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Comparative Assessment of Carbon Capture Technologies: A Review

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Abstract
The use of non-renewable energy sources, such as oil and gas, is increasing every day. The use of various energy sources results in a significant carbon dioxide emission. This greenhouse gas's release into the atmosphere hastens the irreversible effects of global warming. Although Carbon capture and geological storage (CCS) is one of the most promising technologies to reduce greenhouse gas emissions and mitigate climate change, significant challenges remain in identifying the most effective, scalable and economically viable solutions for large-scale implementation. This research assesses the efficiency and developments of carbon capture technologies in reducing greenhouse gas emissions, with an emphasis on how broadly applicable they are to various industrial sectors. Although lowering CO_2 emissions is essential to halting climate change, the efficiency, affordability, and scalability of current carbon capture technologies vary widely. Effective techniques for capturing and storing carbon emissions are of paramount importance, considering the steadily increasing amount of carbon dioxide (CO_2) in the atmosphere due to the burning of fossil fuels by gas plants and other industrial and man-made products. The study assesses the scalability and effectiveness of various carbon capture technologies by figuring out each one's economic feasibility and environmental effects, as well as which carbon capture method is most appropriate for specific industries and applications.

Keywords: energy, gas, renewable energy, scalability

Introduction

The escalating concentration of greenhouse gases, particularly carbon dioxide (CO_2), in the earth's atmosphere has become a critical driver of climate change, posing significant threats to ecosystems, human health, and socioeconomic stability. As a result, there is a pressing need for effective strategies to mitigate carbon emissions and limit global warming to mitigate the adverse impacts of climate change. The high concentration of carbon dioxide (CO_2) in the atmosphere has negative effects on the environment therefore, it is necessary to reduce its emission (Petru *et al*., 2016).

Due to several human activities, the amount of CO_2 released into the atmosphere has been rising extensively during the past few years. There has been a net increase in carbon dioxide concentrations in the atmosphere from about 280 ppm in 1850 to 364 ppm in 1998. The main reason is due to human activities during and after the Industrial Revolution. Humans have been increasing the amount of carbon dioxide in the air by burning fossil fuels, producing cement, deforestation, and carrying out land clearing and forest combustion. About 24% of the current atmospheric CO_2 concentrations exist due to these human activities, considering that there is no change in natural amounts of carbon dioxide. This increase in CO_2 is harmful to humans, animals, and plants. During the past few decades, global warming and consequent climate change have been heavily discussed, and several techniques and technologies have been developed to remove CO_2 from the atmosphere.

Carbon capture and storage (CCS) technologies have emerged as promising solutions for reducing CO_2 emissions from various industrial processes and energy production activities. CCS 7 involves capturing CO_2 emissions from point sources such as power plants, industrial facilities, and natural gas processing plants, transporting the captured CO_2 to suitable storage sites, and securely storing it underground in geological formations, depleted oil and gas reservoirs, or saline aquifers.

In recent years, significant advancements have been made in the development and deployment of carbon capture technologies, driven by increasing recognition of the urgency to address climate change and the growing demand for low-carbon energy solutions. Various carbon capture technologies have been proposed and implemented, including post-combustion capture, pre-combustion capture, oxy-fuel combustion, and direct air capture (DAC), each with its unique advantages, challenges, and applications. Despite the progress made, the widespread adoption of carbon capture technologies still faces several challenges, including technical, economic, regulatory, and public acceptance barriers.

Technical challenges include improving the efficiency, scalability, and cost-effectiveness of carbon capture processes, optimizing capture materials and sorbents, and minimizing energy penalties associated with capture and compression. Economic challenges relate to the high capital costs of implementing CCS projects, uncertain revenue streams, and the lack of clear market incentives or regulatory frameworks to incentivize carbon capture deployment.

Given these challenges and opportunities, there is a need for comprehensive research and assessment of carbon capture technologies to inform decision-making, policy development, and investment strategies.

Overview of Carbon Capture and Storage (CCS) Technologies

Industry and petroleum refineries are among the largest contributors to anthropogenic CO_2 emissions. In 2006, these two sectors together emitted more than 11 Gigatons (Gt) of CO_2 directly and indirectly, accounting for nearly 40% of total global CO_2 Emissions (IEA, 2006). CO_2 capture and storage (CCS), when combined with energy efficiency improvements, renewable energy sources, and nuclear energy, is seen to be a viable way to achieve a sizable decrease in CO_2 emissions. In addition to its high CO_2 emissions, CCS has a lot of promise in industry and petroleum refineries since many industrial processes produce petrol streams rich in CO_2 or even pure CO_2, which might lower the cost of CCS.

Farla *et al.*(1995) Conducted one of the first thorough investigations on the techno-economic performance of CO_2 capture from carbon-intensive industrial processes. The study focuses on using chemical absorption to extract CO_2. It concluded that the cost of CO_2 collection from a thermal power plant's flue emission is equivalent in the iron and steel sector but greater in the petrochemical sector.

The IEA Greenhouse Gas R&D Programme (IEA GHG) also delivered a set of reports on the techno-economic performance of CO_2 capture from cement plants and oil refineries in the late 1990s (IEA, 2000; IEA, 1999). These studies look into the performance of CO_2 capture technologies other than the chemical absorption approach. For the cement industry, the results indicate that kiln operation in a CO_2/O_2 atmosphere may be a promising technique for recovering CO_2, while the chemical absorption method appears less appropriate due to the high heat requirement, which is not readily available from the cement production process. For refinery heaters, amine-based flue gas capture and oxy-fuel combustion capture have extremely similar economic performance (Birat and Lorrain, 2009).

Since coal has been among the main sources of energy used worldwide, emissions of carbon dioxide (CO_2) have increased from approximately 180 to 280 parts per million (ppm) before industrialization. Between 1750 and 2011, the amount of CO_2 released into the atmosphere was 2040 ± 310 Gt CO_2. According to the Intergovernmental Panel on Climate Change Report (IPCC, 2007), by the end of the twenty-first century, the environment's temperature might rise by 1.1–2.9 °C at a lower emission rate or 2.4–6.4 °C at a higher emission rate as a result of unchecked greenhouse gas (GHG) emissions. Among GHGs, CO_2 emission is a major contributor to global warming (57.0%), followed by CH_4 (20.0%), CFCs (15.0%), and N_2O (~6.0%) (International Energy Agency, 2019).

Figure 1 illustrates the rise in CO_2 emissions over the past ten years across several energy sectors, with power plants experiencing the largest increase.

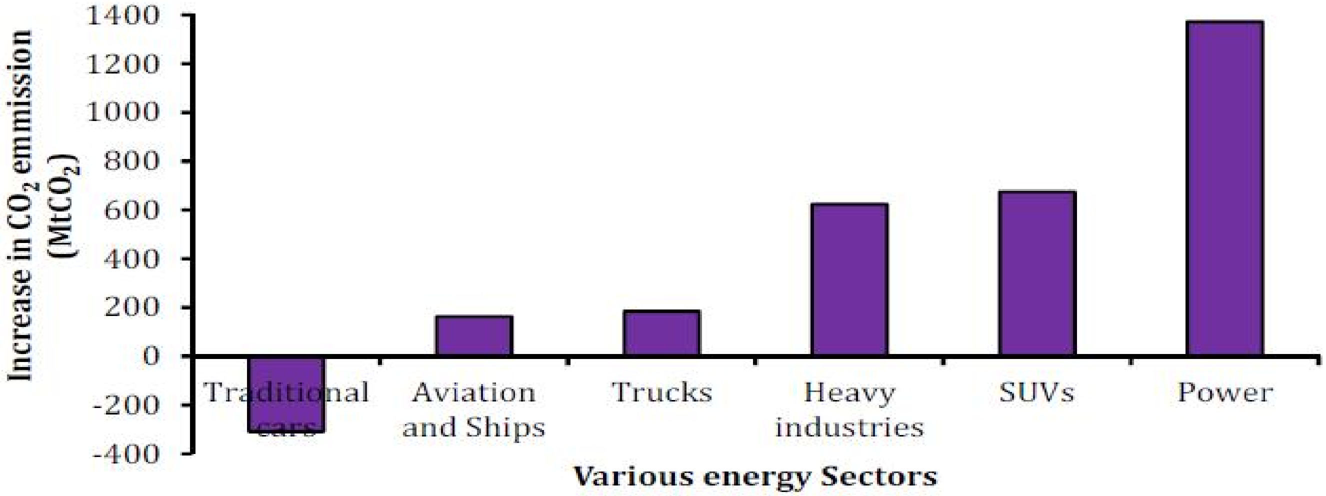

Fig 2 **Fig. 1.** Global scenario of CO_2 emissions in energy sector during 2010-2021 (IEA, 2021).

Carbon Capture and Storage (CCS) Technologies

With increasing concerns about the rising atmospheric concentration of anthropogenic greenhouse gases, efficient CO_2 emission reduction technologies such as Carbon Capture and Storage (CCS) are necessary to offset this trend. CCS is a "process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere." (IPCC, 2005). According to this concept, CCS consists of three main stages: (a) CO_2 separation, (b) transportation, and (c) Storage. There are three major approaches for CCS: Post-combustion capture, Pre-combustion capture and Oxyfuel combustion process (IPCC, 2005), with an addition of Direct air capture (DAC) in this report.

Post-combustion capture

Post-combustion capture involves removing CO_2 from exhaust gases emitted by industrial processes or power plants.

Post-combustion capture has some advantages since it allows existing combustion technology to be employed without requiring drastic adjustments. This makes post-combustion capture easier to install as a retrofit option for existing facilities than the other two methods. The benefit is at the expense of the efficiency of the power-producing process. The separation stage (CO_2 capture) consumes a lot of energy and so accounts for a significant percentage of the CCS process's cost. It accounts for around 75-80% of the total cost of CCS (Davison, 2007). Several separation technologies could be employed with post-combustion capture. These include (a) adsorption, (b) physical absorption, (c) chemical absorption, (d) cryogenics separation, and (e) membranes-based separation (see, for example, IPCC, 2005). The many separation technologies available for post-combustion capture are categorized in Figure 2. This review paper's context will be established with a quick introduction to these technologies.

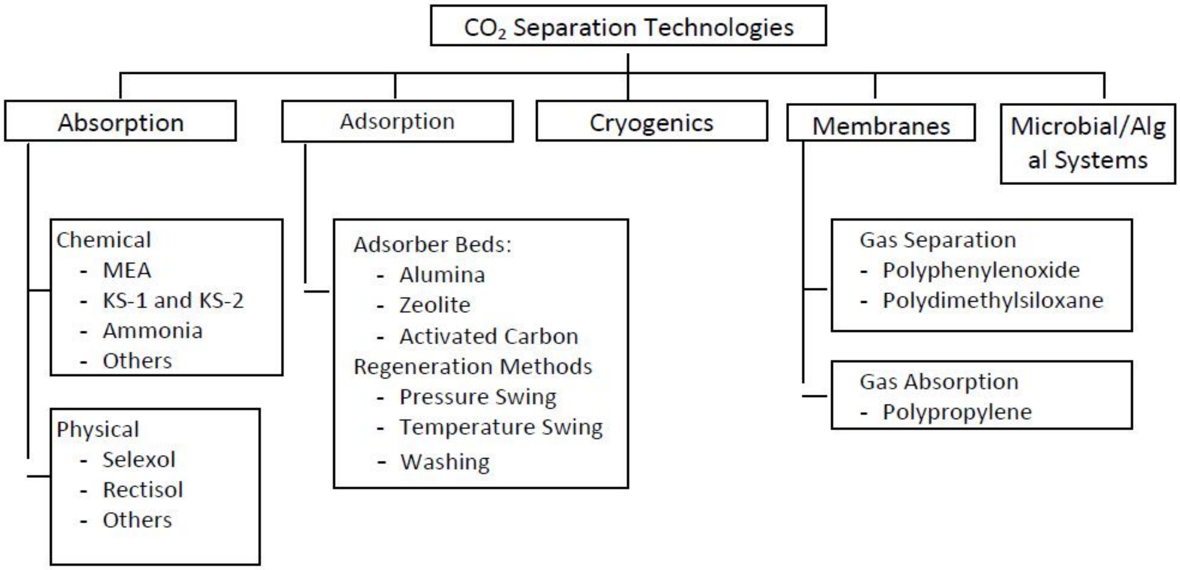

Figure 2: Process technologies for post-combustion CO_2 capture adapted from (Rao and Rubin,2002)

- Adsorption

Adsorption is a physical process that involves the attachment of a gas or liquid to a solid surface. The adsorbent is regenerated by the application of heat (temperature swing adsorption, TSA) or the reduction of pressure (pressure swing adsorption, PSA) (). Adsorbents which could be applied to CO_2 capture include activated carbon, alumina, metallic oxides and zeolites (IEA GHG, 1993; Zhao *et al.,* 2007). The majority of accessible adsorbents have limited adsorption capacities, which could present serious problems at this scale. Additionally, due to the relatively low selectivity of the majority of available adsorbents, the flue gas streams that need to be treated must include large quantities of CO_2. For instance, zeolites have a stronger affinity for water vapour. (IEA 2004, IEA 2007, Zhao *et al.,* 2007)

- Physical Absorption

This involves the physical absorption of CO_2 into a solvent, according to Henry's law. Regeneration can be accomplished using heat, pressure decrease, or both. Absorption occurs at high CO_2 partial pressures. As a result, the main energy requirements come from flue gas pressurisation. Physical absorption is consequently not cost-effective for gas streams with CO_2partial pressures less than 15vol% (Chakravati*et al.,* 2001; IEA 2004). Selexol (dimethyl ethers of polyethene glycol) and Rectisol (methanol) are common solvents (IEA GHG 1993).

- Chemical Absorption

Chemical absorption is the reaction of CO_2 with a chemical solvent to yield a weakly bound intermediate product that can be regenerated using heat to produce the original solvent and a CO_2 stream (IPCC, 2005). The selectivity of this type of separation is quite great. In addition, a relatively clean CO_2 stream may be created. These features make chemical absorption ideal for CO_2 capture from industrial exhaust gases.

- Cryogenic separation

Cryogenics separation separates CO_2 from the flue gas stream by condensation. At atmospheric pressure, CO2 condenses at -56.6°C (IEA GHG, 1993). This physical process is suitable for treating flue gas streams with high CO_2 concentrations, considering the costs of refrigeration. This is also used for CO_2 capture for the oxyfuel process.

- Membrane-based separation

Membrane-based separation provides selectivity through the membranes themselves. These are typically composed of thin polymeric films and distinct mixes based on the relative rates at which constituent species infiltrate. Permeation rates would vary depending on the relative sizes of the molecules and the diffusion coefficients in the membrane material. The difference in partial pressure between the components on either side of the membrane acts as the driving force for permeation. However, the selectivity of this separation process is low. Thus, only a portion of the CO_2 is caught. In addition, the purity of the captured CO_2 is low for the same reason (IEA, 2004; IEA GHG, 1993). Multistage separation is employed to capture a higher proportion of incurring extra capital and operating costs (Chakravati*et al.,* 2001; IEA, 2004; IEA GHG, 1993).

Pre-combustion capture

Pre-combustion capture is the process of separating CO_2 from fuel by blending fuel, air, and/or steam to create a distinct CO_2 stream that may be stored and hydrogen for combustion. This is achieved for coal-fuelled power plants by a process known as partial oxidation, or gasification, which involves reacting coal with steam and oxygen at high temperatures and pressures. The end product is a gaseous fuel that may be burned to produce electricity. This fuel is mostly composed of hydrogen and carbon monoxide and is referred to as "synthesis gas" or "syngas". Following the removal of particle contaminants from the syngas, carbon monoxide is converted to CO_2 in a two-stage shift reactor by reacting with steam (H_2O). A combination of CO_2 and hydrogen is the end product. A chemical solvent then absorbs the CO_2, leaving behind a stream of almost pure hydrogen. One popular commercial product that does this is Selexol, which uses a solvent based on glycol. This is burned to create electricity in a combined-cycle power plant called an integrated gasification combined-cycle plant (IGCC).

Oxy-fuel combustion capture

By using pure oxygen rather than air for combustion, the oxy-fuel combustion capture process yields a flue gas mostly composed of CO_2 and water, which can be easily separated. The CO_2 may then be compressed, transported, and stored. The creation of oxygen, which is necessary for the burning of oxygen fuel, is probably accomplished using a cryogenic process. Utilising pure oxygen has the benefit of removing a significant amount of nitrogen from the flue gas stream, which lowers the production of pollutants that cause smog, such as nitrogen oxides. Projects involving oxy-fuel combustion are now being conducted at the lab or bench size, with the possibility of pilot-scale verification testing.

Selection of Technologies

The technologies were selected based on their prevalence in recent literature and their practical applications in Industrial settings (Wang et al., 2021, Jones et al., 2022). Each technology represents a distinct mechanism of CO_2 capture.

Chemical Absorption

It is the most well-known technique for capturing CO_2. It depends on a chemical solvent and carbon dioxide reaction. Alkanolamines like monoethanolamine (MEA), diethanolamine (DEA), or methyl diethanolamine (MDEA) in aqueous solution are typical solvents. Figure 3 displays a schematic depiction of chemical adsorption. There are two stages to the process. To capture CO_2, the absorber's solvent reacts with the flue gas in the first stage. The rich loading solution is then transported to the stripper, where it is heated to a high temperature to regenerate CO_2. The lean-loading solution, which has no trace of CO_2, is returned to the absorber column. From the desorber, a high-purity carbon dioxide stream is transferred for compression, storage, or use. The chemical industry has long employed the chemical absorption method. High levels of carbon dioxide purity and process efficiency are attained by using the commonly used 30% MEA and MDEA solutions.

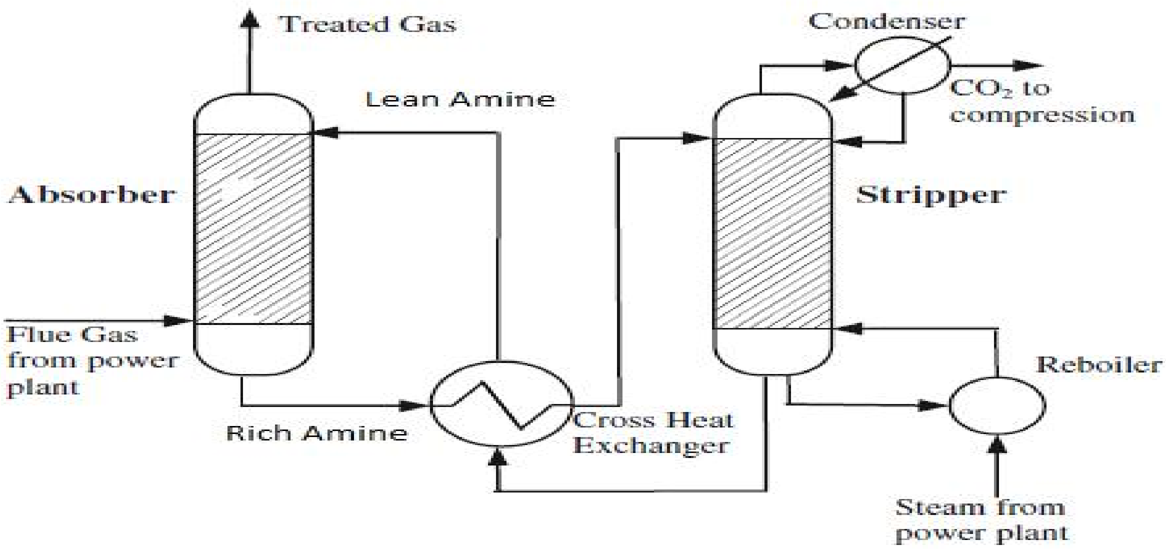

Figure 3: Schematic representation of a chemical adsorption system

Physical Absorption

Using a chemically inert liquid, the physical absorption method physically absorbs CO_2. Either water or organic absorbers (methanol, Nmethyl-2-pyrrolidone, dimethyl ether) are used for absorption. The best results are obtained with this procedure when the separated gas has high pressure and low temperature. As a result, it is employed to absorb carbon from the gasification of coal. There are several distinct solvent-using methods in this approach, including Selexol™, Rectisol™, Ifpexol™, Fluor™, Purisol™, Sulfinol™, and Morphysorb™. A streamlined physical absorption unit is depicted in Figure 4.

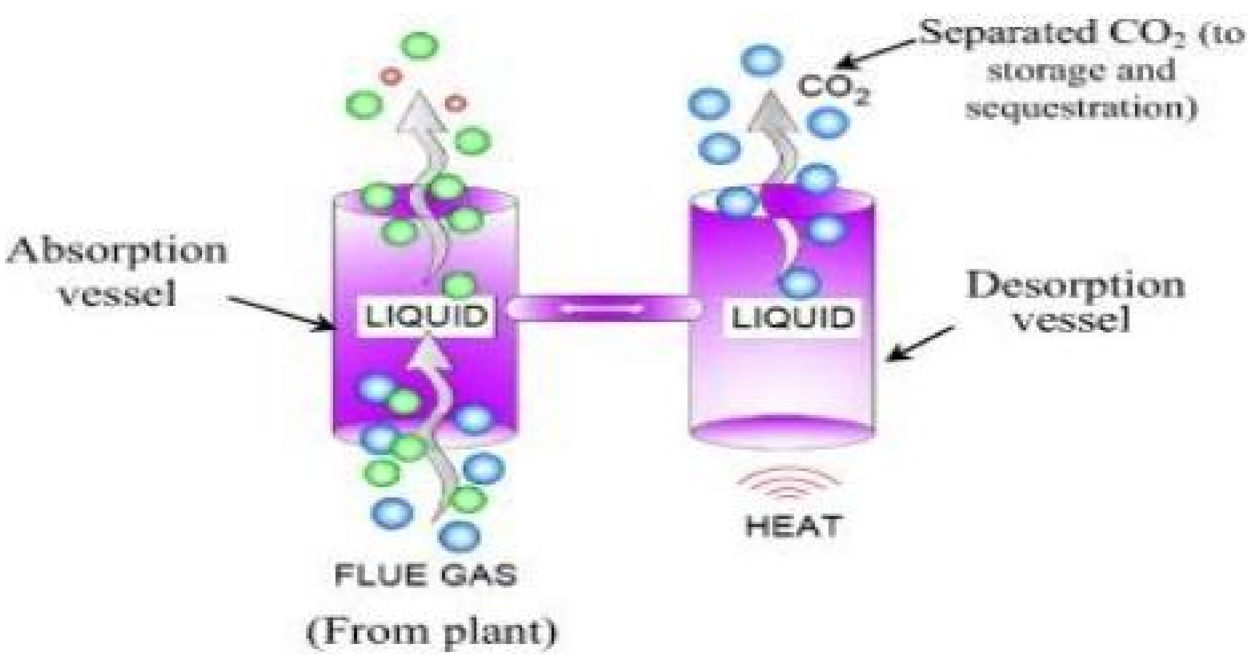

Figure 4: Schematic diagram of a Physical absorption unit

Adsorption

The process of retaining gas or liquid molecules on a solid surface is called adsorption. Regenerative zeolites, such as 13X (silico-aluminates that exist naturally or are synthesized), are used in carbon capture procedures.

Additionally, metal-organic frameworks such as MG-MOF-74 are under consideration. The amount of CO_2 that can be collected increases with decreasing temperature and increasing CO_2partial pressure in the gas to be treated, much like physical solvents do. Adsorption is not the optimum technique for coal or cement applications since it requires pure input gas. Adsorption processes can be classified as temperature swing adsorption (TSA) or pressure swing adsorption (PSA) based on the regeneration technique. For pre-combustion procedures, PSA is more appropriate. It is better suitable to use TSA or VSA (Vacuum Swing Adsorption) for post-combustion carbon collection. Figure 5 displays a TSA system schematic diagram.

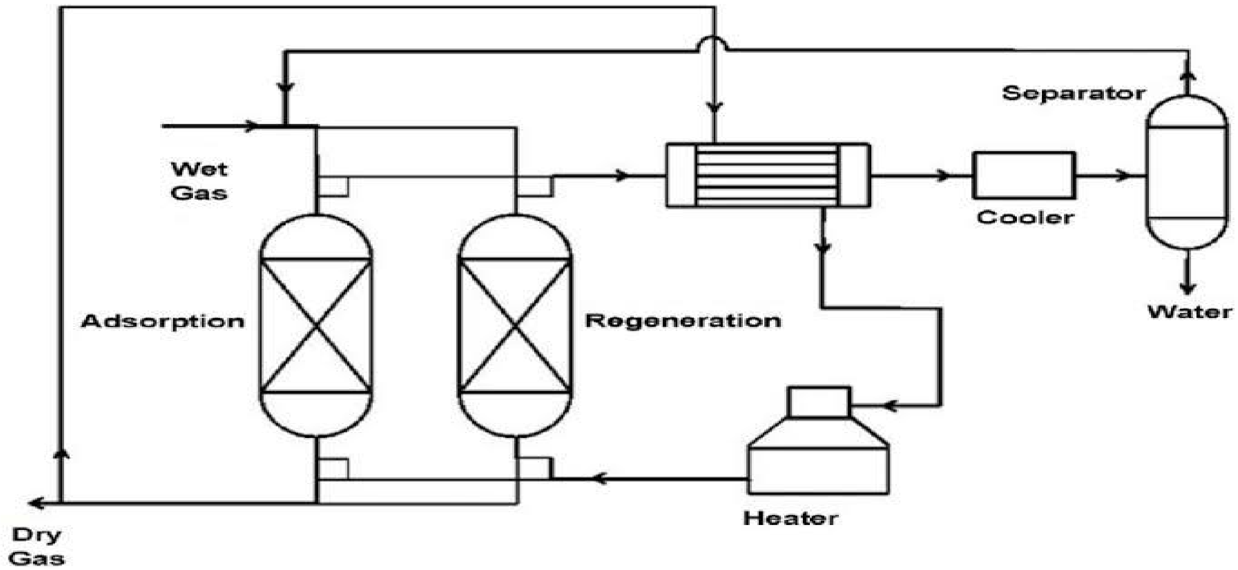

Figure 5: Schematic diagram of temperature swing adsorption (TSA) system

Membrane separation

Membrane separation extracts CO_2 from gas streams using selective membranes. Other gases are trapped by the membranes, which let CO_2 through. CO_2 can be separated from flue gas via membrane through selective permeability of the membrane material. CO_2 will selectively permeate the membrane if its permeability—which is determined by multiplying its solubility and diffusivity—is higher than that of other species in the flue gas. To improve the membrane's selectivity for CO_2, chemical agents that react only with CO_2 may occasionally be introduced. A membrane can only be transported by CO_2 if one side of the membrane has a higher partial pressure than the other.

As seen in Figure 6a, this partial pressure gradient can be achieved by creating a vacuum on one side of the membrane, pressurizing the flue gas on the other, or by doing both. As seen in Figure 6b, several membrane stages can be required, depending on the membrane's selectivity, to get a high enough CO_2 purity.

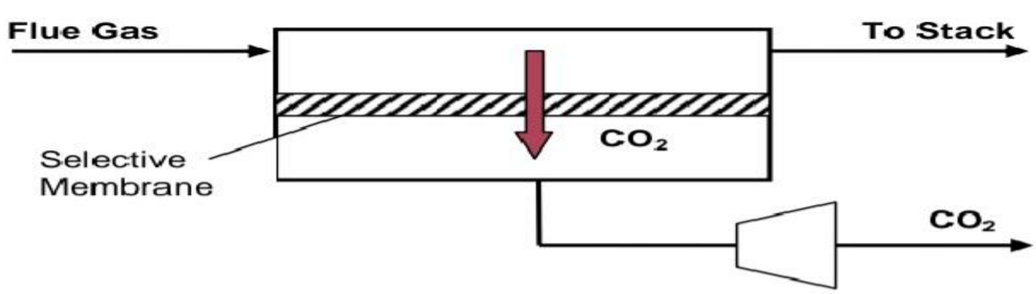

Figure 6a: Membrane separation process

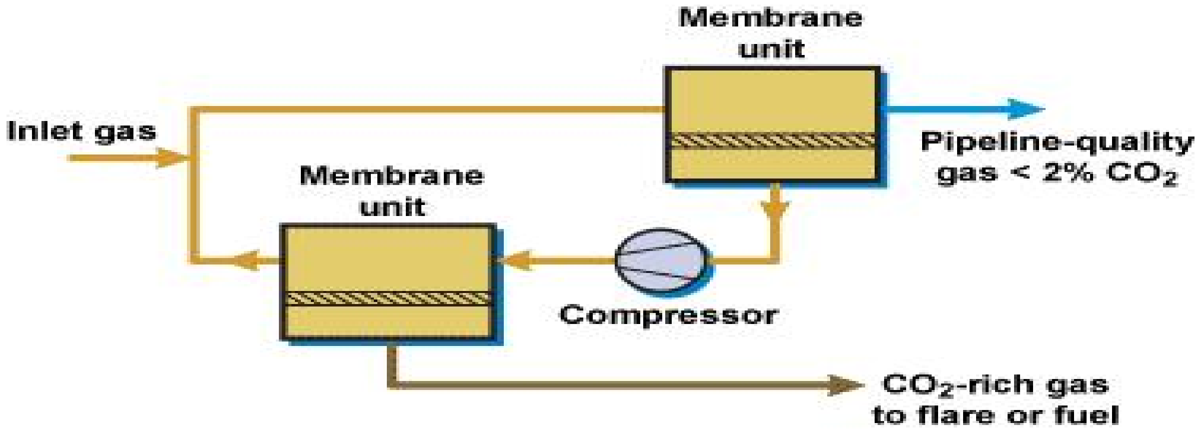

Figure 6b: Membrane separation using several membranes

Methods of Carbon Capture Data Collection and Analysis

1. Carbon capture rate:
   Determine how much CO_2 is captured in a given amount of time. Take into account the gas flow rate and the variation in CO_2 content before and after the procedure.

$$capture\ rate = \frac{flow\ rate\ of\ gas * (CO2in - CO2out)}{100} \quad (1)$$

2. Cost per capture:
   Materials costs: calculate the cost of the absorbent, adsorbent, or membrane material used energy costs: calculate the cost of energy consumed during the process.
   Operational cost: maintenance and regeneration cost

$$Total\ cost\ per\ unit\ CO2\ captured = \frac{Total\ cost\ of\ operation}{Total\ CO2\ captured} \quad (2)$$

3. Energy consumption:
   Determine the total amount of energy consumed for pumping, heating, and cooling during the process.

$$Energy\ consumption\ per\ unit\ CO2 = \frac{Total\ energy\ used(kWh)}{Total\ CO2\ captured(kg)} \quad (3)$$

Assessment of Common Carbon Capture Technologies

Table 1: Results for carbon capture technologies

TECHNOLOGY	CAPTURE EFFICIENCY (%)	CO_2 CAPTURE RATE (kg CO_2/m^3 gas)	COST PER CAPTURE ($/kg CO_2)	ENERGY CONSUMPTION (kWh/kg CO_2)
Chemical absorption	90	0.90	~50	~0.65
Physical absorption	85	0.85	~45	~0.50
Adsorption	78	0.78	~60	~0.75
Membrane separation	70	0.70	~55	~0.60

The above table shows the results of the experiments carried out on each technology.

- From the chemical Absorption process (using monoethanolamine MEA), the carbon capture rate was high at 0.90kgCO_2/m^3 of gas. This efficiency is consistent with various literature, where MEA-based absorption is known for its strong reactivity with CO_2, which allows the efficient capture of CO_2 even at low concentrations.
- Unlike chemical absorption, the physical absorption method showed a reduced capture efficiency but was the least energy intensive at 0.50kWh/kg of CO_2. This is a result of its lower operational temperature and pressures, reducing the energy demand.
- The adsorption method using activated carbon adsorbent captured CO_2 at the rate of 0.78kgCO_2/m^3 of gas while having the highest cost per capture due to the high cost of adsorbent material, which has to be periodically regenerated or replaced, making it consumed the most energy 0.75kWh/kg CO_2.
- Unlike the rest of the methods, the membrane separation capture method has a low capture efficiency and a fairly high cost due to the need for high-quality membranes for capture. This method is less mature than the others but offers modularity and potential for integration into various industrial processes. Its efficiency depends heavily on the membrane material and the pressure difference across the membrane.

Energy Consumption

Energy consumption is a critical factor in the evaluation and deployment of carbon capture technologies. The amount of energy required to capture and store CO_2 from industrial sources not only impacts the operational cost but also determines the overall environmental benefits of the carbon capture process. If the energy demand for carbon capture is too high, it could offset the gains made in reducing CO_2 emissions, thereby diminishing the effectiveness of the technology. Chemical absorption is one of the most energy-intensive carbon capture technologies due to the significant amount of energy required for the regeneration of the solvent. The process typically involves using amine-based solvents, such as monoethanolamine (MEA), which react with CO_2 to form a compound that can be separated later by heating the solvent. The energy required for physical absorption is generally lower than that for chemical absorption, primarily because the absorption and regeneration processes do not involve chemical reactions. Physical absorption is more energy-efficient for high-pressure applications but is less effective at low pressures, where the solubility of CO_2 is reduced. The energy required for adsorption processes varies depending on the adsorbent material and the method used for regeneration. Thermal regeneration, which involves heating the adsorbent to release the CO_2, is the most energy-intensive method, typically requiring 2-3 GJ/tonne of CO_2 (Siriwardane et al., 2001). Membrane separation is generally more energy-efficient compared to other carbon capture technologies, with energy consumption typically ranging from 0.2-1.0 GJ/tonne of CO_2 (Baker, 2002).

Economic Viability and Cost Effectiveness

The economic viability and cost-effectiveness of carbon capture technologies (CCTs) are crucial considerations for their widespread adoption in mitigating climate change. Carbon capture, utilization, and storage (CCUS) technologies have the potential to significantly reduce CO_2 emissions from industrial and energy sectors, but the costs associated with implementing these technologies often pose significant barriers.

Capital Cost: The initial capital investment required to implement carbon capture technologies can be substantial. These costs include the construction of the capture facility, integration with existing industrial or power generation systems, and the development of CO_2 transport and storage infrastructure.

Operational Cost: Operational costs include energy consumption, maintenance, labour, and the cost of consumables such as solvents or adsorbents. Energy consumption, in particular, is a major operational expense, as CCTs typically require significant amounts of energy for CO_2 capture and compression.

Cost Per Tonne of $C0_2$ Captured: The cost per tonne of CO_2 captured varies widely depending on the technology, application, and specific conditions. For chemical absorption, the cost is typically in the range of \$40 to \$100 per tonne of CO_2 captured (Rubin et al., 2015). Physical absorption, adsorption, and membrane separation can have lower or higher costs depending on the application and energy efficiency. Industrial applications, such as CO_2 capture from cement or steel plants, often have higher costs per tonne due to the complexity of integrating CCTs into existing processes and the variability of flue gas compositions (Haszeldine, 2009).

The significant capital investment required for carbon capture infrastructure remains a major barrier to widespread adoption. Financing large-scale CCUS projects is challenging, especially in regions without strong policy incentives or carbon pricing mechanisms.

The economic viability of carbon capture technologies is sensitive to fluctuations in energy prices, carbon prices, and the availability of government incentives. These uncertainties can deter investment in CCUS projects.

The economic viability and cost-effectiveness of carbon capture technologies are influenced by a range of factors, including capital and operational costs, economies of scale, technological advancements, and policy support. While the initial costs of implementing CCTs are high, there is significant potential for cost reductions through ongoing R&D, larger-scale deployment, and supportive policy frameworks. The integration of carbon capture with CO_2 utilization could further enhance economic viability by creating new revenue streams. However, achieving widespread adoption of carbon capture technologies will require addressing the economic challenges through coordinated efforts between governments, industry, and research institutions.

Scalability and Integration with Renewable Energy Sources

As global efforts to mitigate climate change intensify, the scalability and integration of carbon capture technologies (CCTs) have become central to discussions about reducing CO_2 emissions from industrial and energy sectors. The ability to scale up CCTs and integrate them seamlessly with existing infrastructure is crucial for achieving significant reductions in atmospheric CO_2. Different carbon capture technologies are at varying levels of technological maturity, which influences their scalability. Technologies such as chemical absorption using amines are well-established and have been implemented at commercial scales, demonstrating their potential for large-scale deployment (Rochelle, 2009). However, other technologies, like adsorption and membrane separation, are still evolving, with scalability dependent on further technological advancements and cost reductions (IEA, 2020). The scalability of CCTs also depends on the availability of suitable materials and the efficiency of the capture process. For example, the widespread use of solid adsorbents or advanced membrane materials requires mass production capabilities that can meet the demand for large-scale deployments (Bui et al., 2018).

Scaling up carbon capture involves not only the capture technology itself but also the development of extensive infrastructure for CO_2 transport and storage. This includes pipelines, compression stations, and storage sites such as depleted oil and gas fields or saline aquifers. The deployment of CO_2 transport networks is particularly challenging due to the need for extensive capital investment and regulatory approvals. However, existing infrastructure, such as natural gas pipelines, can potentially be repurposed for CO_2 transport, reducing the costs and complexities associated with new infrastructure development (GCCSI, 2016). The scalability of carbon capture technologies is also influenced by geographic factors, such as the availability of suitable storage sites and proximity to industrial CO_2 sources. Regions with abundant storage capacity and large industrial emitters, such as North America and parts of Europe, are well-positioned to scale up CCTs (Global CCS Institute, 2019).

Environmental Impact

While these technologies offer significant environmental benefits by preventing CO_2 from entering the atmosphere, they also present various environmental challenges. These impacts can arise from the energy consumption associated with the capture process, the handling and disposal of captured CO_2, and the production and use of chemicals or materials required for the capture systems.

Amine solvents can degrade over time, leading to the formation of byproducts such as ammonia, nitrosamines, and nitramines, which can be harmful to human health and the environment if released into the air or water (Feron& ten Asbroek, 2006). These byproducts require careful management and can contribute to environmental pollution. The cooling and pressurization required for physical absorption processes consume significant amounts of energy. If this energy comes from non-renewable sources, it can contribute to indirect CO_2 emissions, as well as other pollutants associated with energy production, such as sulfur dioxide (SO_2) and nitrogen oxides (NOx) (Rubin et al., 2015). While adsorption can be more energy-efficient than chemical absorption, the energy required for regeneration can still be significant, particularly for thermal regeneration methods. This can contribute to indirect environmental impacts, depending on the energy source (Bui et al., 2018). Membrane separation does not require chemical solvents, reducing the risk of chemical pollution and making it a cleaner option compared to chemical and physical absorption (Koros& Mahajan, 2000).

While carbon capture technologies offer significant environmental benefits by reducing CO_2 emissions, they also present environmental challenges that must be carefully managed. Chemical absorption, despite its effectiveness, poses risks related to solvent degradation and high energy consumption. Physical absorption involves potential solvent-related pollution and energy demands, while adsorption presents challenges related to material degradation and energy use. Membrane separation, though less environmentally intrusive, still faces issues with membrane production and disposal. To maximize the environmental benefits of carbon capture technologies, it is essential to continue improving their efficiency, minimizing their environmental impacts, and integrating them with renewable energy sources wherever possible.

Conclusion

The increasing concentration of carbon dioxide (CO_2) in the atmosphere is a primary driver of global climate change, necessitating urgent efforts to reduce greenhouse gas emissions. Carbon capture and storage (CCS) technologies have emerged as vital tools in this battle, offering the potential to significantly reduce CO_2 emissions from industrial sources and power generation. To reduce emissions of greenhouse gases associated with global climate change, the research has attempted to present a realistic assessment of the prospects for better, less expensive CO_2 capture technologies for use in power plants and other industrial facilities. Carbon capture may be in hybrid systems that combine the benefits of many methods. Combining adsorption with membrane separation could increase efficiency and lower costs by exploiting the capabilities of both technologies. Ongoing research into new materials, such as more durable adsorbents and high-performance membranes, will be critical to improving the performance and cost-effectiveness of carbon capture technologies. Regulatory frameworks and financial incentives will also be important factors in the adoption of carbon capture systems. Carbon pricing, tax incentives, and emissions restrictions can all help to drive CCS adoption by making it economically viable for industries to invest in carbon capture infrastructure. To effectively reduce global CO_2 emissions, governments, businesses, and academia must work together to address technical and economic hurdles connected with CCS. In summary, while substantial progress has been made in creating and upgrading carbon capture technology, further research and development (R&D), innovation and interdisciplinary collaboration are required to overcome the remaining problems. The successful adoption of CCS will be an important component of worldwide efforts to combat climate change and cut greenhouse gas emissions so we can move to a more sustainable energy future.

Declarations

Competing interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contributions

E A: *Conceptualization, Methodology, Original draft preparation, Performed experimental work, and Writing*

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