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Review Article

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Strategies for Industrial Integration of Carbon Capture, Utilization, and Storage Technologies: A Critical Review

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Abstract: This critical review examines the current landscape, challenges, and future directions of Carbon Capture, Utilization, and Storage (CCUS) technologies in industrial applications. Despite contributing 24% of global greenhouse emissions, heavy industries face significant economic, technical, and policy-related barriers in implementing CCUS solutions. The review analyzes various CCUS methodologies, including post-combustion capture, pre-combustion capture, and direct air capture, evaluating their commercial readiness and economic viability. Notable findings indicate that post-combustion capture has achieved high technological readiness levels (TRL 9), but widespread adoption remains limited due to high capital costs, energy penalties, and infrastructure requirements. The study examines successful implementations, such as the Boundary Dam and Petra Nova projects, while highlighting critical integration challenges, including geological constraints, transportation infrastructure, and regulatory frameworks. Analysis of policy mechanisms reveals that tax credits and government incentives play crucial roles in facilitating CCUS deployment, though current support structures require strengthening. The review concludes that successful CCUS implementation demands a coordinated approach combining technological innovation, robust policy frameworks, and strategic industry partnerships, while emphasizing the need for continued research and development to reduce costs and improve efficiency.

Keywords: Carbon Capture, Storage, Emissions, Technology Policy.

INTRODUCTION

Even though the industry has continuously improved its operations in terms of efficiency, cost effectiveness, and reduction in carbon emissions, the heavy industry still contributes to overall global greenhouse emissions (Worrell *et al.*, 2008). According to the United States Environmental Protection Agency (EPA) 2019 report, Electricity and Heat Production contributed to 34% of global greenhouse emissions, Industry contributed to 24% global emissions, Agriculture, Forestry and Other Land Use contributed to 22%, whilst transportation and Building contributed to 15% emissions, and Building 6%. Globally, GHG emissions continue to rise across all sectors, with the transportation and industry sectors reporting the most rapid emission rates (Dhakal, *et al.*, 2023). The key industries that have been highlighted for the 24% emissions include metals, petrochemicals, and cement, which account for three-quarters of the emissions (Gielin and Saygin, 2018).

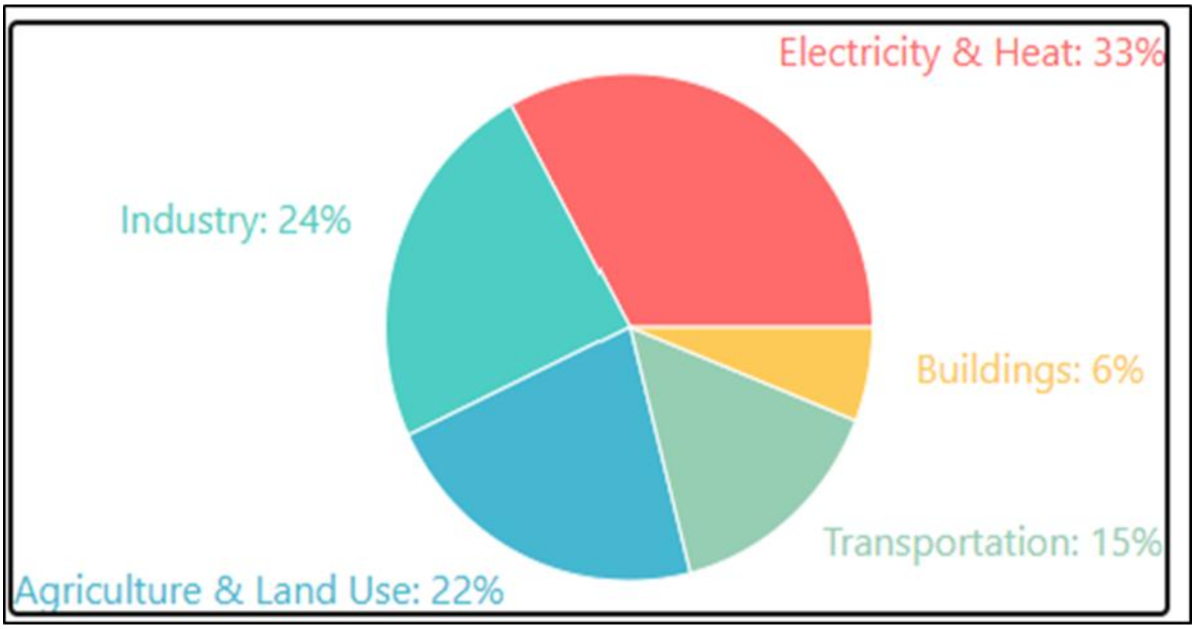

Figure 1: Pie chart showing the 2023 breakdown with industry maintaining its 24% share

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Current state of CCUS technology adoption

In the quest to mitigate the levels of carbon emissions, CCS technologies are being widely adopted globally. According to the Global CCS Institute (2024), the total number of facilities being developed for carbon capture has seen a 60% surge to 628. Since 1997, the U.S Department of Energy(DoE) Office of Fossil Energy (FE), National Technology Laboratory (NETL) have developed storage programs that have significantly advanced carbon capture, utilization, and storage (CCUS) science and technology, with more than 10.5 million metric tons (MMT) of CO_2 safely stored till date (Sullivan *et al.*, 2019). These initiatives are an example of bold steps to ultimately close the gap between CCS rhetoric and technical progress and thus call for the development of strong international cooperation on CCS technologies (Dhakal *et al.*, 2023).

Economic and technical barriers to implementation

Belani and Gerard further argued that, with the objectives of net-zero, there is a requirement for much larger volumes of CO_2 to be sequestrated permanently in the subsurface to enable the decarbonization efforts. However, the deployment of CCS technology has its own challenges. (Zakkour and Heidug, 2019) argued that the lack of a well-defined policy framework that effectively incentivizes the permanent storage of Carbon in underground reservoirs poses a major roadblock to its development. Further stating that CCS are mainly relegated to cases where CO_2 sequestration has some commercial value, such as in enhanced oil recovery purposes. Another challenge which was identified is that sequestration solutions are still in their formative stages which are associated with huge costs, uncertain market viability to longer-term potential. This requires tailored policy support to achieve deployment at the scale needed for meeting net-zero emissions targets.

Carbon Capture, Utilization, and Storage (CCUS) technology represents a vital solution for achieving global net-zero emissions targets, particularly in hard-to-decarbonize sectors like heavy industry and power generation. While CCUS offers direct environmental benefits through CO_2 emission reduction and the potential for historical emission mitigation, its successful implementation faces significant challenges including energy requirements, infrastructure needs, and potential environmental risks and policies. Despite these challenges, CCUS remains a crucial bridge technology that can help maintain economic growth while transitioning to a low-carbon future, though it requires careful implementation to maximize benefits while minimizing negative environmental impacts.

Current State of CCUS Technologies

With the fast paced expansion of the energy and industrial sector there has been massive spike in the release of CO_2 into the atmosphere by stationary sources, thus raising concerns about the looming dangers of climate change (Dziejarski *et al.*, 2023)

Various approaches are currently in use to remove CO_2 from the atmosphere.

Carbon Capture and Storage(CCS): Generally involves the direct capture of CO_2 from industrial sources. The captured CO_2 goes through a series of chemical treatment and separation processes, compressed and conveyed through pipeline structures where they are injected into underground reservoirs permanently (Zhang *et al.*, 2018, Ighomuaye et al, 2024)

Carbon Capture and Utilization(CCU): This process bears the same capturing process as CCS, however, in CCU, the captured CO_2 is transformed into useful products. More often used in Enhanced oil recovery, production of chemicals, building and construction, etc (Gao *et al.*, 2020).

Carbon Capture and Mineral Carbonation (CCMC): In this case, CO_2 is reacted with metal oxides to produce stable compounds that can be stored safely or used in other useful applications (Dziejarski *et al.*, 2023).

Bioenergy with Carbon Capture and Storage(BECCS): This process usually combines the process of Carbon Capture with bioenergy, such that biomass absorbs CO_2 while growing, which is then burned to produce energy, whilst capturing the CO_2 from the incineration process for storage underground (Hanssen *et al.*, 2020).

Direct Air Capture: Using solid sorbents or liquid solvents, these chemicals are designed to bind to CO_2 found directly in the atmosphere. The absorbed(captured) Cos can then be stored or utilized(McQueen *et al.*, 2021).

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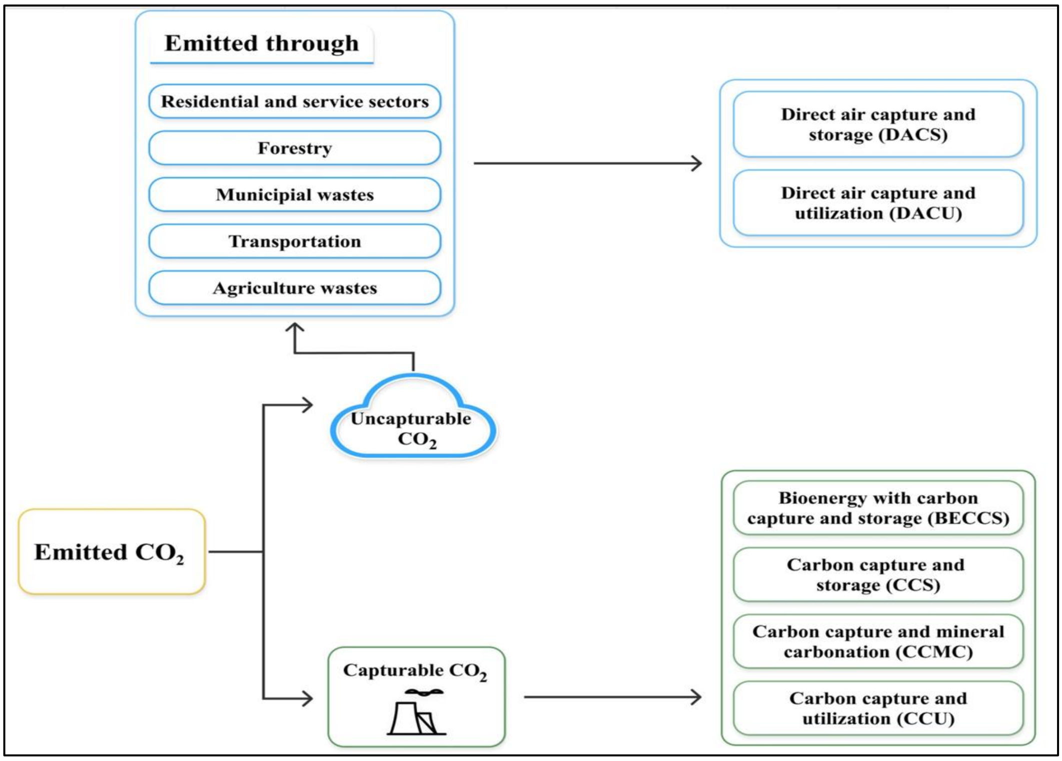

Fig. 2: Methodology of operation of CCS, CCU, CCMC, BECCS, and DAC technologies (Dziejarski *et al.*, 2023).

Technical maturity levels

There are numerous ways of establishing the maturity of carbon capture technologies, with the most commonly used one in industry being the Technological Readiness Level(TRL) metrics. This metric indicates the degree of development of a technology (Hamidreza & Myhrvold., 2017). Subsequently, a paper by Bukar & Asif, (2024) examined the maturity trends in carbon capture by looking at the capturing methods of carbon capture, which was based on their levels of technological readiness (TRL). Even though both pre-combustion and post-combustion capture are mature technologies achieving TRL 9, the most popular carbon capture technique is post-combustion capture. This study was based on 79 CCS projects, where 58 of these projects were centered on post-combustion.

Cost considerations

With regards to the different technologies used in carbon capture and the significant differences various organizations use to estimate the cost of CCS, systems, research by Rubin *et al.*, (2013) highlights key areas requiring standardization, including project scope, cost quantification methods, financial assumptions, and overall cost measures such as levelized cost of electricity and cost of CO_2 avoided. In a case study of the state of capture technology in Kuwait, Naseeb et al(2022) highlighted that Carbon capture technology is only economically viable under very specific conditions: low operational costs, stable and low fuel prices, and continued government support through tax waivers and subsidized workforce salaries. The paper further highlights that financial sustainability is quite fragile and can quickly become unfeasible with relatively small changes in costs or fuel prices.

Researchers have estimated that capturing and storing carbon dioxide(CO_2) from power plants to purposefully fight climate change may be more challenging than we think. Four main challenges to the fast development of CCS technology were identified which include: i) a tenfold up-scaling in size (MW) from pilot plants to that of commercial demonstration, (ii) a tenfold increase in number of large scale demonstration plants actually being constructed, (iii) a tenfold increase in available annual funding over the coming 40 years and, (iv) a tenfold increase in the price put on carbon dioxide emissions (Nykvist, 2013).

For carbon capture technology to succeed, it needs two key things: ongoing technological

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breakthroughs and strong government backing. The challenges we've identified show that this isn't just about scientific innovation - it needs serious political and financial support from governments to become a reality. Throwing more light on what needs to make carbon capture technology cheaper and better, strong research and development efforts need to be encouraged. We need to move from testing to real-world commercial use of the developed technology and identify actual markets where these technologies are actually needed. However, unless government regulations create the initial push for companies to adopt it, the technology would struggle to be widely adopted and cheap (Rubin, *et al.*, 2012).

Success stories and case studies

The establishment of crucial science and technology CCS infrastructures in advanced countries has become the driving force for CCS technological innovation. It is crucial to note that the development of CCS requires a transition from pilot-scale science and technology infrastructures to large-scale commercial infrastructures, and this must go hand in hand with incentive policies (Ma *et al.*, 2022). In a study analyzing the first successful commercial scale CCS technology deployment in the world in Saskatchewan, the study essentially highlighted how successful communication and local contextual factors contributed to the acceptance of a groundbreaking carbon capture technology in the area (Hurlbert *et al.*, 2023). The paper by Kuramochi et al. (2012) presented a comprehensive technical and economic assessment of CO_2 capture technologies across three key industrial sectors: iron and steel, cement, and refineries/petrochemicals. Below is a summary of the key findings

Iron and Steel Industry:

The iron and steel industry presents unique opportunities and challenges for CCUS implementation, with multiple technological pathways offering varying economic feasibility and emission reduction potential. Short-term technologies such as top gas recycling blast furnace (TGRBF) systems have demonstrated promising economic viability, achieving CO_2 avoidance costs ranging from 41-66 dollars per tonne of CO_2, making them among the most cost-effective CCUS applications in heavy industry. These systems work by capturing and recycling blast furnace gases, reducing overall carbon intensity while maintaining production efficiency. Long-term technological developments focus on advanced smelting reduction techniques that could fundamentally transform steel production processes, potentially achieving deeper emission reductions through process redesign rather than end-of-pipe capture solutions. The Direct Reduced Iron (DRI) process has emerged as a particularly promising pathway for low-carbon steel production, utilizing hydrogen or natural gas as reducing agents instead of coke, thereby significantly reducing process emissions while enabling easier CO_2 capture from concentrated streams. The industry's high emission intensity, coupled with growing global steel demand, makes these technological advances critical for achieving industrial decarbonization targets.

Cement Sector:

The cement industry faces distinct challenges in CCUS implementation due to the fundamental nature of process emissions, which stem both from energy consumption and the chemical decomposition of limestone during clinker production. Post-combustion CO_2 capture emerges as the most technically feasible near-term solution for the cement sector, though economic costs remain substantial with short-term implementation costs ranging from 71-138 dollars per tonne of CO_2 captured. This wide cost range reflects variations in plant size, capture technology selection, and local economic conditions, highlighting the need for tailored approaches to different facilities. Long-term technological innovations offer more promising economic prospects, with advanced technologies such as oxyfuel combustion and calcium oxide (CaO) looping showing potential to reduce capture costs to 25-55 dollars per tonne of CO_2, representing a significant improvement in economic viability. Oxyfuel combustion involves burning fuel in pure oxygen rather than air, producing a flue gas stream that is primarily CO_2 and water vapor, simplifying capture processes and reducing energy penalties. The CaO-looping process utilizes the reversible carbonation-calcination reaction of calcium oxide to capture CO_2, offering potential for integration with existing cement production processes while reducing overall energy requirements.

Refineries and Petrochemicals:

The refining and petrochemical sectors present favorable conditions for CCUS deployment due to their existing infrastructure for gas processing and high-pressure operations that align well with CO_2 capture and compression requirements. Economic analysis indicates that oxyfuel CO_2 capture technologies offer superior short-term economic performance in these sectors, with costs ranging

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from 51-61 dollars per tonne of CO_2 avoided, making them more economically attractive than many other industrial CCUS applications. This economic advantage stems from the sector's experience with gas separation technologies, existing pipeline infrastructure, and concentrated emission sources that reduce capture complexity and costs. However, post-combustion capture costs remain comparatively high in refining applications due to the diverse nature of emission sources and varying flue gas compositions that complicate capture system design and operation. The petrochemical industry offers additional advantages through potential CO_2 utilization pathways, where captured carbon can be converted into valuable chemical products such as methanol, synthetic fuels, or polymer precursors, creating revenue streams that can offset capture costs. Integration challenges include managing multiple emission sources within complex facilities, coordinating capture operations with existing process schedules, and ensuring capture system reliability that matches the high availability requirements of continuous processing operations (Kuramochi *et al.*, 2012).

The Boundary Dam, a 846MW coal plant, and one of the largest projects undertaken by Sak Power. It is known for being the first power station to successfully adopt CCS technology. With an estimated cost of about 1.5 billion USD, this project facilitated the reduction of atmospheric pollution by preventing the entry of approximately four million tons of carbon dioxide into the atmosphere, which was equivalent to taking one million vehicles off the road for a year(Kumar, 2022).

The Petra Nova Project $1 billion joint Venture project by NRG Energy and JX Nippon Oil and Gas Exploration. It is the world's largest post-combustion carbon capture project. The facility captures 1.6 million metric tons of CO_2 annually. The captured CO_2 is transported 81 miles through pipelines to the West Ranch Oil Field, which is used for Enhanced Oil Recovery, increasing production from 500 to 15,000 bbls/day. The Petra Nova project became commercially viable through a creative three-part financing structure: a $167 million government grant to offset initial costs, revenue from enhanced oil recovery (where NRG smartly took partial ownership of the oil field rather than just selling the CO_2), and risk-tolerant loans from Japanese export credit agencies that were interested in the project's strategic value (Jenkins, 2015). Another project that is worthy of mention is the Sleiper project, which commenced in 1996. It was a pioneering project for industrial-scale CO_2 storage, injecting approximately 1 million tons of CO_2 annually into the Utsira Sand saline aquifer. This initiative was a response to environmental regulations, ultimately storing over 13 million tons by 2011 (Chadwick, 2013).

INTEGRATION CHALLENGES

Even though CCS has been earmarked as a transformative technology to help tackle carbon emissions, there have been major roadblocks in the deployment of the technology. Apart from the fact that the technology is still young and needs further research, there are a myriad of other challenges which have been identified. A paper by Shirmohammadi et al. (2020) identified high capital and operational cost, Energy penalties, the lack of market Incentives, Legal and regulatory barriers, public perception and awareness, technical challenges, funding, skilled workforce, and slow policy implementation as key roadblocks to the deployment of CCS technology. Other challenges include technical, geological, transportation, safety and regulatory hurdles. Geological challenges often involve accurate site characterization, complex subsurface modeling, and predicting CO_2 migration and trapping, which are hindered by data inconsistencies and limited information. Issues of transportation stem from the construction of pipelines, which also introduce some cost components and issues of integrity and efficiency. Safety challenges such as monitoring CO_2 containment, mitigating leakage risks, and preventing induced seismicity due to excessive injection pressures. Additionally, regulatory challenges, such as inconsistent policies, lengthy permitting processes, and insufficient financial incentives, further hinder project scalability and investment attractiveness (Rui et.al., 2024).

The challenges of carbon capture and storage (CCS) as a corporate technology strategy, as outlined in Bowen (2011), can be summarized into four key strategic barriers:

Precautionary Nature:

- CCS investments are made as a precaution against future climate risks, but the benefits are intangible and long-term.
- There is a lack of immediate rewards for companies investing in CCS.
- Public acceptance of both CCS technology and climate change mitigation is a barrier.

Sustaining vs. Disruptive Innovation:

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- CCS is generally a sustaining innovation that allows existing energy systems to continue operating with lower emissions, rather than a disruptive shift to renewables.
- Firms prefer CCS because it aligns with current fossil fuel-based operations, rather than transitioning to alternative low-carbon technologies.

Cumulative Nature:

- CCS investments have cumulative benefits, meaning early adoption leads to greater emissions reductions over time.
- High initial costs and technological uncertainties deter companies from making early investments.
- Companies struggle with the decision of when and how to invest in CCS, given uncertain future regulations and market conditions.

Situated Nature:

- CCS deployment depends on geographic, industrial, and political contexts.
- Some regions and industries are better positioned to develop and adopt CCS than others.
- Policy inconsistencies, national political interests, and technology transfer challenges impact global adoption.

Policy Framework and Support Mechanisms

In order to fully harness the potential CCUS has to contribute to emission reduction and reduce raw material consumption, strong policy support is needed in overcoming the current barriers. to Thielges et al. (2022), the main policy instruments to incentivize the implementation of CCUS in the US are tax credits. Moreover, funding exists for research and development efforts. In a paper that analyzed both policy frameworks and stakeholder perceptions in 3 European countries, that is, France, Spain, and Poland, key highlights were made on how public perceptions and opinions influence the successful adoption of CCUS technologies. Regulatory Environments, government support, and public engagement have been observed to determine the deployment of CCUS technology (Wesche *et al.*, 2023).

The policy framework and support mechanisms for the deployment of Carbon Capture, Utilization, and Storage (CCUS) in the United States, as detailed by Edwards et al. (2018) and Ighomuaye et al, 2025, highlight a combination of economic incentives, infrastructure development, and coordinated government-industry collaboration. The introduction of financial incentives, such as the Section 45Q tax credits, has made CCUS more economically feasible for low-cost capture sources like ethanol biorefineries. However, the viability of large-scale CCUS deployment is still challenged by high infrastructure costs and the need for extensive government support. The study suggests that without significant government financing—either through direct investment, loans, or other incentives—private-sector-led pipeline networks would be economically unfeasible. The analysis underscores the importance of coordinated policy efforts, including state and federal collaboration, regulatory streamlining, and infrastructure planning, to create a sustainable and scalable CCUS network. Additionally, aligning CCUS projects with Enhanced Oil Recovery (EOR) and long-term geological storage goals is critical for maximizing economic and environmental benefits. This policy framework is essential for addressing uncertainties, reducing financial risks, and ensuring that CCUS can meet climate targets effectively.

FUTURE DIRECTIONS AND RECOMMENDATIONS

Emerging technologies and innovations

The primary principles underlying CCUS involve capturing CO_2, transporting it, utilizing it in productive ways, and safely storing it to mitigate climate change (Ampomah et al. 2024). The future of Carbon Capture and Utilization (CCU) technologies is poised for transformative developments across multiple interconnected domains. Technological innovation stands at the forefront, with researchers focusing on enhancing capture methodologies through sophisticated approaches like advanced solvent systems, innovative membrane technologies, and intelligent adsorption techniques (Gupta & Li., 2022). The strategic incorporation of artificial intelligence and machine learning promises to revolutionize process optimization, potentially reducing both operational complexities and economic barriers(Yan *et al.*, 2021).

Simultaneously, the field is exploring increasingly diverse pathways for CO_2 conversion, seeking to transform what was once considered a waste product into valuable resources. Emerging chemical and biological processes aim to convert carbon dioxide into a wide range of products, including sustainable fuels, advanced polymers, and construction materials (Modak *et al.*, 2020). This approach not only addresses environmental

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challenges but also creates potential economic opportunities.

Renewable energy integration emerges as a critical strategy. By coupling CCU technologies with solar and wind energy sources, researchers aim to create more sustainable and environmentally friendly carbon utilization methods. A study published in Energy & Environmental Science discusses the synergistic integration of renewables and flexible carbon capture with fossil power plants. Renewable energy provides clean power for carbon capture processes, while flexible carbon capture systems can act as energy storage, mitigating the variability inherent in renewable sources (Zantye *et al.*, 2021). This synergy could significantly reduce the overall carbon footprint of industrial processes.

Policy frameworks and economic mechanisms will play a pivotal role in CCU's future trajectory. Governments are being encouraged to implement robust support structures, including carbon pricing mechanisms, targeted tax incentives, and funding for demonstration projects. International collaboration on standardizing carbon markets could accelerate global adoption and create more consistent regulatory environments. On the international stage, the adoption of operational standards for the Paris Agreement's Article 6.4 mechanism at COP29 marks a significant step toward a global carbon market.

Infrastructure development represents another crucial aspect, with significant investments needed to establish comprehensive CO_2 transport and storage networks. Key industrial sectors like cement, steel, and petrochemicals will be instrumental in scaling up these technological solutions.

Environmental assessment remains paramount. Researchers emphasize the importance of conducting rigorous lifecycle analyses to ensure that CCU technologies genuinely contribute to net CO_2 reductions and align with broader climate mitigation strategies. This requires a holistic approach that considers not just immediate carbon capture, but the entire environmental impact of these technologies.

Lastly, public engagement and stakeholder communication emerge as fundamental to CCU's success. Building awareness, addressing concerns, and fostering understanding among policymakers, industries, and the general public will be essential for widespread technological adoption.

The path forward for CCU technologies demands a comprehensive, multidisciplinary approach. By harmonizing technological innovation, economic feasibility, policy support, and social acceptance, these technologies can potentially become a significant tool in global efforts to mitigate climate change and transition towards a more sustainable future.

CONCLUSION

The comprehensive analysis of CCUS technologies reveals both their transformative potential and persistent challenges in industrial decarbonization efforts. Several key findings emerge from this review:

First, while CCUS technologies have demonstrated technical feasibility through successful projects like Boundary Dam and Petra Nova, widespread adoption remains constrained by economic barriers. The high capital and operational costs, coupled with energy penalties, continue to challenge commercial viability without substantial government support.

Second, the integration of CCUS technologies requires addressing multiple interconnected challenges. These include geological considerations for storage, transportation infrastructure development, and the establishment of comprehensive regulatory frameworks. The review highlights that successful implementation depends on resolving these technical and logistical challenges while ensuring environmental safety and public acceptance.

Third, policy support mechanisms, particularly tax credits and direct government funding, play a crucial role in bridging the economic gap. However, current policy frameworks vary significantly across regions and often lack the consistency and long-term certainty needed to drive substantial private investment.

Looking forward, several key areas require attention:

- Enhanced research and development efforts focused on reducing costs and improving efficiency of capture technologies
- Development of standardized international frameworks for carbon pricing and trading

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- Establishment of comprehensive CO_2 transportation and storage networks
- Stronger coordination between government policies and industry needs
- Increased public engagement and stakeholder communication

The path to successful CCUS implementation requires a coordinated approach that combines technological innovation, supportive policy frameworks, and strategic industry partnerships. Future research should focus on optimizing integration strategies, reducing costs, and developing innovative financing mechanisms to accelerate adoption. Only through such comprehensive efforts can CCUS fulfill its potential as a crucial tool in achieving global climate mitigation goals.

REFERENCES

1. *Global Greenhouse Gas Overview, US Environmental Protection Agency (EPA)*
2. De Coninck, H., Stephens, J. C., & Metz, B. "Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration." *Energy Policy* 37.6 (2009): 2161-2165.
3. Dziejarski, B., Krzyżyńska, R., & Andersson, K. "Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment." *Fuel* 342 (2023): 127776.
4. Bukar, A. M., & Asif, M. "Technology readiness level assessment of carbon capture and storage technologies." *Renewable and Sustainable Energy Reviews* 200 (2024): 114578.
5. Bakhtiary-Davijany, H., & Myhrvold, T. "On methods for maturity assessment of CO2 capture technologies." *Energy Procedia* 37 (2013): 2579-2584.
6. Nykvist, B. "Ten times more difficult: Quantifying the carbon capture and storage challenge." *Energy Policy* 55 (2013): 683-689..
7. Ighomuaye, E., Dudun, A., Boukadi, F., & Osumanu, J. "Comparative Study of CO2 Storage Capacity Estimation in Depleted Oil & Gas Reservoir: A Case Study in Vermillion Basin Gulf of Mexico." *Petroleum & Petrochemical Engineering Journal,* 8(1), (2024). 1-10.
8. Rubin, E. S., Mantripragada, H., Marks, A., Versteeg, P., & Kitchin, J. "The outlook for improved carbon capture technology." *Progress in energy and combustion science* 38.5 (2012): 630-671.
9. Ma, J., Li, L., Wang, H., Du, Y., Ma, J., Zhang, X., & Wang, Z. "Carbon capture and storage: history and the road ahead." *Engineering* 14 (2022): 33-43.
10. Hurlbert, M., & Osazuwa-Peters, M. "Carbon capture and storage in Saskatchewan: An analysis of communicative practices in a contested technology." *Renewable and Sustainable Energy Reviews* 173 (2023): 113104.
11. Kuramochi, T., Ramírez, A., Turkenburg, W., & Faaij, A. "Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes." *Progress in energy and combustion science* 38.1 (2012): 87-112.
12. Kumar, B. R. "Case 38: Boundary Dam Power Station." *Project Finance: Structuring, Valuation and Risk Management for Major Projects*. Cham: Springer International Publishing, 2022. 275-277.
13. Chadwick, R. A. "Offshore CO2 storage: Sleipner natural gas field beneath the North Sea." *Geological storage of carbon dioxide (CO2)*. Woodhead Publishing, 2013. 227-253e.
14. Rui, Z., Zeng, L., & Dindoruk, B. "Challenges in the large-scale deployment of CCUS." *Engineering* 44 (2025): 17-20.
15. Bowen, F. "Carbon capture and storage as a corporate technology strategy challenge." *Energy Policy* 39.5 (2011): 2256-2264.
16. Thielges, S., Olfe-Kräutlein, B., Rees, A., Jahn, J., Sick, V., & Quitzow, R. "Committed to implementing CCU? A comparison of the policy mix in the US and the EU." *Frontiers in climate* 4 (2022): 943387.
17. Gupta, S., & Li, L. "The potential of machine learning for enhancing CO2 sequestration, storage, transportation, and utilization-based processes: a brief perspective." *Jom* 74.2 (2022): 414-428.
18. Modak, A., Bhanja, P., Dutta, S., Chowdhury, B., & Bhaumik, A. "Catalytic reduction of CO 2 into fuels and fine chemicals." *Green Chemistry* 22.13 (2020): 4002-4033.
19. Zantye, M. S., Arora, A., & Hasan, M. F. "Renewable-integrated flexible carbon capture: a synergistic path forward to clean energy future." *Energy & Environmental Science* 14.7 (2021): 3986-4008.
20. Bowen, F. "Carbon capture and storage as a corporate technology strategy

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challenge." *Energy Policy* 39.5 (2011): 2256-2264.
21. Collaborating For A Net-Zero Future-Global Status Of Ccs 2. (2024).
22. Dhakal, S., Minx, J. C., Toth, F., Abdel-Aziz, A., Figueroa Meza, M. J., Hubacek, K., ... & Wiedmann, T. "Emissions trends and drivers (chapter 2)." (2022): 215-294.
23. Edwards, R. W., & Celia, M. A. "Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States." *Proceedings of the National Academy of Sciences* 115.38 (2018): E8815-E8824.
24. Gielen, D., & Saygin, D. "Global Industrial Carbon Dioxide Emissions Mitigation." (2018).
25. Jenkins, J. "A case study of the Petra Nova carbon capture project." *The Paulson Institute: Chicago, IL, USA* (2015).
26. Naseeb, A., Ramadan, A., & Al-Salem, S. M. "Economic feasibility study of a carbon capture and storage (CCS) integration project in an oil-driven economy: the case of the State of Kuwait." *International Journal of Environmental Research and Public Health* 19.11 (2022): 6490.
27. Shirmohammadi, R., Aslani, A., & Ghasempour, R. "Challenges of carbon capture technologies deployment in developing countries." *Sustainable Energy Technologies and Assessments* 42 (2020): 100837.
28. Sullivan, M., Rodosta, T., Mahajan, K., & Damiani, D. "An overview of the Department of Energy's CarbonSAFE Initiative: Moving CCUS toward commercialization." *AIChE Journal* 66.4 (2020): e16855.
29. Wesche, J., Germán, S., Gonçalves, L., Jödicke, I., López-Asensio, S., Prades, A., ... & Dütschke, E. "CCUS or no CCUS? Societal support for policy frameworks and stakeholder perceptions in France, Spain, and Poland." *Greenhouse Gases: Science and Technology* 13.1 (2023): 48-66.
30. Worrell, E., Bernstein, L., Roy, J., Price, L., & Harnisch, J. "Industrial energy efficiency and climate change mitigation." *Renewable energy*. Routledge, 2018. Vol1_548-Vol1_568.
31. Yan, Y., Borhani, T. N., Subraveti, S. G., Pai, K. N., Prasad, V., Rajendran, A., ... & Clough, P. T. "Harnessing the power of machine learning for carbon capture, utilisation, and storage (CCUS)–a state-of-the-art review." *Energy & Environmental Science* 14.12 (2021): 6122-6157.
32. Zhang, Z., Tohid, N.G., Borhani, Muftah H. El-Naas,Chapter 4.5 - Carbon Capture, Editor(s): Ibrahim Dincer, C. Ozgur Colpan, Onder Kizilkan, "Exergetic, Energetic and Environmental Dimensions." *Academic Press,* (2018)
33. Gao, W., Liang, S., Wang, R., Jiang, Q., Zhang, Y., Zheng, Q., ... & Park, S. E. "Industrial carbon dioxide capture and utilization: state of the art and future challenges." *Chemical Society Reviews* 49.23 (2020): 8584-8686.
34. Hanssen, S. V., Daioglou, V., Steinmann, Z. J. N., Doelman, J. C., Van Vuuren, D. P., & Huijbregts, M. A. J. "The climate change mitigation potential of bioenergy with carbon capture and storage." *Nature Climate Change* 10.11 (2020): 1023-1029.
35. McQueen, N., Gomes, K. V., McCormick, C., Blumanthal, K., Pisciotta, M., & Wilcox, J. "A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future." *Progress in Energy* 3.3 (2021): 032001.
36. Zakkour, P., & Heidug, W. "A Mechanism for CCS in the Post-Paris Era." *King Abdullah Petroleum Studies and Research Center. https://doi. org/10.30573/KS--2019-DP52* (2019).
37. Dziejarski, B., Krzyżyńska, R., & Andersson, K. "Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment." *Fuel* 342 (2023): 127776.
38. Bakhtiary-Davijany, H., & Myhrvold, T. "On methods for maturity assessment of CO2 capture technologies." *Energy Procedia* 37 (2013): 2579-2584.
39. Rubin, E. S., Short, C., Booras, G., Davison, J., Ekstrom, C., Matuszewski, M., & McCoy, S. "A proposed methodology for CO2 capture and storage cost estimates." *International journal of greenhouse gas control* 17 (2013): 488-503.
40. Ampomah, W., Morgan, A., Koranteng, D. O., & Nyamekye, W. I. "CCUS perspectives: Assessing historical contexts, current realities, and future prospects." *Energies* 17.17 (2024): 4248.
41. Dhakal, S., Minx, J. C., Toth, F., Abdel-Aziz, A., Figueroa Meza, M. J., Hubacek, K., ... & Wiedmann, T. "Emissions trends and drivers (chapter 2)." (2022): 215-294.
42. Ighomuaye, E., Annankra, J. A., & Yakin, Z. "A Critical Review of the Regulatory and

Publisher: SARC Publisher

Policy Landscape Governing Carbon Capture, Utilization, and Storage (CCUS) Technologies in the United States: Challenges, Opportunities, and Future Directions." (2025).

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