A Comprehensive Review on Carbon Capture, Utilization, and Storage (CCUS)

Prateek Kumar Tiwari[1], Vaishali Pendse[2], Debabrata Mukhopadhyay[3]

1 Research Scholar, Environmental Engineering, Raipur Institute of Technology, Raipur, India

2 Professor, Head of the Department, Chemical Engineering, Raipur Institute of Technology, Raipur, India

3 Professor, Dean, Chemical Engineering, Raipur Institute of Technology, Raipur, India

ABSTRACT

Carbon Capture, Utilization, and Storage (CCUS) encompass a suite of technologies designed to capture carbon dioxide (CO_2) emissions from industrial operations, harness the captured CO_2 for beneficial applications, and securely sequester it in underground geological formations or other appropriate repositories. The underlying imperative and objectives of CCUS are centered on combatting climate change, curbing CO_2 emissions, facilitating the transition to a low-carbon economy, upholding energy security, fostering sustainable development, and promoting technological innovation. This current research review article provides a comprehensive examination of the various processes associated with CCUS, offering insights into ongoing global projects. The article also delves into innovative technologies for carbon capture, transportation, utilization, and storage, while providing an overview of approaches to mitigate CO_2 in the environment. Finally, it outlines future avenues for research and development in this field.

Keyword: - *Carbon capture; Carbon transportation; Carbon utilization; Carbon Storage; Greenhouse gas mitigation; Global projects; Innovative technologies of CCUS*

Nomenclature

GHG	Greenhouse gas
CCUS	Carbon Capture Utilisation and Storage
CO_2	Carbon Dioxide
CCS	Carbon Capture Storage
CCU	Carbon Capture Utilisation
RCP2.6	Representative Concentration Pathway 2.6
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
MEA	Mono Ethanol Amine
ACS	American Chemical Society
PSA	Pressure Swing Adsorption
EOR	Enhanced Oil Recovery
UAE	United Arab Emirates
USA	United States of America
K	Kelvin
°C	Degree Celsius
MPa	Mega Pascal
Mt	Metric Ton
Mtpa	Metric Ton Per Annum
IGCC	Integrated Gasification Combined Cycle
CNPC	China National Petroleum Corporation

1. INTRODUCTION

Human activity has led to unprecedented levels of greenhouse gas emissions (GHGs) in human history, resulting in a long-term warming effect on the climate [1]. Carbon Capture, Utilization, and Storage (CCUS) is a technology and process specifically designed to address climate change. Its primary goal is to capture CO_2 emissions before they are released into the atmosphere, repurpose the captured CO_2 for various beneficial uses, and safely store it to prevent its contribution to climate change [2]–[6].
Global warming disrupts ecosystems and societies, leading to rising sea levels, warmer oceans, reduced ice coverage, and higher surface temperatures. Adaptations in resource management and habitation patterns are crucial [7]. Mitigating climate change is essential to prevent extreme events such as heatwaves, wildfires, floods, droughts, and cyclones. These events threaten ecosystems and hinder global progress. Experts recommend limiting the increase in surface temperatures to below 2°C compared to pre-industrial levels, with the goal of achieving CO_2-equivalent emissions of around 450 parts per million (ppm) by 2100 (RCP2.6, IPCC's most stringent pathway) [8]. To curb global warming, a combination of adaptation and mitigation strategies is essential. These strategies require a 40% to 70% reduction in greenhouse gas (GHG) emissions by 2050 compared to 2010 levels, with the aim of achieving net-zero to negative emissions by the end of the century. To guide implementation and provide climate projections, specific adaptation and mitigation scenarios have been developed, outlining the necessary actions and measures to achieve the desired goals [9], [10].

1. Climate Change

Climate change refers to the long-term alterations in the Earth's global climate, which have significant implications for precipitation patterns, ocean currents, extreme weather events, and a substantial increase in temperatures. The Paris Agreement sets the objective of limiting global warming to well below 2°C compared to pre-industrial levels, with a need for a 1.5°C limit to avoid severe impacts on the global climate. Achieving this goal requires a reduction in activities and products that contribute to greenhouse gas emissions. Furthermore, it involves replacing greenhouse gas-intensive technologies and products with those that are greenhouse gas-neutral. Another crucial approach involves reducing the concentrations of carbon dioxide already present in the atmosphere by capturing it specifically from exhaust gases and the air [1].
The dataset developed by the International Energy Agency (IEA) encompasses global projects involving the capture, transport, storage, and utilization of CO_2, initiated since the 1970s, with a declared capacity exceeding 100,000 tonnes per year (or 1,000 tonnes per year for direct air capture facilities)[2]. It focuses on projects that offer significant opportunities for emissions reduction while excluding CO_2 capture for utilization in sectors with low climate benefits (such as food and beverages) or those integrated into conventional industrial processes (such as internal use for urea production). Additionally, the dataset does not include projects related to the utilization of naturally occurring CO_2 for enhanced oil recovery purposes [2]. Figure 1 represents the operational and planned capture capacity for sources of emissions affected by CO_2.

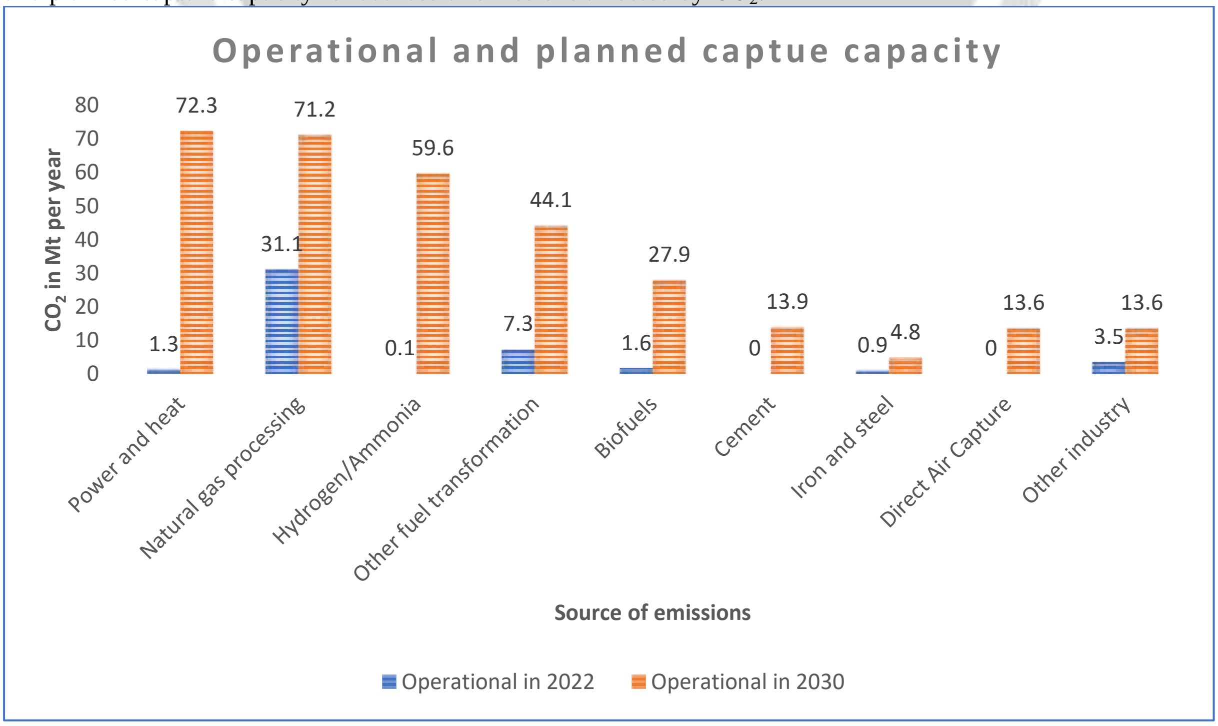


Fig - 1: Operational and planned capture capacity (By Sector) [2].

2. LITERATURE REVIEW

Table 1 provides a summary of the key literature published on CO_2 capture for CCUS from the early stages up to date.

Table 1: Summary of review papers to address the CO_2 capture processes.

Source	Year	Description	Reference
Environmental Research	2022	Life cycle assessment of combustion-based electricity generation technologies integrated with carbon capture and storage: A review	[3]
Front. Energy Res.	2021	Different This Time? The Prospects of CCS in the Netherlands in the 2020s	[4]
Chem Nano Mat	2021	Chemical Fixation of Carbon Dioxide by Heterogeneous Porous Catalyst	[5]
ACS	2020	Sustainable Chemistry and Engineering Catalytic Solvent Regeneration for Energy Efficient CO_2 Capture	[6]
Clean Energy	2020	Carbon capture and storage in the USA: The role of US innovation leadership in climate-technology commercialization	[7]
	2017	Ancient Vedic wisdom from India to tackle the global warming problem	[8]
Trends in Biotechnology	2011	Algae culture process has the potential to considerably decrease the expenses associated with carbon capture.	[9]

3. CARBON CAPTURE

Carbon capture is a process that entails the capture of CO_2 emissions from various sources, including power plants, industrial facilities, and other point sources, to prevent their release into the atmosphere. Carbon capture plays a pivotal role in mitigating greenhouse gas emissions and addressing climate change. By capturing and either storing or utilizing CO_2, it helps decrease the volume of CO_2 released into the atmosphere, thus mitigating its contribution to global warming. Carbon capture technologies are continuously evolving and improving to enhance their efficiency, reduce costs, and ensure the long-term storage and utilization of the captured CO_2 [10]–[17].

3.1. Processes for different types of CO_2 capture

Carbon dioxide (CO_2) capture plays a vital role in various industrial processes, and as a result, commercially available technologies for the separation and capture of CO_2 from flue gas streams have been in existence for many years. The two most advanced and commonly employed capture technologies are chemical absorption and physical separation. Furthermore, aside from these methods, there are other technologies at our disposal, such as membranes and looping cycles, including chemical looping and calcium looping.

This section provides a comprehensive overview of various methods and techniques for carbon dioxide (CO_2) capture, along with their characteristics and applicability in the steel industry based on prior research. The steel sector has witnessed research efforts in carbon capture and storage (CCS) within global initiatives to reduce CO_2 emissions, such as ULCOS in the European Union and COURSE50 in Japan. Recent studies have identified CO_2 capture technologies like VPSA, MEA, Selexol, Aqua ammonia, MOF, and MDEA/Pz solvent, in combination with approaches like top gas recycling for the blast furnace (TGR-BF), direct reduction (DR) with an electric arc furnace (EAF), and the emerging technology of ore electrolysis or electrowinning (EW) as having significant long-term potential for the iron and steel industry.

However, it's important to note that the capture stage can account for a substantial proportion, ranging from 70% to 90%, of the total operating costs of a CCS system. Given the considerable associated costs, extensive research has been conducted in the field of CO_2 capture. Currently, CO_2 capture technology can be classified into four primary categories, each requiring a unique approach to CO_2 capture. These categories encompass (1) post-combustion, (2) Pre-combustion, (3) Oxy-combustion, and (4) Chemical looping combustion. Figure 2, illustrates the various CO_2 capture technologies applied in industrial sectors [18].

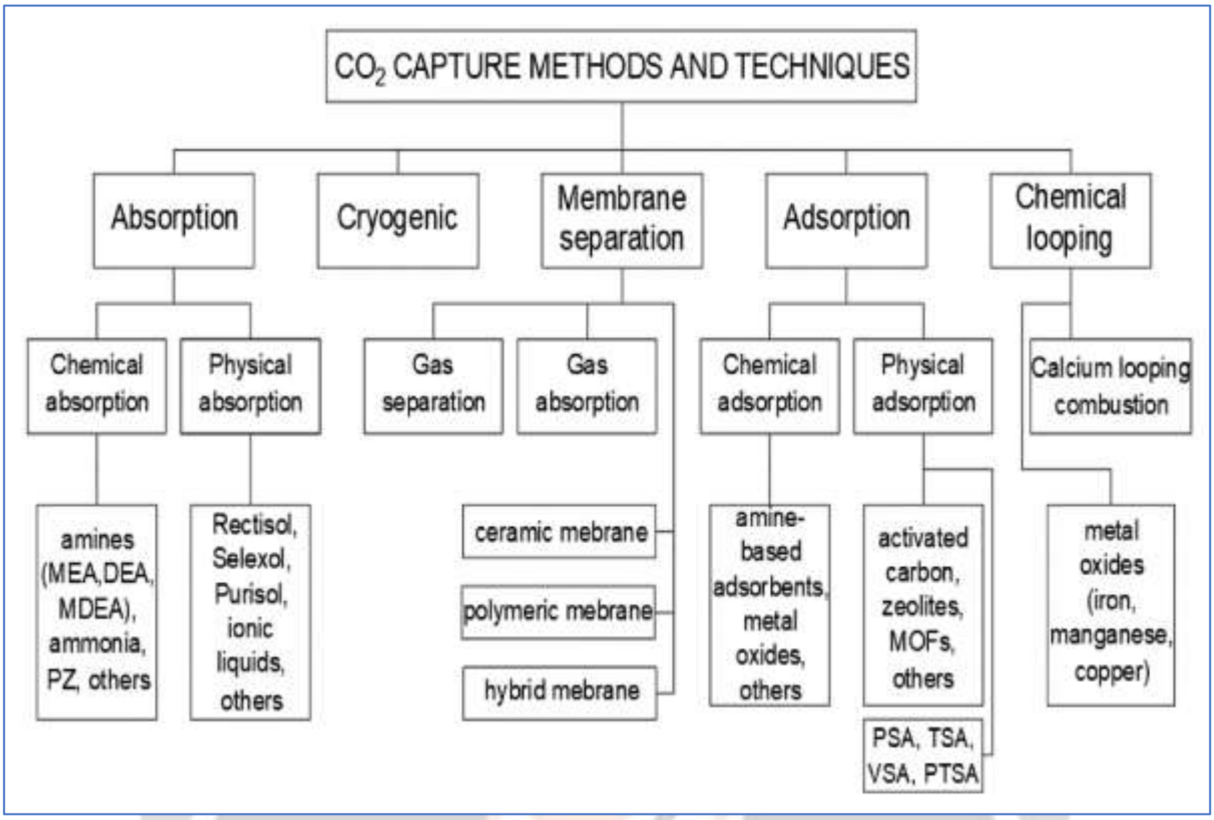


Fig - 2: Methods and techniques for CO_2 captured [19]

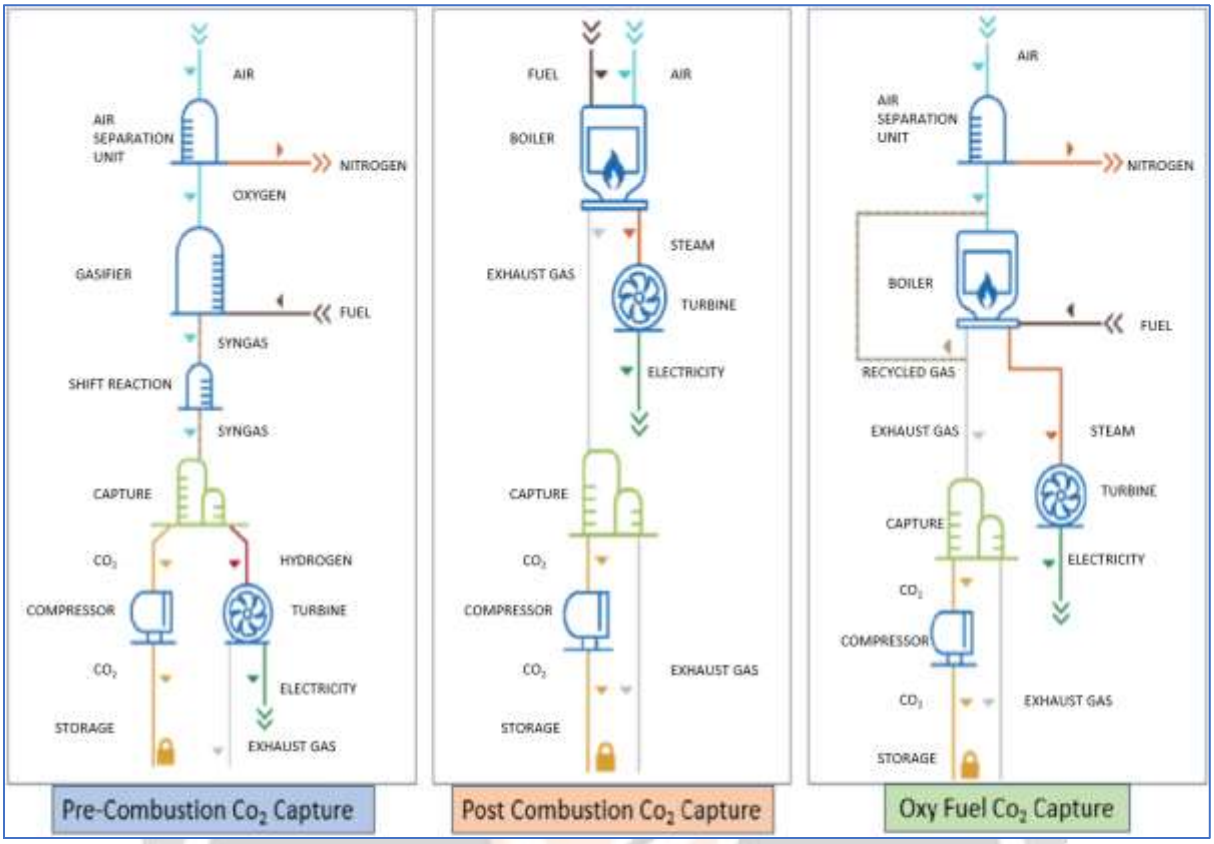
3.2. HOW IS CO_2 CAPTURED?

In carbon capture and storage (CCS) processes targeting point sources, the main objective is to capture carbon dioxide (CO_2) before its release into the atmosphere. Point sources encompass various industries such as cement and steel production, hydrogen generation from fossil fuels, waste incineration, and power generation. Typically, these sources emit impure CO_2 mixed with nitrogen, water, and other gases. The capture process involves purifying the CO_2 to enable cost-effective storage. There are three primary methods of CO_2 capture, as shown in Figure 3.

3.2.1. Pre-combustion Capture: This approach involves capturing CO_2 from the fuel before it undergoes combustion. It is commonly used in integrated gasification combined cycle (IGCC) plants. The fuel undergoes gasification, converting it into a mixture of hydrogen (H2) and carbon monoxide (CO). CO_2 is then separated from this mixture using various techniques such as pressure swing adsorption (PSA) or membrane separation[20], [21].

3.2.2. Post-combustion Capture: Post-combustion capture entails capturing CO_2 from the flue gases emitted by power plants and industrial facilities after the fuel has been burned. The most widely used technology for post-combustion capture is amine-based absorption, where CO_2 is absorbed by a solvent such as MEA [6], [22]–[25].

3.2.3. Oxyfuel Combustion with Post-combustion Capture: Oxyfuel combustion involves burning the fuel in a mixture of oxygen and recirculated flue gases, resulting in flue gas primarily composed of CO_2 and water vapor. CO_2 is then captured by condensing and separating it from the flue gas, leaving behind the water vapor. This approach combines the advantages of both oxyfuel combustion and post-combustion capture [1], [26], [27].



(a) (b) (c)

Fig - 3: Methods for CO_2 capture [28]

4. TRANSPORTATION OF CARBON DIOXIDE

Transporting captured CO_2 is a crucial aspect of CO_2 mitigation that often receives less attention compared to other phases of the process. It's essential to recognize that CO_2 transport presents both technical and operational challenges. Successful CO_2 transport necessitates collaboration among diverse stakeholders and industries [4], [5].

Various methods are available for transporting captured CO_2 from power plants and industrial emitters, including pipelines, ships, railways, and road transport [26]. Research findings indicate that the main cost drivers in carbon capture projects are transport costs, followed by capture costs, with storage costs having minimal impact. For large-scale CO_2 transportation, pipelines emerge as the most cost-effective option, particularly for long-term supply chain planning. Ship and barge connections also represent competitive alternatives to pipelines. However, rail and road connections are cost-effective primarily for short distances or when dealing with smaller CO_2 transport volumes [27].

When considering distances of 250 km or more, the costs of pipeline and carrier transport of CO_2 are similar in terms of capacity, as depicted in Figure 4 [16]. This initial analysis has proven valuable in establishing that pipelines and water carriers are the primary transportation choices for CCUS (Carbon Capture, Utilization, and Storage) carriers [26]. This summary provides an overview of various transportation solutions for CO_2, focusing on their estimated transport capacities and specific conditions, while also addressing the main challenges associated with each system. The expenses associated with shipping projects have been comprehensively examined in the pertinent literature, encompassing various aspects such as transport capacity and transport expenses, as depicted graphically in Figure 4 and comparison shows in table 2.

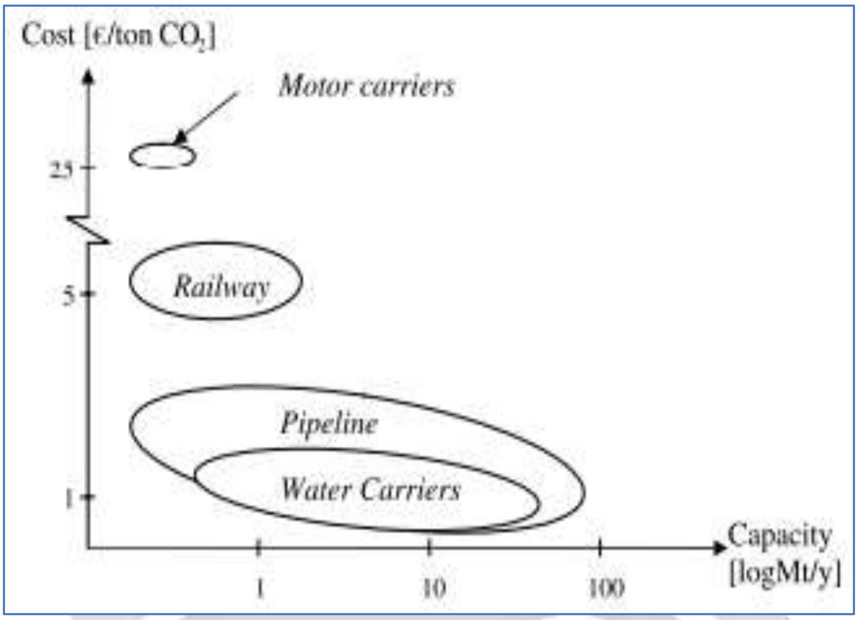


Fig - 4: Cost and capacity for transportation alternatives at 250 km [21].

Table 2: Alternatives for Carbon Dioxide Transportation [21]–[27], [29]–[34].

Transportation method	Conditions	Phase	Capacity	Remarks
Pipelines	4.8–20 MPa, 283–307 K	Vapour, dense phase	~100 Mt CO_2/year 6500 km of pipeline transport in operation	Higher capital costs, lower operating costs Low-pressure pipeline system is 20% more expensive than dense phase transmission. Well-established for EOR use.
Ships	0.65–4.5 MPa, 221–283 K	Liquid	>70 Mt CO_2/year	Higher operating costs, lower capital costs Presently utilized within the food and brewery sector to handle smaller volumes and diverse environments. Enhanced sink-source matching
Motor carriers	1.7–2 MPa, 243–253 K	Liquid	>1 Mt CO_2/year	2–30 tonnes per batch Not economical for large-scale CCUS projects. Boil-off gas emitted 10% of the load
Railway	0.65–2.6 MPa, 223–253 K	Liquid	>3 Mt CO_2/year	No large-scale systems in place Loading/unloading and storage infrastructure required Only feasible with existing rail line More advantageous over medium and long distances

5. USE OF CARBON DIOXIDE

The ultimate utilization of captured CO_2 can be categorized into two primary options: utilization and permanent storage. These choices dictate the management of the captured CO_2, whether it is transformed into other products or stored indefinitely. Here are the details:

Utilization: Captured CO_2 can find applications in various industries, offering potential economic value and reducing the dependence on CO_2 derived from fossil fuels. Examples of utilization include:

- **Urea Production:** CO_2 serves as a raw material in the manufacture of urea, a nitrogen-based fertilizer widely utilized in agriculture.
- **Chemical Transformation:** CO_2 can be converted into various chemicals through processes like methanation, methanol synthesis, or ethanol production. These chemicals can act as feedstocks for diverse industrial processes.
- **Emerging Applications:** Ongoing research and development efforts are exploring novel applications for captured CO_2, such as its incorporation into the production of construction materials like aggregates or its use as a component in carbon-based materials.

Utilizing captured CO_2 presents a potential avenue for emission reduction and the creation of valuable products, contributing to a more sustainable and circular economy [2], [35]–[39]. Carbon capture and utilization pathways, along with the global status of CCU projects, are depicted in Figure 5 and Table 3, respectively.

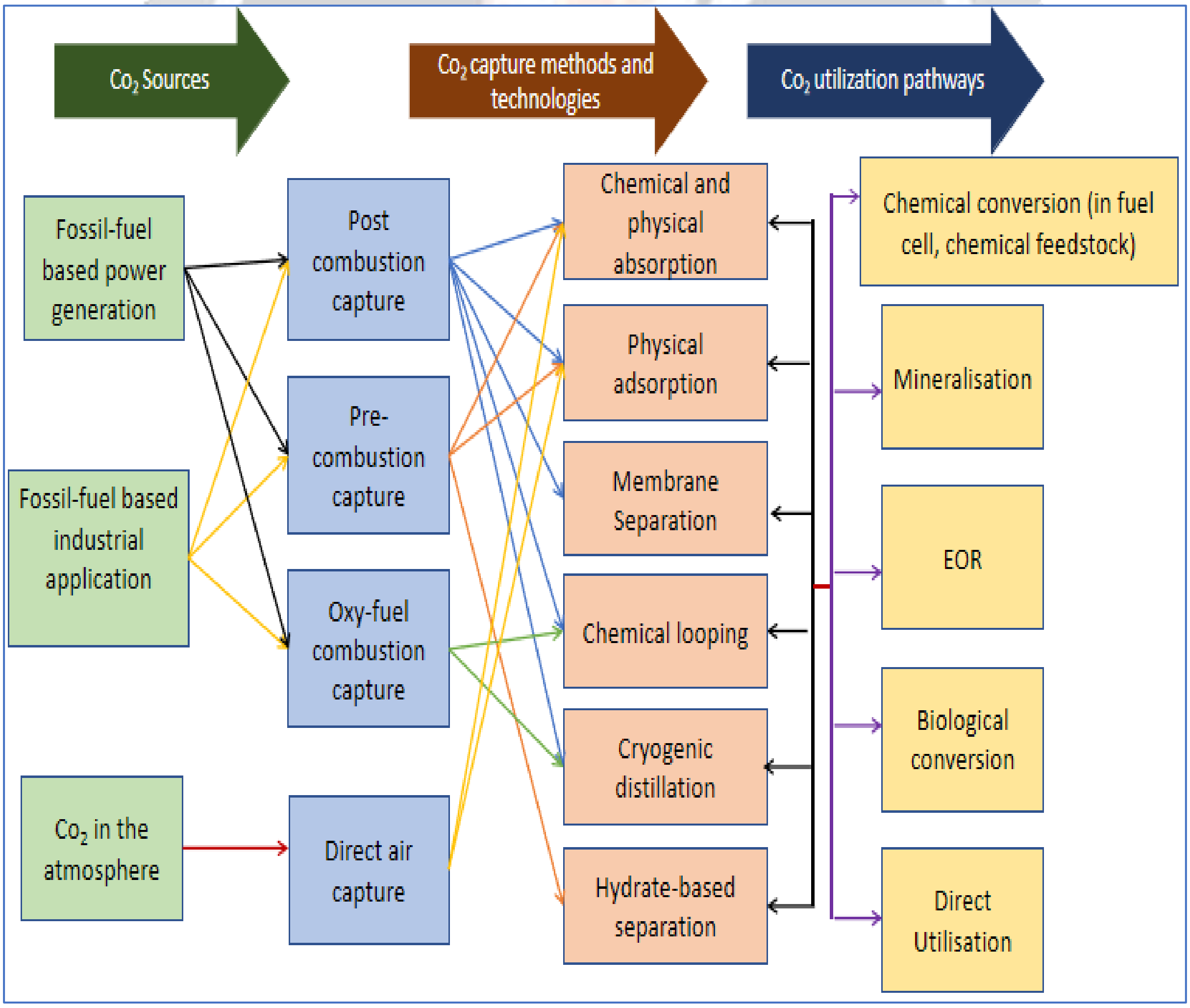


Fig - 5: Carbon capture and utilization routes [27]

Table 3: Global status of CCU projects [26].

Project	**Status**	**Year**	**Country**	**Industry**	**Scale**	**Capacity (Mtpa)**	**Utilization route**
The CNPC Jilin Oil Field project	Operational	2018	China	Natural gas processing	Large scale	0.6	EOR
Petra Nova Carbon Capture Operational	Operational	2017	USA	Power generation	Large scale	1.4	EOR
Abu Dhabi CCS	Operational	2016	UAE	Iron and steel production	Large scale	0.8	EOR
Uthmaniyah CO_2-EOR demonstration	Operational	2015	Saudi Arabia	Natural gas processing	Large scale	0.8	EOR
Boundary DAM CCS	Operational	2014	Canada	Power generation	Large scale	1	EOR
Petrobas Santos Basin Pre-salt Oil Field CCS	Operational	2013	Brazil	Natural gas processing	Large scale	3	EOR
Coffeyville Gasification Plant	Operational	2013	USA	Fertiliser production	Large scale	1	EOR
Air Products Steam Methane Reformer	Operational	2013	USA	Hydrogen production for oil refining	Large scale	1	EOR
Lost Cabin Gas Plant	Operational	2013	USA	Natural gas processing	Large scale	0.9	EOR
Century Plant	Operational	2010	USA	Natural gas processing	Large scale	8.4	EOR
Great Plains Synfuels Plant and Weyburn-Midale	Operational	2000	USA	Synthetic natural gas	Large scale	3	EOR
Shute Creek Gas Processing Plant	Operational	1986	USA	Natural gas processing	Large scale	7	EOR
Enid Fertiliser	Operational	1982	USA	Fertiliser production	Large scale	0.7	EOR
Terrel Natural Gas Processing Plant	Operational	1972	USA	Natural gas processing	Large scale	0.4~0.5	EOR

6. CARBON DIOXIDE STORAGE

Permanently storing captured CO_2 is an alternative to its utilization, aimed at preventing its release into the atmosphere. There are several storage options available, including:

- **Depleted Oil and Gas Reservoirs (EOR):** CO_2 can be injected into depleted oil and gas reservoirs to enhance oil production. While the primary objective is oil extraction, a substantial amount of CO_2 is securely stored underground [27]. Globally, EOR-CO_2 sequestration has an estimated capacity of 20 to 65 gigatons of carbon [31].
- **Deep Saline Aquifers:** These are subterranean geological formations that contain brine or saline water. CO_2 can be injected into these aquifers, where it is securely stored and mineralizes over time [27], [40].
- **Basaltic Rock Formations:** Certain types of basaltic rocks have the ability to react with CO_2, forming stable carbonates. Injecting CO_2 into basalt formations allows for long-term storage through this mineralization process [4], [21].

These permanent storage options ensure that the captured CO_2 is securely stored underground, mitigating its contribution to climate change. It is important to note that the choice between utilization and permanent storage depends on various factors, including economic viability, available infrastructure, local regulations, and environmental considerations. Different industries and regions may prioritize distinct approaches based on their specific circumstances and objectives, as discussed in Table 6 [3], [41]–[44].

Table 2: Summary of various factors affecting the choice between utilization and permanent storage.

Affecting Factors	Description of the process	Highlights
Economic Viability	Economic viability entails assessing the potential value of CO_2 utilization as a feedstock or for creating marketable products. Utilization options can offer economic benefits and help offset capture and storage costs.	Revenue generation Cost of infrastructure Market demand and price Policy incentives and carbon pricing Long-term financial liability
Available Infrastructure	The presence of suitable infrastructure is crucial for both utilization and storage. Utilization requires transportation networks and facilities to deliver CO_2 to end-users, while permanent storage relies on secure sites like underground geological formations.	Infrastructure for CO_2 transport Utilization facilities End-user infrastructure Infrastructure for CO_2 transport Storage site infrastructure Monitoring and verification infrastructure
Local Regulations	Compliance with local regulations is essential, encompassing aspects such as capture, transportation, storage, and risk mitigation associated with utilization or storage activities. Adhering to these regulations ensures legal compliance and public acceptance.	Permitting and Compliance Risk Assessment and Management Liability and Financial Responsibility Reporting and Monitoring Public Engagement and Consent
Environmental Considerations	Environmental considerations are significant in decision-making. Utilization options should be evaluated for their environmental benefits and potential drawbacks, such as energy consumption and emissions. Permanent storage must prioritize the long-term stability and integrity of storage sites to prevent CO_2 leakage and minimize environmental impact.	Potential environmental benefits Environmental drawbacks Technological maturity Climate change mitigation Long-term stability Potential risks

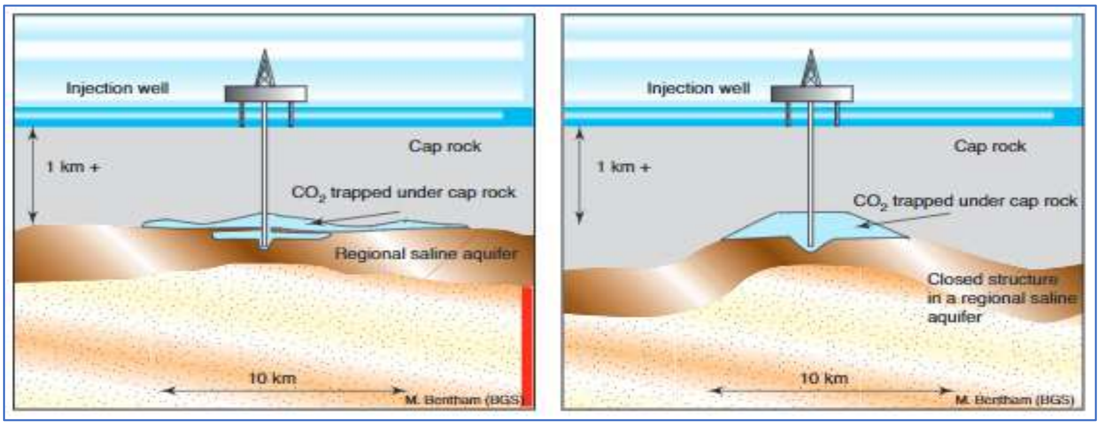


Fig - 6: Conceptual diagrams of storage in unconfined and confined aquifers [32].

The storage of carbon dioxide (CO_2) in saline aquifers can take place in both "confined" and "unconfined" aquifers, as indicated in Figure 6. In the case of storage within unconfined aquifers, buoyant CO_2 is confined by structural features such as anticlines or geological characteristics like sandstone pinchouts. This approach is akin to the storage practices employed in hydrocarbon fields and resembles the natural gas storage methods applied in subsurface aquifers.

Storage in unconfined aquifers involves the injection of CO_2 into expansive regional aquifers that lack specific significant structural or geological closures as a target. Subsequently, the CO_2 migrates upwards through the most permeable pathways until it reaches the impermeable cap rock, where further vertical movement is obstructed. Consequently, the predominant movement of CO_2 occurs horizontally, driven by buoyancy, towards higher structural levels along the boundary between the cap rock and the reservoir. It follows the most permeable pathways situated in the uppermost portions of the aquifer [45].

7. CONCLUSION

This research paper offers an extensive examination of Carbon Capture, Utilization, and Storage (CCUS) technologies, highlighting their critical role in mitigating climate change and advancing sustainability objectives. The assessment of various CCUS processes and international projects underscores their diverse approaches and progress. CCUS plays a pivotal role in curtailing CO_2 emissions, facilitating the shift towards a low-carbon economy, and bolstering energy security and sustainable development. Continuous research and development efforts are essential to enhance CCUS efficiency, explore novel methodologies, and optimize economic feasibility. Collaboration among governments, industries, and research institutions is imperative for expediting the deployment of CCUS and effectively tackling global carbon emissions. In summary, this paper lays a solid foundation for forthcoming CCUS research, contributing to a cleaner and more environmentally responsible world. The discoveries and prospects outlined in this paper lay a solid foundation for ongoing research and development in the field of Carbon Capture, Utilization, and Storage (CCUS), paving the way for a cleaner and more environmentally responsible world. Future research in CCUS technology can concentrate on several crucial areas:

- Enhanced Capture Technologies: Strive to develop more efficient and cost-effective capture methods, enhancing capture efficiency while minimizing energy consumption.
- Innovation in Utilization: Explore novel technologies and processes for CO_2 utilization, optimizing utilization pathways and environmentally beneficial utilization methods.
- Carbon-Negative Technologies: Progress in carbon-negative approaches that actively remove CO_2 from the atmosphere and convert it into stable minerals.
- Storage Site Characterization and Monitoring: Enhance our comprehension of subsurface storage sites to ensure the long-term integrity of storage.
- Integration with Renewable Energy: Investigate the integration of CCUS technologies with renewable energy systems to achieve synergistic and sustainable solutions.
- Life Cycle Assessment and Environmental Impact: Conduct comprehensive life cycle assessments to evaluate the environmental footprint of CCUS technologies, pinpoint areas for improvement, and ensure overall sustainability.

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