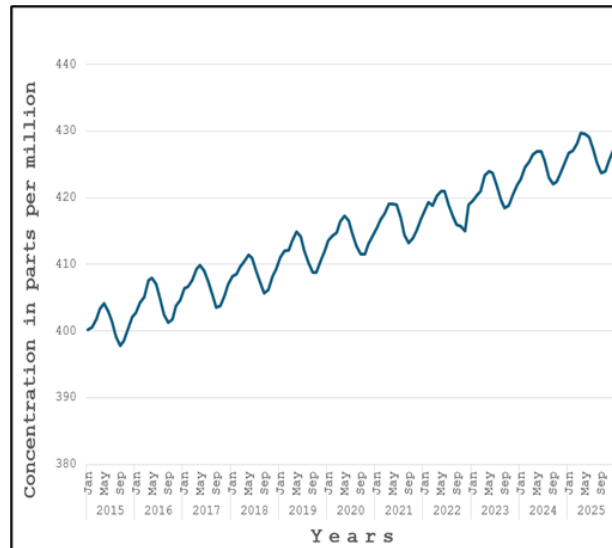


Figure 1. Average monthly carbon dioxide levels in the atmosphere worldwide from 2015 to 2025 [13]

The global focus on producing clean energy from conventional power plants has increased the importance of Carbon dioxide Capture and Storage (CCS). This technology is a realistic near-term solution for capturing carbon before it reaches the atmosphere and contributes to sustainable energy systems. It includes three basic approaches: pre-combustion, oxy-fuel combustion, and post-combustion. Each technology has its own advantages, challenges, and limitations [14–16].

The primary goal of minimizing greenhouse gas emissions, particularly carbon dioxide, must be to find urgent solutions that reduce these emissions without compromising economic growth or industrial practices in both developed and developing countries [17]. Efforts should focus on investing in reliable and cost-effective strategies that have already been developed. More specifically, emphasis should be placed on practically deployable technologies with high CO₂ capture efficiency, reduced energy consumption per ton of CO₂ captured, and low investment and operating costs [18].

Among various carbon capture methods, post-combustion carbon dioxide recovery is considered the most efficient and adaptable technology for integration with coal-fired power plants, requiring minimal retrofitting [19]. The post-combustion process involves extracting CO₂ from exhaust emissions generated by industrial activities, including power plants, cement kilns, and steel production, before they are released into the atmosphere. Flue gas from these sources typically contains 3–15% CO₂, in addition to nitrogen, water vapor, oxygen, and trace impurities. Due to the dilute nature of CO₂ and the presence of high temperatures and particulate matter, specialized separation technologies are required for effective capture [20].

Various separation methods can be used to lower CO₂ levels in flue gas streams, including chemical absorption, physical absorption, physical adsorption, and membrane techniques [21, 22]. Chemical absorption is seen as the most effective because it can capture up to 90% of CO₂ from large exhaust flows and achieve purity levels above 99%. Its main drawbacks are high thermal energy needs and potential environmental issues caused by solvent degradation and disposal. Membrane CO₂ capture is a practical and promising approach because of its simple design, renewable energy potential, and environmental benefits. However, it may also compete with traditional CO₂ separation methods in terms of cost and energy use. Additionally, membrane technology is considered a feasible option for removing CO₂ in post-combustion processes [23–25].

This review provides a comprehensive overview of carbon capture technologies and differs from other reviews in its methodology for analyzing current and emerging sources up to 2025. This approach offers a thorough comparison, particularly between membrane and hybrid systems, in terms of performance, cost, energy efficiency, and environmental impact. The assessment focuses on the potential advantages and challenges of current developments

and the integration of renewable energy, with an emphasis on practical applications and their technical and economic feasibility.

Feasibility analysis of environmental projects and the identification of gas emissions that contribute to global warming are critical. With the advancement of numerous technologies, CCS and Carbon Capture and Utilization (CCU) have become essential for effective environmental risk mitigation. These technologies enable the capture of carbon dioxide emissions from major sources, including upstream oil and gas operations, for long-term storage in geological formations. CCS and CCU are projected to account for up to 32% of CO₂ reductions by 2050 and are pivotal for achieving net-zero emissions [26, 27].

1.1 Literature Reviews

Experimental studies on the process of capturing carbon dioxide from membranes integrated into various industrial facilities have led to numerous publications outlining the key factors that directly influence the performance of post-combustion carbon dioxide capture technologies. This study covers publications from 2015 to 2025.

White et al. [28] illustrated the functionality of a substantial pilot project (600 MW) Coal-Fired Power Plant (CFPP) in Alabama utilising Polaris™ membranes with a CO₂ permeance of 1000–2000 GPU and selectivity of 50–60, attaining over 90% recovery via a two-stage configuration incorporating both vacuum and sweep-gas enhancement. Pohlmann et al. [29] investigated membrane integration in a coal-fired facility with a CO₂ concentration of 14.5% and emphasised the stability of operation during start-up and shutdown critically influences system reliability; a two-stage design could result in 95% quality.

Baker et al. [30] documented various membrane configurations for the extraction of carbon dioxide produced by natural gas combined cycle power plants, whereby the CO₂ concentration ranges from 3% to 4% owing to the operation of gas turbines utilizing substantial volumes of air. The scientists demonstrated that a larger capture rate may be attained through an increased membrane surface area and the pressure differential across the membrane module, which consequently elevates power consumption. The authors have presented another finding indicating that capital costs can be reduced by enhancing membrane selectivity. A related parametric framework proposed by Gabrielli et al. [31] Investigated an inclusive methodology that establishes guidelines for the optimal configuration and operation of membrane CO₂ capture processes. The authors examined flue gas generated by a CFPP with a flow rate of 4.5 mol/s and 14% CO₂ content to conduct a parametric analysis of various process designs and determine the impact of configuration and operational parameters on factors such as membrane area and power consumption. The author's findings indicate that a capture efficiency of 90% with a purity of 95% can be achieved using at least a two-stage membrane design. Ultimately, they found that changing the pressure ratio across the membrane unit consistently results in a reduction in membrane area for a given capture rate, hence increasing energy requirements.

Industrial-scale simulations have confirmed the effectiveness of hollow-fiber fixed-site-carrier membranes. For example, Hägg et al. [32] Examined two phases of membrane technology in two scenarios, utilizing the recycling stream from the second phase, integrated with a cement plant in Norway to extract carbon dioxide at a high concentration of 19.4%. A hollow fiber Fixed Site Carrier (FSC) membrane material was utilized in the simulation, achieving a capture rate of 80% with 95% purity. The authors asserted that 70% CO₂ purity can be readily achieved with a single-stage process with an 87 CO₂/N₂ selectivity. The influence of flue-gas pressure and CO₂ fraction was examined by Xu et al. [33] Performed a gas recovery analysis to investigate the influence of flue gas pressure and carbon dioxide concentration on membrane capture of carbon dioxide in post-combustion coal-fired power plants. A spiral-wound membrane was employed and optimized to minimize the total membrane surface area and the energy consumption related to membrane auxiliaries. The membrane configurations for one and two units were evaluated using a flue gas flow rate of 22 kmol/s and a carbon dioxide flow rate of 2.97 kmol/s. The authors said that power consumption for the proposed integration can be reduced by modifying the initial compressor pressure from 5.5 to 6.5 bar. They delineated a reduction scenario for the greenhouse gas recovery price by utilizing high carbon dioxide permeability together with medium selectivity in the first membrane unit, while the second unit should employ medium permeability with high selectivity.

The hybridisation approach has also been a key area of focus for economic optimisation. Ren et al. [34] Investigated a hybrid methodology involving two selective membranes for CO₂ and N₂, assessing pressure differentials and various designs to minimize membrane surface area and energy usage. Polaris® membranes were employed in a system optimization to capture 90% of carbon dioxide produced by a 550 CFPP, with the potential for reduced carbon dioxide capture costs. The authors found the zone of restricted selectivity that informed two distinct strategies for price reduction: either by enhancing selectivity or by decreasing the cost factor. Nonetheless, they determined that the enhancement of nitrogen selectivity in membranes remained inadequate for gas separation applications. Similarly, Chiwaye et al. [35] also used a superstructure-based optimisation for 13.5% CO₂ flue gas and found that hybrid and multi-membrane N₂/CO₂ systems reduce total membrane area, which increases cost efficiency. These observations were supported by industry-wide comparisons. Studies such as He et al. [36] Investigated multiple membrane configurations utilising four distinct materials for diverse post-combustion carbon dioxide recovery systems in

cement and fossil fuel-fired power plants. The simulation results indicated that a 60% CO₂ removal efficiency can be achieved from a single membrane stage in a coal-fired power plant and cement factory, attributable to the higher carbon dioxide concentrations in the gas mixture, while a 40% efficiency is observed in the case of the natural gas power plant. Consequently, the authors recommended prioritising the integration of membrane technology in cement plants due to its reduced gas flow. Furthermore, they disclosed a capture rate of 70% as a conventional membrane procedure employed to minimise overall costs when utilising two membrane stages to achieve 95% purity standards.

In this research, the influence of the technological and economic incorporation of spiral-wound polymer membranes, created under the CO₂ Hybrid research initiative, into a 330 MW supercritical coal-fired power station (Rovinari, Romania), utilizing CHEMCAD 8.1 simulations. Three configurations were examined: (i) single-stage without vacuum, (ii) single-stage with vacuum, and (iii) two-stage membranes in series. The single-stage process without vacuum attained a goal capture efficiency of 90% solely at elevated compression pressure (8.5 bar) and wide membrane area (300,000 m²), albeit with suboptimal purity (50%). The incorporation of a vacuum pump diminished the requisite pressure (4.5 bar) and surface area (200,000 m²), in addition to decreasing power consumption; nonetheless, purity remained constrained (maximum 84%). A two-stage system enhanced CO₂ purity to 97% and capture efficiency to 93%; however, it required significant energy requirements (57% of plant output) and a reduction in overall plant efficiency from 45.78% to 23.96%. Economic analysis indicated that membrane surface area (SA1) and first-stage pressure (CP1) significantly impact CAPEX, OPEX, and LCOE, with elevated CP1 resulting in an LCOE increase of up to 42%. The authors assert that enhancing CO₂ permeability is essential for future sustainability [20].

Polymeric membranes for pre-combustion CO₂ recovery were assessed in an Integrated Gasification Combined Cycle (IGCC) environment in addition to post-combustion situations. The study [37] conducted a theoretical analysis of the integration of the pre-combustion process utilizing a CO₂-selective polymer membrane to capture over 95% of carbon dioxide with equivalent purity. In the oxygen-blown IGCC approach, a single membrane stage was considered, including a CO₂ permeability of 4.3×10^{-9} mol/s.m².Pa and a CO₂/H₂ selectivity of 30 to attain a high purity of recovered carbon dioxide. The authors disclosed the importance of CO₂/H₂ selectivity, which enhances CO₂ purity, alongside CO₂ permeance that directly affects the capture rate. The membrane CO₂ recovery pre-combustion process has been shown to be a viable technique that might be implemented into IGCC to achieve a high removal rate and purity.

Recent studies have revealed a steady trend in multi-stage membrane topologies for post-combustion CO₂ capture in coal-fired power plants. The study [38] performed an extensive process simulation of a two stages of the membrane method at varying CO₂ permeance and CO₂/N₂ selectivity to achieve a 90% CO₂ capture ratio with over 95% purity for CFPP. A comprehensive examination of membrane performance and operating pressures utilizing a high CO₂-selective membrane (> 300) has been performed to evaluate the membrane area and fractional energy. This paper examined an input gas of 117,745 kmol/h, comprising 12.46% CO₂, 14.97% H₂O vapor, and 72.57% N₂. The research demonstrated that enhancing the membrane's CO₂ permeability results in a reduction of the total membrane area required for a separation procedure, hence decreasing CO₂ capture expenses. The Huanghua proposal has successfully assessed the impact of membrane selectivity on economic evaluation.

A further examination conducted by Alabid and Dinca [39] performed a sensitivity analysis of post-combustion CO₂ capture from a 600 MW coal-fired power plant utilizing membrane technology, emphasizing the impact of membrane material permeability (300, 1000, and 3000 GPU) in conjunction with process variables including stage number, membrane surface area, and compressor pressure. Simulations evaluated one-, two-, and three-stage setups to achieve 90% capture efficiency and up to 99% CO₂ purity. A single-stage system reduced energy usage and costs but achieved poor purity (maximum 77%), rendering it inadequate for high-purity applications. Two steps enhanced purity but resulted in excessive energy consumption (340 MW) and elevated capture costs, rendering them commercially unviable. Three-stage systems attained 90% capture and 99% purity while utilizing around 12% less energy than two-stage systems, resulting in a 17% reduction in CO₂ capture costs and a 15% decrease in LCOE. High-permeability membranes (3000 GPU) improved recovery rates by as much as 87% and reduced power requirements. The research determined that three-stage designs exhibiting elevated CO₂/N₂ selectivity are both technically and economically advantageous, especially in large-scale facilities or under stringent CO₂ taxation scenarios.

An evaluation study [40] assessed the technical and economic performance of a two-stage membrane system for post-combustion CO₂ capture in a 1000 MW lignite-fired supercritical power plant. A single-stage membrane achieved 90% capture efficiency but only 70% CO₂ purity, necessitating a second stage to enhance purity. Using membranes with a CO₂/N₂ selectivity of 50 and a permeability of 1000 GPU in the second stage increased purity by 26%, reaching 95%. However, this enhancement necessitated substantial energy consumption approximately 53% of the plant's output (537 MW) primarily owing to compressor requirements. Parametric analyses indicated that increasing the first-stage pressure from 6 to 8 bar enhanced capture efficiency by 16%, but augmenting membrane area from 600,000 to 1,800,000 m² improved efficiency by 29%. The second stage, characterised by a reduced

surface area, improved CO₂ purity while lowering pressure demands, and the recycling of flue gas further augmented capture efficiency by 54%. Although target performance levels were achieved, the high capital cost (2190 M€) and energy-related operational costs reduced the net present value. The present work investigates the performance of improving CO₂ membrane permeance is essential for making the technology more economically viable in the future.

Recent study aims to amalgamate capture and conversion. An electrocatalytic membrane (eCatMem) [41] presented a new approach to CO₂ capture and electrochemical conversion through the use created by laser-induced graphene processing of a gas-separation membrane. The system, improved with Bi-based electrocatalysts, effectively separated CO₂, achieving a CO₂/N₂ selectivity of 20, while reducing it to formate with a Faradaic efficiency of 70% and current densities ranging from 10 to 50 mA cm⁻². The performance of pure CO₂ and 10% CO₂/N₂ mixtures was consistent, with the eCatMem achieving 18 mA cm⁻² at 1 V versus RHE. This method removes the necessity for distinct capture and utilization units, thereby simplifying the process and potentially decreasing costs by employing affordable, scalable materials and fabrication techniques. The research emphasizes the capability of integrated CCUS systems to reduce energy usage and enhance efficiency, suggesting that future efforts should focus on optimizing catalytic performance and operational stability to promote commercial viability.

Molecular-level study [42] utilized molecular dynamics simulations to evaluate the effects of hydrocarbon contamination (C₈H₁₈ films) on CO₂/N₂ separation through porous graphene membranes. Two nanopore varieties - oleophobic N24 and oleophilic C24 - were evaluated under identical conditions. The findings indicated that N24 demonstrated enhanced CO₂ transport rates and CO₂/N₂ selectivity post-contamination. The enhanced performance was associated with diminished hydrocarbon affinity, alleviating pore obstruction, and advantageous quadrupole interactions between CO₂ and N24. Conversely, the enhanced hydrocarbon selectivity of C24 resulted in considerable transport restriction. Simulations performed in GROMACS with periodic borders at 350 K demonstrated that oleophobic designs can reduce contamination effects, providing significant insights for the actual application of graphene membranes in CO₂ capture.

Park et al. [43] This review analyzed membrane-based CO₂ capture across the power, cement, steel, and biogas sectors, utilizing pilot-scale and simulation studies to evaluate the influence of gas properties on system design and performance. This underscores the adaptability of multi-stage, recycle, and vacuum-assisted configurations, emphasizing that process optimization is as important as material innovation. Expanding on this optimization-focused methodology Hara et al. addressed the process of separating carbon dioxide, its emission concentrations, and improving it by using a single-stage membrane. It also demonstrated the increase in costs with the increase in carbon emissions. Using a machine learning-based multi-objective Genetic Bayesian Optimization (MLB-MOGBO) algorithm, demonstrated that higher CO₂ purity generally reduces costs and emissions but alters the balance between capital and operating expenses. Pareto solutions found that increasing carbon dioxide emissions leads to increased energy consumption and lower costs. As for membrane area, increasing it reduces carbon emissions but increases costs [44].

In a complementary approach, Niesporek et al. [45] proposed and analyzed a hybrid system integrating membrane-based direct air capture (m-DAC) with CO₂ separation from a Combined Cycle (CC) power plant. Various ratios of air and flue gas were examined using single- and multi-stage membrane configurations to assess recovery rate, permeate purity, and energy intensity. A reference case aimed for 99% CO₂ product purity, revealing that standalone m-DAC is uncompetitive because of its substantial energy requirement (>30 GJ/tCO₂). Integration with a CH₄-fueled CC system markedly enhanced performance, reaching energy intensities as low as 2.22 GJ/tCO₂ when atmospheric air constituted 10% of the feed. The system exhibited scalability, excess electricity production, and the potential for net-zero or negative emissions; however, future research should incorporate life-cycle and techno-economic evaluations. Finally, Kim et al. [46] the researcher designed a catalytic membrane system for CO₂ capture, utilizing gas-solvent contactors combined with hydrophobic nanofiber membranes. The incorporation of SO₄²⁻/MCM-41 nanocatalysts into a 5 M MEA solution led to significant enhancements in CO₂ absorption and desorption change at relatively low regeneration temperatures. The catalytic sites enabled the cleavage of carbamate bonds, thus enhancing CO₂ release and decreasing the energy requirements for solvent regeneration. This method addresses prevalent challenges associated with solvent-based systems, such as degradation, fouling, and corrosion, while facilitating catalyst recovery and reuse. The research findings indicate that catalytic membrane contactors provide a sustainable and efficient method for CO₂ capture, especially when integrated with renewable or waste heat sources.

1.2 Summary

Membrane-based CO₂ capture has evolved from pilot-scale demonstrations to complex, multi-stage and hybrid configurations exhibiting capture efficiencies above 90% and product purities exceeding 95%. Despite these advancements, most systems remain constrained by high energy penalties associated with compression, vacuum, and gas recycling, which substantially erode net plant efficiency. Although many studies focus on process level optimisation, a significant research vacuum remains concerning long-term membrane stability, large-scale operational reliability, and techno economic integration under fluctuating load conditions. Additionally, the coupling of high-

permeability, high-selectivity membranes with renewable or waste-heat-driven auxiliaries remains insufficiently validated beyond simulation environments. The scarcity of experimental data on hybrid catalytic membranes further hinders the use of laboratory advancements in commercial settings. Consequently, future research should ideally focus on hybrid systems and materials engineering that will contribute to achieving a balance between sustainability, capture, and cost-effectiveness. This is one of the objectives of reviewing studies from that period up to the present year. Recent reviews [43–46] have extended these findings to cross-sectoral applications, optimization via machine learning algorithms, and catalytic membrane contactors combining gas solvent systems with nanostructured catalysts, all emphasizing that enhancing permeance and selectivity while reducing energy intensity remains the central challenge for the next generation of membrane-based CO₂ capture.

2 Overview of Carbon Capture Process

Carbon Capture and Storage technologies are designed to isolate gases in their purest form, supporting both economic feasibility and environmental sustainability [47]. The process is typically divided into three main phases: pre-combustion, oxy-fuel combustion, and post-combustion.

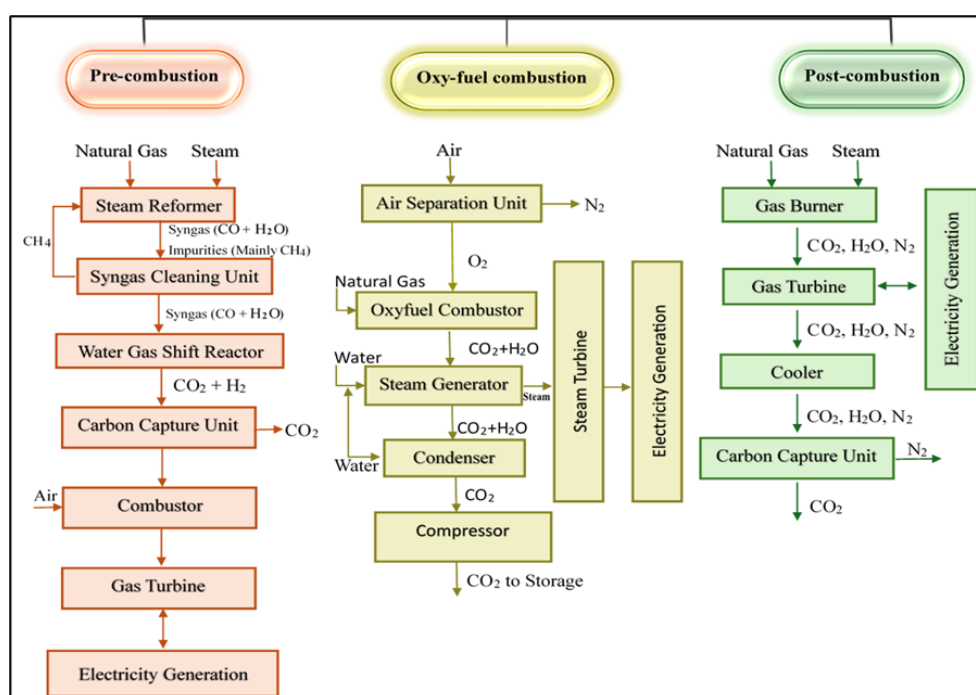


Figure 2. Carbon capture processes with main sources

Figure 2 illustrates three carbon dioxide capture systems used in power generation: pre-combustion, oxy-fuel combustion, and post-combustion. During pre-combustion, natural gas is initially converted into syngas (consisting of carbon dioxide and water) via steam reforming. In a gas-to-water reactor, the gas is purified and treated to produce carbon dioxide, which is captured before combustion. In oxy-fuel combustion, air is fractionated to yield pure oxygen, which is subsequently utilised to consume natural gas, generating a gas stream predominantly composed of carbon dioxide and water vapour. Carbon dioxide is captured post-combustion. In post-combustion, natural gas is burned with air, producing flue gases containing carbon dioxide, which are subsequently cooled before being collected. In each method, the carbon dioxide is separated and prepared for storage or later use.

2.1 Pre-Combustion Carbon Capture

This technique utilizes either natural gas or gasified hydrocarbon feedstock as fuel. Natural gas undergoes Auto Thermal Reforming (ATR) to produce CO and H₂, followed by the conversion of CO into CO₂ via the shift reaction. Suppose a hydrocarbon (such as coal or heavy oil) is subjected to gasification with steam and air or oxygen at high temperature and pressure. In that case, it is subsequently processed through the shift reaction to produce CO₂, H₂, COS, and other gaseous compounds, depending on the composition of the hydrocarbon [48, 49].

The pre-combustion pathway is an important method in carbon capture technologies (see Figure 3). A common fuel like coal reacts with air or pure oxygen to produce syngas through partial oxidation [21]. Alternatively, or in combination, steam reforming can be used, with the heat from the exothermic partial oxidation providing heat to the endothermic steam reforming process. This combined technique is known as autothermal reforming (ATR) [50, 51].

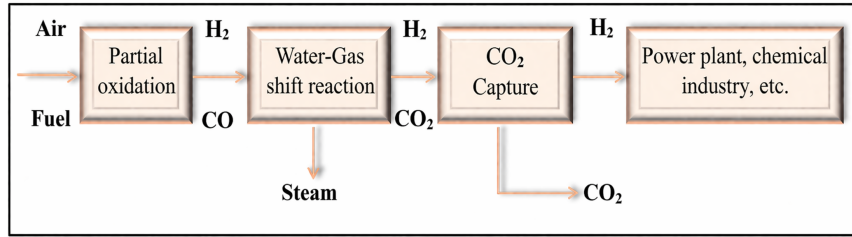


Figure 3. Streamlined diagram of the pre-combustion pathway

2.2 Oxy-Fuel Combustion Carbon Capture

Oxy-Fuel Combustion (OFC) is a promising technology for power plants and various industrial sectors, designed to achieve clean combustion that produces primarily CO_2 and water vapor, thereby facilitating carbon capture and reducing nitrogen emissions (see Figure 4). One of the primary challenges of this method is producing high-purity oxygen at a reasonable cost [7, 52].

The application of oxy-fuel combustion in coal-fired power plants is categorized into two types: Oxy-fuel Pulverized Coal Combustion (Oxy-PCC) and Oxy-fuel Fluidized bed combustion (Oxy-FBC) [53]. Oxy-PC relies heavily on Recycled Flue Gas (RFG) to control combustion conditions, whereas Oxy-FBC offers unique advantages, including the potential to reduce furnace size by increasing the oxygen concentration of the incoming air and decreasing the RFG recycling rate. This optimization is further enhanced by improved heat recovery from circulating inert bed particles and the flexible heat recovery configuration throughout the furnace. Additionally, the circulating solids in the circulating fluidized bed furnace act as an adjustable parameter for regulating combustion temperatures [54, 55].

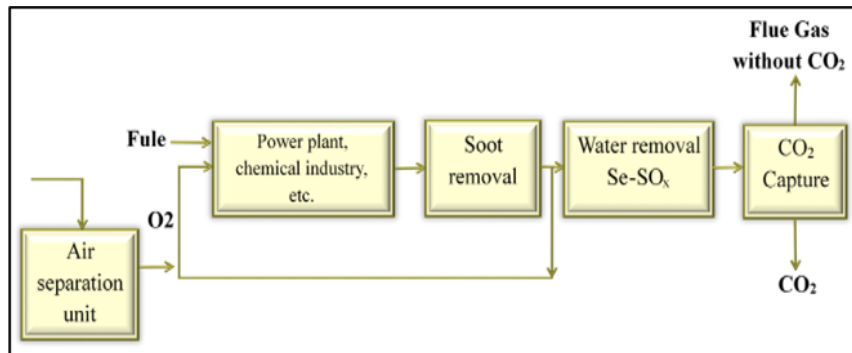


Figure 4. Simplified flowsheet of the oxy-fuel combustion route

2.3 Post-Combustion Carbon Capture

One of the most prominent capture technologies is a method for mitigating carbon emissions from power plants and industrial facilities without requiring major modifications to the system's infrastructure. This approach selectively separates and captures CO_2 from combustion products under conditions of low CO_2 partial pressure and high humidity [56].

In this process, an electrostatic precipitator is used to remove large particles from the hot exhaust gas released from the boiler. A Flue Gas Desulfurization unit (FGD) is then used to remove sulfur by-products. Post-combustion carbon capture technology is applied to purify the FGD outlet gas, as shown in Figure 5 [33, 57]. This technique will be examined in detail in Section 3 (CO_2 Post-Combustion Technologies), along with a discussion of various carbon capture technologies.

2.4 Comparison of the Processes

The method of carbon dioxide separation is a well-established technique that requires CO_2 extraction and has evolved alongside several full-scale industrial implementations. Numerous experimental and simulation studies have been conducted on these processes. The primary advantage of post-combustion capture is its seamless integration into existing power plants; however, the partial pressure and concentration of CO_2 in flue gases are relatively

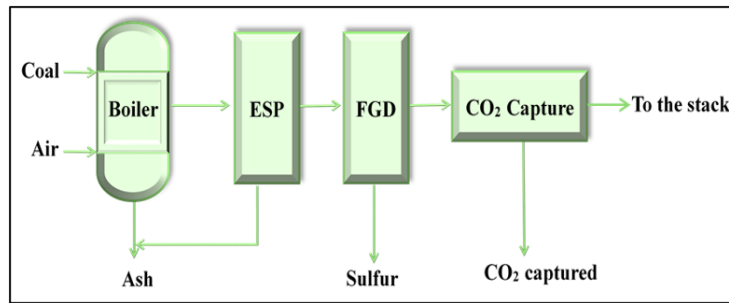


Figure 5. A scheme for cleanup of flue gas in post combustion CO₂ recovery

low. CO₂ must be transported and stored at a low concentration, which means achieving sufficient capture levels requires significant additional energy and cost. During the capture process using the Chemical Absorption Process (CAP), solvent degradation and substantial equipment corrosion can occur. Consequently, considerable investment in solvents and additional equipment is necessary to prepare the captured CO₂ for transportation and storage, which may increase the cost of electricity generation by up to 70% [58, 59].

Novel solvents are being investigated to reduce the cost of CO₂ capture. The substantial capital and operational expenses of this technique primarily arise from the extensive equipment requirements. Pre-combustion CO₂ capture is predominantly employed in process industries and is implemented in full-scale CCS facilities in certain sectors [60]. Unlike conventional combustion gas mixtures, the gas stream in pre-combustion capture contains a significantly higher proportion of CO₂. This approach requires less energy compared to post-combustion capture due to the higher pressure and lower gas volume; however, energy costs remain considerable [61].

The IGCC process primarily utilizes pre-combustion capture. This process requires extensive auxiliary equipment for efficient operation, resulting in higher capital expenditure compared to alternative systems. Nonetheless, power generation methods for CO₂ capture that do not require prior purification are relatively novel and have yet to be implemented at full scale [19, 62].

Oxy-fuel combustion is currently being explored in pilot-scale operations and several small demonstration plants. A notable example is the 50 MWth prototype power plant in Texas, built by Net Power using the Allam cycle concept, which represents a major advancement in oxy-fuel combustion technology and aims to achieve near-zero emissions. Additional advantages of this approach include a reduced equipment footprint, compatibility with various coal types, and the elimination of a permanent chemical plant [61].

However, the process requires a substantial amount of high-purity oxygen. Consequently, oxygen production necessitates an Air Separation Unit (ASU) [63]. Membrane-based CO₂ capture methods, when integrated effectively into the power cycle, may serve as a competitive alternative to cryogenic ASUs. The ASU and CO₂ compression units used in this process lead to a significant reduction in net power output. Additionally, there are technical challenges that require further investigation to fully evaluate the overall system performance. Nonetheless, due to the absence of additional costs specifically for CO₂ capture, this approach remains promising for producing energy at a lower cost with minimal emissions [29].

Table 2 presents a comparison of the thermal efficiency of power plants employing different carbon dioxide recovery methods. The efficiencies listed are based on the Lower Heating Value (LHV) of the fuel. Bituminous coal is considered for coal-based power plants due to its widespread use in energy generation. In an IGCC power plant with a GE-type gasifier, pre-combustion CO₂ capture is implemented using the Selexol process [64].

Table 2. Power production and different efficiencies comparison with several CO₂ recovery methods [65–67]

Fuel Type	Method	Net Efficiency (%)	Net Power (MW)
Coal	No Capture	44	758
	Pre-Combustion	31.5	676
	Oxy-Combustion	35.4	532
	Post-Combustion	34.8	666
	Oxy-Combustion (Allam Cycle)	51	226
Natural Gas	No Capture	55.6	776
	Pre-Combustion	41.5	690
	Oxy-Combustion	44.7	440
	Post-Combustion	47.4	626
	Oxy-Combustion (Allam Cycle)	59	303

3 CO₂ Post-Combustion Technologies

The three main techniques for capturing carbon dioxide precombustion, oxy-fuel combustion, and post-combustion depending on the system design and process requirements, can be implemented using the following methods: chemical and physical absorption, membrane separation, adsorption, microbial/algae-based capture, and cryogenic separation (see Figure 6). Among these, post-combustion capture is the most widely applied method [68–70].

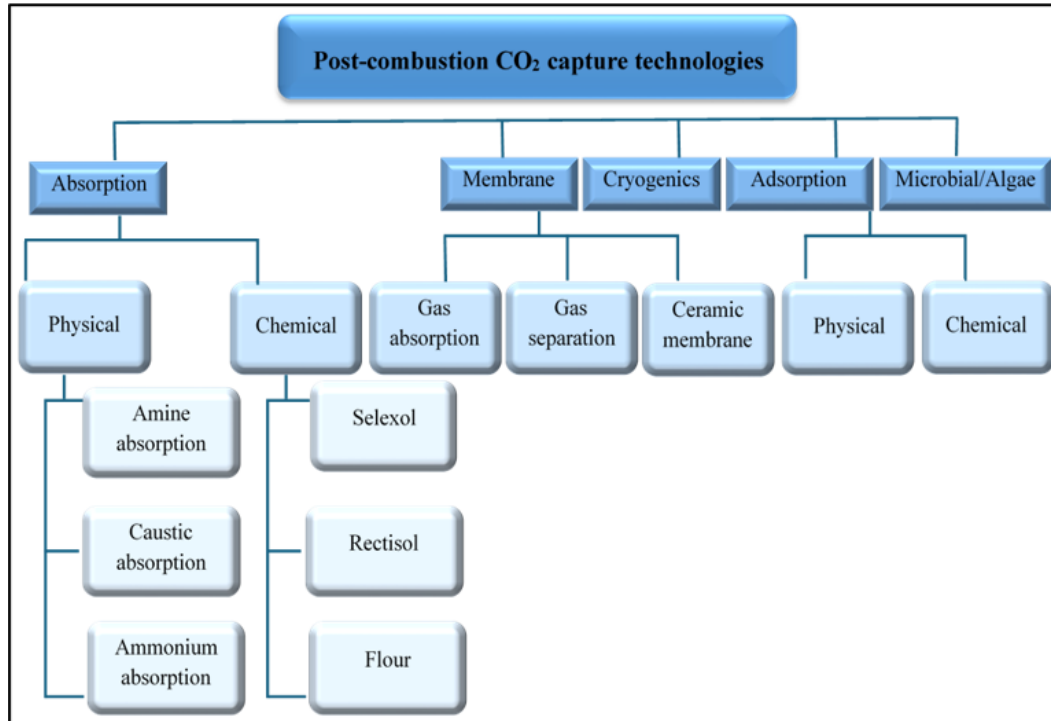


Figure 6. Classification of CCS techniques based on post-combustion process

3.1 Absorption

The most common approach to carbon dioxide recovery involves capturing it from power plant exhaust gases using a solvent. This is followed by stripping the CO₂ from the solvent and regenerating the solvent for reuse in repeated cycles. The captured CO₂ is then injected into deep geological formations or utilized in underground storage sites, such as depleted oil and gas reservoirs, abandoned mines, and offshore drilling wells [71]. Additionally, captured CO₂ serves as a valuable raw material in various industrial applications. For example, it is used in the fertilizer industry to produce urea, in the food and beverage sector as a safe preservative, in the petroleum industry to enhance oil recovery, and in the chemical industry to manufacture compounds such as methanol, ethanol, and ethers.

Carbon capture utilising solvents is classified into two main categories: physical adsorption and chemical adsorption, as shown in Table 3, which compares types. Chemical adsorption generally demonstrates greater efficiency in carbon dioxide removal; however, it incurs higher operational and energy costs relative to physical adsorption methods, which, although more economical, exhibit reduced efficiency. The results indicate the potential advantages of integrating adsorption techniques to enhance performance.

3.2 Cryogenics

Cryogenic separation technology involves a series of cooling and compression processes conducted at sub-ambient temperatures and high pressures to separate gaseous components from the carrier stream. This technology is widely used to produce high-purity liquid carbon dioxide, particularly for food processing applications. It is commonly applied in pre-combustion capture processes, which typically handle gas streams with high CO₂ concentrations (i.e., greater than 90% by volume) [76, 77].

3.3 Adsorption

The adsorption process is a separation technique in which carbon dioxide molecules from flue gas migrate to the surface of a solid sorbent, such as activated carbon or zeolite, and adhere through physical interactions (e.g., van der Waals forces) or chemical bonding mechanisms (e.g., ion exchange). This mechanism relies on the extensive surface

Table 3. Comparison of chemical and physical absorption [72–75]

Aspect	Chemical Absorption	Physical Absorption
Core Principle	Chemical reaction between CO ₂ and solvent (e.g., amines).	Physical dissolution of CO ₂ in solvent (Henry's Law).
Operating Conditions	Low temperature, low CO ₂ partial pressure.	Low temperature, high CO ₂ partial pressure (>3.5 bar).
Typical Solvents/Applications	MEA, DEA, MDEA, DGA (amines); post-combustion (power plants, cement, steel).	Methanol, Selexol, NMP, Fluor, Morphysorb; pre-combustion (natural gas, syngas, hydrogen plants).
Technology Maturity	Most established CO ₂ capture method.	Commercialized for specific high-pressure systems.
CO ₂ Capture Efficiency	Very high (>90% with MEA).	High at elevated pressures.
Regeneration Method	Thermal stripping (high energy consumption).	Pressure reduction or heating (lower energy demand).
Advantages	High capture rate, suitable for retrofits.	Lower cost, low corrosion, compact equipment in high-pressure systems.
Limitations	High energy use, corrosion, solvent degradation by flue gas impurities.	Requires high pressure, less effective at low pressure, high compression energy.
Corrosion Risk	High (amine degradation and corrosion).	Low (stable, less reactive solvents).
Equipment Size	Larger due to low driving force.	Smaller when CO ₂ partial pressure is high.

area and active binding sites of the sorbent, which enhance its capacity to collect and retain carbon dioxide molecules selectively [78]. During saturation of the sorbent material, carbon dioxide is released (absorbed) either by reducing the system pressure in Pressure Swing Adsorption (PSA) or by increasing the system temperature in Temperature Swing Adsorption (TSA). The processes of adsorption and desorption facilitate the reuse of the sorbent, making the method renewable and suitable for repeated carbon dioxide capture [79].

3.4 Microbial and Algae

One of the most promising technologies for capturing carbon from power plants (flue gases), petrochemical plants, food and supplement industries, water treatment facilities, and biohydrogen and biogas production plants involves the development and simulation of systems that enhance algae growth by absorbing CO₂ for photosynthesis [80].

While previous studies have successfully achieved the mass transfer of CO₂ into algae systems, the focus on manipulating water chemistry as a controlled parameter is novel in the context of optimizing carbon utilization efficiency [81].

3.5 Membrane

Membrane technology is a promising and efficient approach that can compete with traditional carbon dioxide mitigation methods in terms of energy efficiency while maintaining the existing infrastructure and operational layout of the plant [82].

Notwithstanding these advantages, significant challenges remain—particularly in the selection of suitable membrane materials and the design of processes to enhance separation performance. Gas separation through membranes is fundamentally based on differences in physical or chemical interactions between the gas species and the membrane material. This enables preferential transport, allowing certain components to permeate the membrane more readily than others [83].

In most membrane systems, gas separation is governed by the solution-diffusion mechanism, in which a pressure differential between the feed and permeate sides serves as the primary driving force for gas transport. Membrane processes offer operational advantages by mitigating common issues associated with traditional absorption systems, such as foaming, flooding, channeling, and weeping. Furthermore, membranes enable efficient management of gas and liquid flows while providing a large surface area for mass transfer [38].

However, the efficiency of membrane systems generally decreases at lower CO₂ concentrations, limiting their applicability in certain contexts. Despite this, membrane-based CO₂ capture remains a versatile option, with potential applications in coal-fired power generation, natural gas processing, and various sectors of the chemical industry [33, 84].

Due to the widespread occurrence of industrial pollution and insufficient regulation of harmful emissions, membrane technology has emerged as an effective solution that can be seamlessly integrated into both conventional and renewable energy facilities, as well as other industrial systems. Membranes can separate emitted gas molecules without complex chemical reactions or significant energy input. Membrane technology can be applied pre-combustion to enhance fuel quality, where flammable components are used to adjust gas composition. It is also

employed post-combustion to recover the resultant gases or redirect them to alternative industrial applications for further utilization [43].

Figure 7 illustrates a schematic of membrane technology integrated into a coal-fired power plant for the post-combustion process [40].

Regarding membrane CO₂ removal design, the application of a single-stage membrane under any operating conditions yielded suboptimal CO₂ capture, indicating that a two-stage membrane system is more economically viable than a three-stage configuration. The three-stage arrangement showed only a marginal reduction in CO₂ capture costs compared to the two-stage system, while also being more complex. The membrane surface area and compressor energy requirements are widely recognized as the primary factors influencing the overall cost of membrane technology [39].

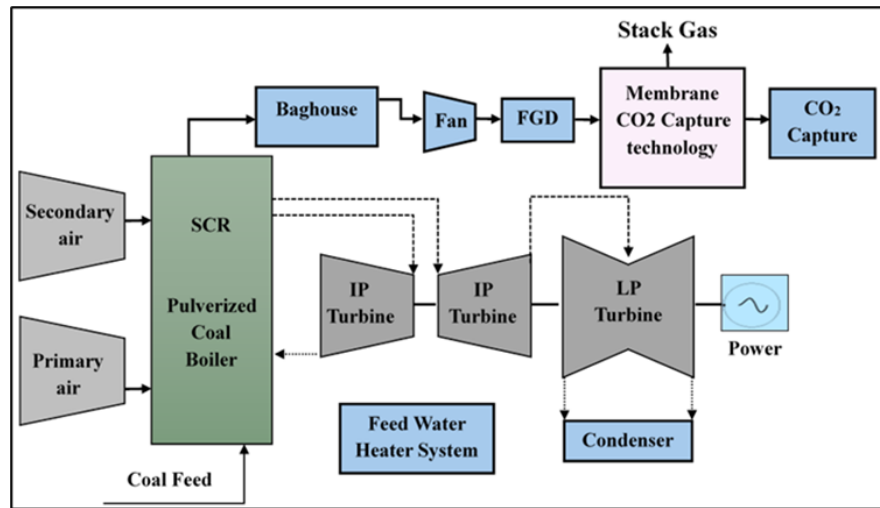


Figure 7. Diagram of the supercritical coal-fired power plant

According to the study [40], a steam cycle plan is essential for the design of a multi-stage membrane CO₂ removal process to achieve high efficiency and purity. In this design, the residual stream from the second membrane stage is recirculated to the mixer before the first compressor, which helps reduce carbon dioxide emissions and increase the overall capture rate. The use of two separate compressors—one before each membrane stage—along with the addition of an expander to the residual stream from the first membrane, was also examined to determine the optimal configuration and enhance the performance of the supercritical CFPP. Figure 8 illustrates the approved schematic, emphasizing the integration of a steam cycle to achieve high efficiency and purity in the multi-stage membrane CO₂ removal process.

The implementation of an expander unit in the nitrogen-rich stream improved the economic performance of the overall CO₂ capture system. The Levelized Cost of Electricity (LCOE) was reduced by 19%, achieving higher capture efficiency and purity. Integrating the expander into the membrane CO₂ capture system also increased project profitability by approximately 11% compared to a similar project without the expander unit [40].

This versatility underscores the multi-functional nature of membranes and their ability to be integrated into various energy systems, positioning them as a key component in the development of environmentally friendly separation technologies. Table 4 presents the different aspects of this technique when applied across the main separation methods [55, 85, 86].

3.5.1 Membrane gas separation

The membrane is a physical barrier or thin layer that acts as a filter, allowing selective molecules to pass through. This is illustrated in Figure 9, which depicts the membrane separation process, where the driving force is typically a pressure or concentration gradient across the membrane [87].

To reduce the costs and energy requirements of the CO₂ recovery process, various alternatives have been proposed, employing absorbents and membranes to achieve a projected removal cost of 40 EUR per tonne of CO₂ by 2025, according to DOE/NETL [88].

Membrane carbon capture technology has emerged as a viable alternative for gas separation in recent years. Compared to traditional gas separation methods (such as Chemical Absorption Processes, CAP), membrane technologies offer significant economic and design advantages and present opportunities for further development [89]. As a result, many companies and industries have adopted membrane systems due to their benefits, which include [20]:

- Ease of combination with traditional capture processes, also known as hybrid processing.

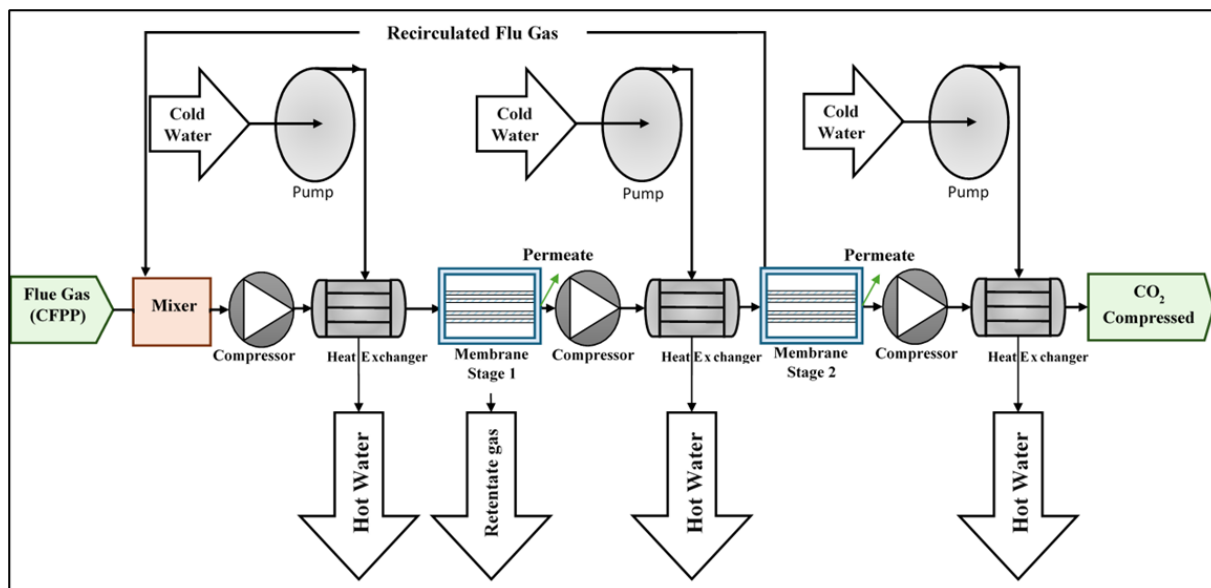


Figure 8. Scheme of a two-stage process for the membrane

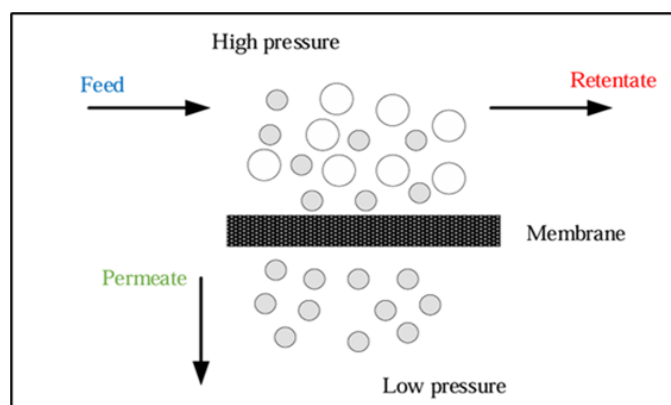


Figure 9. Membrane gas separation principle

- The ability to overcome thermodynamic limitations.
- Flexibility in operation and maintenance.
- Low environmental impacts.
- Ease of installation.
- Energy efficiency.

3.5.2 Hybrid membrane systems with other technologies

Combining membrane technology with other separation methods, such as absorption, cryogenic separation, and adsorption, is a strategy that can enhance CO₂ capture efficiency. Hybrid systems leverage the advantages of each technology, thereby reducing energy consumption and lowering costs. Hybrid CO₂ capture processes can be classified into three primary configurations: series, parallel, and integrated arrangements. The series configuration is the predominant approach for integrating multiple CO₂ capture processes in hybrid systems due to its distinctive CO₂ collection efficiency, which has recently attracted significant research interest. This evaluation focuses on the series arrangement. Additionally, the integrated system, which incorporates the well-studied membrane contactor technique, represents another complex yet promising approach.

Recent studies have assessed the energetic and economic advantages of in-series hybrid systems. A review by Yu et al. [90] demonstrates that membrane-cryogenic or membrane-absorption hybrids in series can diminish specific energy consumption to approximately 1.6–2.0 GJ per tonne of CO₂ captured (for flue-gas CO₂ concentrations in the 13–20% range) while attaining CO₂ purities exceeding 90%. A membrane-cryogenic series configuration attained approximately 1.65 GJ/tCO₂, with a capture cost of around US\$ 36/tCO₂.

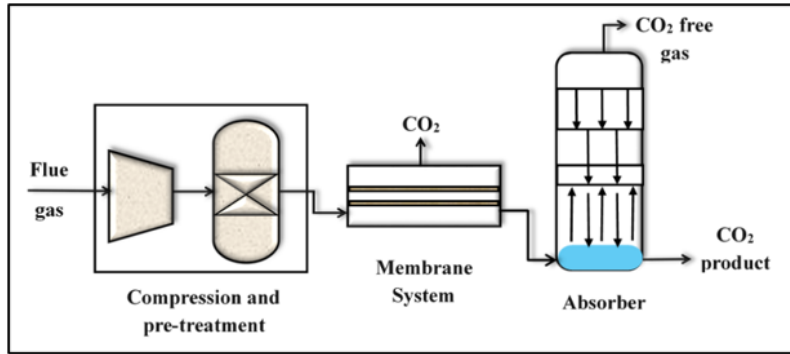
(1) Membrane-Absorption Hybrid Systems

Table 4. Comparison of membrane-based CO₂ capture for the three major technologies

Aspects	Pre-Combustion	Oxy-Combustion	Post-Combustion
Feed Gas Characteristics	High CO ₂ concentration and high pressure (syngas)	Nearly pure CO ₂ with N ₂ largely removed by oxygen firing	Low CO ₂ concentration at near-atmospheric pressure (flue gas)
Driving Force for Separation	Strong (due to high pressure and CO ₂ fraction)	Moderate to strong (depending on system design)	Weak (low partial pressure difference)
Membrane Requirements	High selectivity and chemical resistance under high pressure and temperature	High stability to handle high CO ₂ concentration and possible impurities	High performance to reduce large membrane area and energy demand
Process Integration	Often combined with cryogenic or PSA units for purity enhancement	Linked with oxygen production and flue gas recycling	Integrated with flue gas treatment (e.g., SO _x /NO _x removal, cooling)
Energy Intensity	Lower than chemical absorption	Moderate; dominated by oxygen production cost	Higher because of dilute CO ₂ streams and large gas volumes
Cost Competitiveness	Promising, especially with hybrid (membrane-cryogenic) systems	Potentially competitive depending on oxygen supply efficiency	Challenging due to scale and energy penalty
Industrial Application Potential	Suitable for IGCC and hydrogen production plants	Emerging option in advanced combustion systems	Widely applicable in existing power plants but limited by cost

The membrane–absorption hybrid process is the most extensively studied among hybrid CO₂ capture systems. The liquid absorbents used in this method typically include primary amines (e.g., monoethanolamine, MEA), secondary amines (e.g., piperazine, PZ; diethanolamine, DEA), tertiary amines (e.g., triethanolamine, TEA), and blended amines (e.g., methyl diethanolamine, MDEA; N-diethylethanolamine, DEEA–MEA) [91].

As shown in Figure 10, using a membrane for CO₂ pre-concentration reduces the load on the absorption system and minimizes the amount of absorbent required.

**Figure 10.** Schematic representation of the hybrid membrane-absorption system [91]

(2) Membrane-Cryogenic Hybrid Systems

The results of this study indicate that hybrid membrane and cryogenic capture processes benefit from a nitrogen membrane-based pre-concentration system integrated with a cryogenic condensation method [92]. A hybrid membrane–cryogenic CO₂ capture technique, combined with Exhaust Gas Recirculation (EGR), an Energy Recovery System (ERS), and multi-stream cryogenic heat exchangers, is proposed, as shown in Figure 11 [93].

A hybrid membrane–cryogenic process integrating cryogenic condensation with N₂-selective membranes (H3) demonstrated the highest economic efficiency, with an energy consumption of 1.342 GJ/tCO₂ and a capture cost of \$23.36/tCO₂, representing a 5% reduction compared to conventional membrane–cryogenic methods. The process achieved an 8–20% decrease in energy use and a 17–27% reduction in capture costs relative to previous studies. The process design and concept described here can be applied to a variety of CO₂ capture applications, not limited to post-combustion collection in power plants. There is significant potential for membrane-based gas separation in various industrial applications through the integration of cryogenic condensation with membrane modules [94, 95].

Recent techno-economic evaluations indicate that integrating membrane-absorption and membrane-cryogenic systems enhances the energy effectiveness and value of post-combustion carbon dioxide capture. Dong et al. [91]

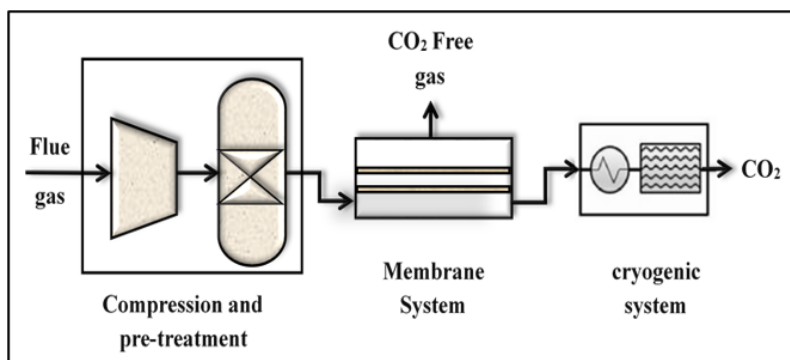


Figure 11. Schematic representation of the hybrid membrane-cryogenic system

report that membrane–absorption hybrids attain CO₂ capture efficiencies of 90–95%, yield 2.5–3.5 GJ of total energy per tonne of CO₂, and incur capture costs ranging from 40 to 55 USD per tonne of CO₂, contingent upon the solvent regeneration method employed. Song and colleagues conducted a study on membrane-cryogenic systems (2024), demonstrating marginally elevated energy consumption (3.5–4.5 GJ t⁻¹ CO₂) while yielding ultra-pure CO₂ (>99.9%) suitable for compression and transport. The systems maintain competitive capture costs of approximately 35–45 USD t⁻¹ CO₂ due to partial cold-energy recovery during CO₂ liquefaction. These investigations collectively indicate that membrane–absorption hybrids are advantageous for medium-scale applications necessitating reduced regeneration energy, whereas membrane–cryogenic designs are better suitable for large-scale operations requiring high CO₂ purity and storage readiness [96].

4 Carbon Capture, Utilization, and Storage Strategies

Carbon capture, utilization, and storage (CCUS) encompasses a range of technologies designed to capture CO₂ emissions, transport them to designated sites, securely store them, and utilize them in various industrial processes. Among these stages, CO₂ capture alone accounts for over 70% of the total operational costs associated with CCS systems [97].

Current trends aimed at diminishing emissions and economic expenditures include the incorporation of renewable energy sources and enhancements in system efficiency. The research conducted by Rizvi et al. [98] in Chhattisgarh indicates that the implementation of grid-connected floating solar power systems can lead to a reduction in CO₂ emissions by as much as 44%.

Monitoring, Reporting, and Verification (MRV) systems are essential for ensuring the operational and environmental safety of CCUS technologies throughout a project's lifespan by tracking performance and detecting potential risks early. MRV procedures serve as critical tools for mitigating operational and environmental hazards, particularly those related to storage safety and sustainability. Risk management during the MRV phase includes regular monitoring of CO₂ behavior within storage reservoirs, accurate verification of stored CO₂ quantities, and timely, transparent reporting based on monitoring and verification data. Collectively, these procedures help ensure regulatory compliance, enhance public confidence, and support the long-term reliability of CCUS projects [99].

4.1 CO₂ Storage

In recent years, there has been a significant increase in the reliance on geological formations to store and secure captured carbon dioxide, driven by the continued rise in greenhouse gas emissions and atmospheric pollution. This strategy supports industrial sectors—including cement production, iron and steel manufacturing, the petroleum and energy industries, and food production—in reducing their carbon footprints by either storing excess CO₂ or recycling it for industrial applications [100–102].

Carbon sequestration methodologies are grounded in scientific principles, particularly absorption mechanisms. Sequestration techniques are generally divided into two main categories: direct and indirect. The capture and storage process consists of four key stages: i) capture, ii) transport, iii) compression, and iv) injection of CO₂. The compressed CO₂ is injected into underground formations under appropriate injection parameters (e.g., injection rate and pressure) [103].

CCU products provide temporary carbon storage. Because the storage is temporary, CO₂ emissions can be postponed, meaning they do not contribute to climate change during the storage period. Consequently, temporary storage does not offer any independent or additional benefit regarding climate change mitigation. The significance of temporary storage depends on the type of CO₂-derived product or fuel under consideration. For CO₂-derived products and fuels that have the same chemical structure and composition as their conventional counterparts, carbon

storage provides no additional advantage, as the product lifespan after manufacture is identical for both types, and the amount of chemically bonded carbon remains the same [104, 105].

Mansour et al. [106] have shown that the total storage capacity in “sustainable development” could reach a substantial 100 Gt of carbon dioxide by 2055 compared estimated to what the International Energy Agency (IEA) estimated for 2020, the global capacity for storing carbon dioxide is estimated to be between 8,000-55,000 Gt, with onshore storage capacities being much better than those at sea.

4.2 CO₂ Utilization

In addition to storing carbon dioxide, CCU technology focuses on exploring diverse applications for CO₂ as a valuable resource, rather than merely treating it as a pollutant. This technology must be economically viable, operationally safe, and environmentally sustainable. Recent studies highlight several promising areas for CO₂ utilization, including: (i) Biological uses: It enhances algae growth and improves agriculture in greenhouses. (ii) Mineralisation and mineral storage: involve the reaction with rocks and minerals to produce stable solid carbonates, which are utilised in construction materials like cement. (iii) Industry: In various industries, such as soft drinks, firefighting, and refrigeration. (iv) Water Desalination: Dissolving CO₂ in salty water produces carbonic acid, which reduces sedimentation and alkalinity, making the water pH 7. This makes the process of removing salts easier using membranes. (v) Enhanced Oil Recovery (EOR): To increase the amount of oil extracted from wells, carbon dioxide, when injected into oil reservoirs, helps reduce the viscosity of the oil, thereby accelerating its flow through oil wells [107–110].

5 Conclusion

CO₂ capture applications are commonly classified into pre-combustion, oxy-fuel combustion, and post-combustion techniques. Pre-combustion involves extracting carbon dioxide from syngas at high pressure before fuel combustion. Oxy-fuel combustion relies on almost pure oxygen to produce a CO₂-rich flue gas, whereas post-combustion focuses on the direct capture of CO₂ from flue gas emissions. Membrane technology, which captures carbon dioxide at moderate concentrations from power plants, has been highly successful without requiring modifications to plant design. Hybrid membrane systems have gained interest in post-combustion applications because they combine the standard advantages of membranes with fewer drawbacks. Recent research, however, emphasizes hybrid membrane systems that integrate membranes with absorption, desorption, and cryogenic separation technologies. Membrane-absorption hybrids operate by treating CO₂ prior to solvent use, while membrane-cryogenic hybrids consume slightly less energy due to a reduced cooling load. These integrations employ membranes to enhance separation processes, with additional methods aimed at achieving maximum CO₂ purification.

Captured carbon dioxide can be compressed and transported for storage in deep saline aquifers, depleted oil and gas reservoirs, or unmineable coal seams, thereby ensuring long-term sequestration. Additionally, it can be utilized for enhanced oil recovery, mineral carbonation, or as a feedstock for chemicals and industrial fuels.

Overall, Future research must focus on optimising materials to improve CO₂ selectivity and permeability, along with implementing system-level hybridisation to reduce capture costs to below 40 USD per tonne of carbon dioxide. Demonstrating at pilot-to-commercial scale is essential for validating long-term stability and energy recovery performance, thereby facilitating the sustainable adoption of membrane-driven carbon dioxide capture in power and process industries.

Author Contributions

Conceptualization, D.A.; methodology, D.A.; validation, D.A. and M.K.I.; formal analysis, D.A.; investigation, D.A.; resources, D.A.; data curation, D.A.; writing—original draft preparation, D.A.; writing—review and editing, D.A. and M.K.I.; visualization, D.A.; supervision, M.K.I.; project administration, M.K.I. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used in this study are derived from published literature and are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Nomenclature

PPM	Parts Per Million
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Utilization and Storage
CFPP	Coal-Fired Power Plant
FSC	Fixed Site Carrier
IGCC	Integrated Gasification Combined Cycle
eCatMem	Electrocatalytic Membrane
CC	Combined Cycle
m-DAC	Membrane-based Direct Air Capture
ATR	Auto Thermal Reforming
OFC	Oxy-Fuel Combustion
Oxy-PCC	Oxy-fuel Pulverized Coal Combustion
Oxy-FBC	Oxy-fuel Fluidized Bed Combustion
RFG	Recycled Flue Gas
FGD	Flue Gas Desulfurization
MLB-MOGBO	Machine Learning-Based Multi-Objective Genetic Bayesian Optimization
CAP	Chemical Absorption Process
ASU	Air Separation Unit
LHV	Lower Heating Value
PSA	Pressure Swing Adsorption
TSA	Temperature Swing Adsorption
LCOE	Levelized Cost of Electricity
MEA	Monoethanolamine

PZ	Piperazine
DEA	Diethanolamine
TEA	Triethanolamine
MDEA	Methyl Diethanolamine
EGR	Exhaust Gas Recirculation
ERS	Energy Recovery System
MRV	Monitoring, Reporting and Verification
AMA	Absorption Membrane Adsorption
EOR	Enhanced Oil Recovery