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Original Research Article

Present and Future Innovations in Carbon Capture, Utilization, and Storage (CCUS): Implementation, Problems, and Vision (2025)

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Abstract

Carbon Capture, Utilization and storage (CCUS) continue to emerge as the most viable technology to reduce the emission of greenhouse gases around the world, the bulk of which is in the hard to abate industries. This paper has presented a systematic review of the existing technological implementation, the key challenges that have been identified, the gaps in knowledge, and also the emerging innovations that have been continuing to shape the field. The review incorporates information in the world deployment databases, state reports, and peer reviewed libraries. CCUS technologies have reached maturity in the realms of capture and storage but the large scale deployment of capturing technology has been limited because of the high cost, the presence of adequate infrastructure and due to policy uncertainty. The review paper presents some recommendations on how to enhance efficiency, lower costs and achieve sustainable industrial integration with net zero emissions.

Keywords: Carbon capture, CO_2 utilization, emission reduction, renewable energy transition, decarbonization, and new technologies in CCUS.

1. INTRODUCTION

Global energy and industrial systems account for more than 70% of anthropogenic CO_2 emissions in the globe. The Intergovernmental Panel on Climate Change (IPCC, 2023) states that CCUS is a significant technology that will be required to achieve net zero emission in the entire world, which will be supplemented by the use of renewable energy and improvements in efficiency. The International Energy Agency (IEA, 2024) calculates that the total capacity of the CCUS must be increased to over 1.2 GtCO2 per year by 2030 in order to reach the net zero target of 2050, which requires an increase in the total capacity of the CCUS to more than 45 $MtCO_2$ per year. This review acknowledges the current CCUS developments across the globe, establishes the barriers, and examines innovations that can speed up the implementation of CCUS.

2. METHODOLOGY OF REVIEW

The PRISMA guidelines were followed in conducting a structured literature review. The data gathered in relation to the sources below:

- Peer-reviewed journals (Science Direct, Springer and ACS)
- The industrial reports included in this report are the IEA and the Global CCS Institute (2023-2025).
- Government databases (DOE NETL, 2024).

As the sources, journals of publications published in 2018-2025 on the topic of CCUS technologies, economic, and policy aspects were selected. The trends in CCUS deployment, as well as technologies efficiency and policy frameworks were analyzed.

3. Introduction to Technologies

CCUS involves three (3) major steps; they include capture, utilization, and storage.

- Capture: Pre-combustion, post-combustion and oxy-fuel are the dominating technologies in capturing technology.
- Utilization: CO_2 may also be utilized in useful production, e.g., fuels and chemicals or construction materials.
- Storage: CO_2 capture storage in geological site in the form of such exhausted oil and gas fields or saline aquifers is the most developed.

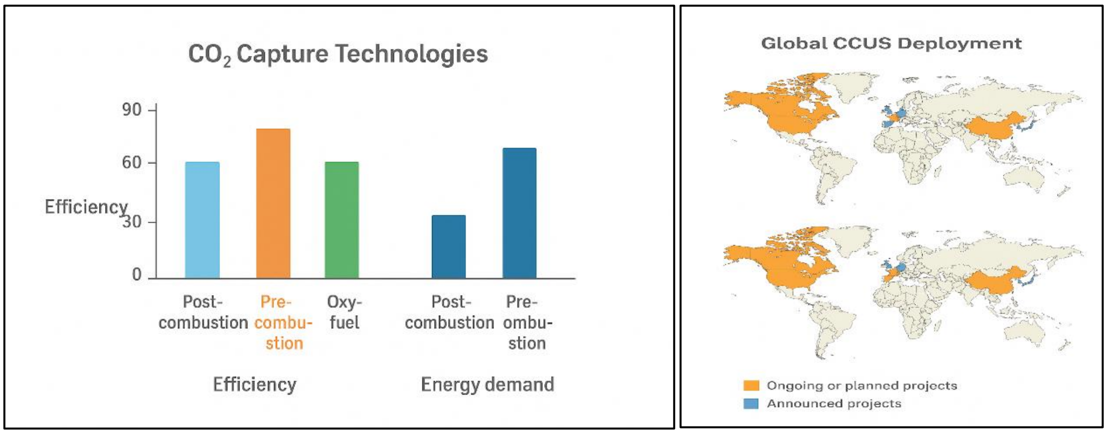

Figure 1 - Technology Comparison Chart

4. Current Deployment Trends

In the world, over 40 large scale CCUS facilities which capture about 45 $MtCO_2$/year are operational as at 2025. The North America is leading followed by Europe, China, and the Middle East (Global CCS Institute, 2025).

Table 1 - CCUS Technologies Cost, Efficiency and Readiness Data Comparison

zTechnology	CO_2 Capture Efficiency (%)	Technology Cost ($/t$CO_2$)	Readiness Level (TRL)
Post-combustion	85	45–70	8
re-combustion	90	40–65	7
Oxy-fuel	88	50–80	6
Direct Air Capture (DAC)	75	120–600	5

Source: IEA (2024) - Global CCS Institute (2024).

Table 1 presents the comparison of the most widespread capture technologies in terms of capture efficiency, degree of technological readiness (TRL), and the approximate cost of the CO_2 captured per tonne, provided by Comparison (IEA, 2024).

5.0 Problem and Research Uncertainty/ Recommendations in CCUS Deployment

5.1 The high capital and operating costs are associated with CCUS Project

Although there is technology improvement in capture technologies the cost of carbon capture is still comparatively higher than \$50 per tonne of CO_2 in an industrial scale plant. The expensive prices are mainly blamed on the intense energy needed to regenerate the solvents, maintain equipment and the implementation of CCUS to the already existing industrial processes. In areas that do not have carbon pricing systems or policies, capture projects are even less economically viable.

Recommendations:

- Expand the research on high-quality sorbents, metal-organic frameworks (MOFs), and hybrid membranes to improve the capture activity and decrease the regeneration energy.
- Encourage pilot scale trials in order to prove cost reduction in terms of process integration and use of waste heat.
- Introduction of price or tax credits to make the projects of CCUS viable.
- Facilitate industrial symbiosis by using captured CO_2 to produce synthetic fuels, building materials or chemicals so as to generate additional sources of revenue

5.2 2 Inadequate Transport and Storage infrastructure.

One of the biggest impediments to the large scale implementation of CCUS is transportation infrastructure; the lack of established CO_2 pipeline systems and licensed geological storage facilities is restricting the full scale implementation of the technology particularly in developing territories. The inability to offer a consistent transport and storage systems implies that captured CO_2 cannot be stored and used effectively and permanently.

Recommendations:

- The regional centers of CO_2 infrastructure are being built to connect different emitters through the shared transportation and storage.
- There is a need for international cooperation on infrastructure planning, particularly on trans-boundary routes of CO transportation.
- Incentives on investment in pipeline and storage development through the development of private public partnerships (PPP).
- Identify and set up national CO_2 storage facilities through geospatial tools to identify possible locations.

5.3 Public Acceptance

The social perceptions on the CCUS are a major bottleneck because of apprehensions regarding leakages, induced seismic activities, and environmental hazards related to underground storage of CO_2. Project delay or cancellation used to follow miscommunication and absence of stakeholders in the region.

Recommendations:

- Enhance social visibility of storage facilities keeping track of outcomes, safety measurements and environmental impact measurements.
- Engaging communities in the initial stages of project design to establish trust and co-establish risk management plans and strategies.
- Promoting the environmental positive effects of CCUS over conventional emissions to the masses.
- Adopt the local media and non-governmental organizations as communication partners to enhance the awareness and credibility of the people.

5.4 Regulatory Fragmentation

Since there is no unified international standards regarding the capture of carbon, its transportation and storage; this prevents investments and collaboration across borders. The differences between the monitoring, reporting, and verification (MRV) standards are causing confusion to project developers and investors.

Recommendations:

- Improvement in coherent measurement, reporting and verification (MRV) schemes in line with international standards such as ISO and IPCC standards.
- Formation of regional CCUS regulatory instruments to facilitate and allow cross border transport.
- Implementing transparent liability methods in the management of long term storage sites and the subsequent post closure procedures.
- The incorporation of CCUS into the climate policies and Nationally Determined Contributions (NDC) to act as the compliance regulator.

5.5 Gap in Knowledge – Real time Data on Storage Integrity

Up till now there is little information available on actual time subsurface movement and performance of CO_2 plume in reservoirs and this leaves the long term integrity of storage in doubt. The current surveillance methods like seismic imaging and pressure sensors need to be enhanced in terms of spatial resolution and affordability.

Recommendations:

- Enhancing investment in the development of more advanced monitoring technology such as fiber optic sensing, remote monitoring by satellite and subsurface modeling.
- Promotion of the data sharing and open access repository for CO_2 storage performance across the world projects.
- Implementing digital twins in order to predict CO_2 plume action and location integrity.
- To address these gaps in knowledge, future researchers should take an interdisciplinary approach that would bridge the gaps between geoscience, data analytics, and environmental monitoring.

6.0 Novel Trends and Developments

There had been numerous innovations and studies in the recent that centered on solvents with low CO_2 capture energy, low energy solid sorbents capture, metal organic frameworks (MOFs), and bioenergy with CCS (BECCS). The popularity of artificial intelligence and digital twins in the application of optimization of capture activities is increasing (Silveira, B. H. M et al., 2023).

6.1 Global CCUS Project Data (2025) Analysis

6.1.1 Regional Distribution

I. The North America (USA and Canada) are presently possess higher operational projects with capacity (~30 MtCO2/yr)

II. Europe (primarily Norway and UK) is on the frontline of integrated storage hubs such as Longship and Northern lights (~10 MtCO2/year).

III. Asia-Pacific (China, Japan and Australia) have the highest growth rate particularly in pilot to commercial transition projects (~6MtCO2/year).

IV. Middle East (Saudi Arabia, UAE and Qatar) are nascent, and CO2-EOR is primarily a motivation of early implementation of CCUS (~4 $MtCO_2$/year).

6.1.2 Technology Deployment

I. The most used CCUS technology in the world is post-combustion amine absorption, which constitutes approximately 40% of the operating capacity.

II. The most advanced CCS technology is gas processing (e.g., Sleipner, Gorgon), as capture streams are simpler.

III. Direct Air Capture (DAC) is still at its infancy in scale up phase where it has captured approximately 1% of total CO_2 but it is starting to experience increased investment momentum.

IV. The best growth potential is hydrogen production with CCS (H_2+CCS) (e.g. Port Arthur, Blue H_2 hubs in the USA and EU).

6.1.3 Economic Trends

The cost of captures in average:

- CSS of industrial and gas processing cost about 35-60/tCO_2.
- Post-combustion is a retrofitted catalytic system that is about the same in cost. $100-200 per ton of CO_2.
- The cost of DAC technologies is between $500/t$CO_2$ (expected to drop to below $250/t$CO_2$ by 2030).

The key scaling enablers are policy incentives, such as the U.S. Inflation Reduction Act (IRA 45Q credits), as well as the EU Innovation Fund.

6.I.4 Future Outlook

- The International Energy Agency projected the possible global CCUS pipeline to be more than 320 MtCO_2/year (IEA, 2025). The areas that need to be focused on in the coming decade:
  - Uniformity of transport/storage networks and infrastructure.
  - Design of hybrid gathers materials (amine-functionalized sorbents, MOFs).
  - Combination with renewable hydrogen and cyclical carbon economic.

Table 2a: Worldwide Major CCUS Projects (2025)

Project	Technology	Stage	Location (Country; Region)	Capacity (MtCO_2/yr)	Details (Cost Notes; Source; Notes)
Sleipner	The gas-processing capture (amine)	Operational	Norway; Europe (North Sea)	1.0	**Cost:** Historic project; cost varies. **Source:** Global CCS Institute. **Notes:** The paper is devoted to the long-term saline aquifer storage of Utsira.
Snøhvit	Gas-processing capture	Operational	Norway; Europe (Barents Sea)	0.7	**Cost:** Offshore injection; project-specific. **Source:** Global CCS Institute. **Notes:** Sandstone offshore oil reservoir.
Boundary Dam	The post-combustion (amine retrofit)	Operational	Canada; North America	1.0	**Cost:** Retrofit on a commercial basis; controversial CapEx.. **Source:** Global CCS Institute. **Notes:** Coal-power retrofit.
Quest (Shell)	Amine capture	Operational	Canada; North America	1.0	**Cost:** Demonstration for oil sands CCS. **Source:** Shell. **Notes:** Oil sands CO_2 capture.
Petra Nova	The post-combustion (amine)	Operational	USA; North America	1.4	**Cost:** Restarted 2023; project volatility. **Source:** Global CCS Institute. **Notes:** Power plant retrofit (Texas).
Gorgon CCS	Gas-processing + injection	Operational	Australia; Asia-Pacific	3.4	**Cost:** Underperformance; high effective cost. **Source:** Chevron. **Notes:** Barrow Island project.
Northern Lights	Open-access transport & storage hub	Operational/Expansion	Norway; Europe	1.5	**Cost:** Expansion planned; major infra investment. **Source:** Northern Lights CCS. **Notes:** Shipping + offshore storage.

Project	Technology	Stage	Location (Country; Region)	Capacity ($MtCO_2$/yr)	Details (Cost Notes; Source; Notes)
ADM Decatur	Ethanol plant capture	Operational	USA; North America	1.0	**Cost:** Early industrial bioethanol CCS. **Source:** ADM. **Notes:** Illinois, USA.
Air Products Port Arthur	Industrial hydrogen plant capture	Operational	USA; North America	9.37	**Cost:** Large industrial capture project. **Source:** Air Products. **Notes:** Texas, USA.
Weyburn-Midale	EOR + storage	Operational	Canada; North America	0.5	**Cost:** Long-running EOR demo; cumulative large. **Source:** Global CCS Institute. **Notes:** Saskatchewan.

Table 2b: Worldwide Major CCUS Projects (2025)

Project	Technology	Stage	Location (Country; Region)	Capacity ($MtCO_2$/yr)	Details (Cost Notes; Source; Notes)
Tomakomai	This capture from refinery (pilot)	Demonstration	Japan; Asia	0.3	**Cost:** The project entails an offshore injection that is piloted. **Source:** JGC. **Notes:** Hokkaido, Japan.
In Salah	Gas field CO_2 reinjection	Suspended (historic)	Algeria; Africa/Middle East	1.2	**Cost:** Injection suspended (integrity issues). **Source:** Global CCS Institute. **Notes:** Historic.
Guohua Jinjie	Coal power capture pilot	Operational/Demo	China; Asia	0.15	**Cost:** Pilot-scale. **Source:** Global CCS Institute. **Notes:** China pilot expansion.
CNOOC Enping	Offshore platform capture	Operational	China; Asia	0.5	**Cost:** Recent project. **Source:** CNOOC. **Notes:** South China Sea.
Longship (aggregate)	Multi-source capture + shipping + storage	Operational/Construction	Norway; Europe	3.0	**Cost:** Gov.-backed flagship project. **Source:** Norwegian Gov't. **Notes:** Includes Northern Lights.
Climeworks (Orca, Mammoth)	The Direct Air Capture (solid sorbent)	Operational/Scale-up	Iceland; Europe	0.004	**Cost:** The product has a small capacity and a high cost. **Source:** Clime works. **Notes:** Orca plant ~4000 t/yr.
Carbon Engineering	The DAC (liquid solvent)	Pilot/Scale-up	Canada/USA; North America	0.01	**Cost:** The pilot stage scaling is planned. The pilot stage scaling is planned. The pilot stage scaling is planned. **Source:** Carbon Engineering. **Notes:** Multiple facilities.

Project	Technology	Stage	Location (Country; Region)	Capacity ($MtCO_2$/yr)	Details (Cost Notes; Source; Notes)
China Industrial Clusters	Industrial capture (varied)	Planned/Under construction	China; Asia	10.0	**Cost:** Aggregate of multiple planned projects. **Source:** IEA. **Notes:** Large expansion underway.
US Industrial CCS (aggregate)	Industrial capture (varied)	Planned/Under construction	USA; North America	15.0	**Cost:** National pipeline (est.). **Source:** IEA. **Notes:** Includes hydrogen, ethanol.
GCC Industrial Projects	Industrial capture + EOR	Planned/Under construction	Saudi Arabia, UAE, Qatar; Middle East	8.0	**Cost:** Aggregate regional estimates. **Source:** IEA. **Notes:** The deployment is spreading throughout the region.

Tables 2a and 2b. The values in the table are the overall estimates of multiple projects, and the stated capacities are in nominal units ($MtCO_2$/yr), which reflects the state of the project when the data was gathered. Cost notes are indicative only and are not directly comparable across different projects because different projects are of different scope and have different reporting limits. This analysis has compiled data, depending on the sources accessed, which are the International Energy Agency (IEA, 2020), the Global CCS Institute (2023, 2025), and project-level disclosures.

7. Future Deployment Recommendations:

I. **Policy support:** It involves the installation of incentives and prices for carbon emissions.
II. **Integration of technology:** Integration of CCUS and renewable energy systems, in particular, production of low-carbon hydrogen, BECCS, and direct air capture (DAC). Research collaboration: Nurture academia, industry, and government collaboration in the implementation of the entire CCUS technology.
III. **Infrastructure investment:** This encompasses the development of shared networks for the transportation and storage of CO_2, including building pipelines, shipping terminals, and the local facilities.
IV. **Public Involvement:** Enhancing on the public awareness by means of open communication.

8. CONCLUSION AND OUTLOOK

CCUS technology is expanding rapidly between pilot and large scale implementation with good prospects of decarbonization of heavy industries. The future advancement lies in the international cooperation, the creation of the consistent policy, and the development of the new materials and processes. When properly coordinated with relevant action CCUS would add more than 15 percent of the total cut of emissions required to achieve 2050 net zero targets.

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Author Contribution

The author only thought, examined and writes final manuscript.

Declaration of Competing Interest

The author asserts that he/she does not have any known competing financial or personal interests that might affect the work that is reported in this paper.

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