International Journal of Basic and Applied Sciences, 14 (SI-1) (2025) 103-106

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/hqy1ma70
Research paper

Advancements in Carbon Capture and Storage Technologies for Climate Change Mitigation

Ramachandran Thulasiram [1] *, Vinod Kumar Singh [2], Dr. Satish Upadhyay [3], B. Reddy [4], Dr. Rima Sahani [5], Dr. Michael Rahul Soosai [6], Amit Kumar [7]

[1] *Professor, Department of Mechanical Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Ramnagar District, Karnataka, India*
[2] *Professor, Department of Science, Maharishi University of Information Technology, Lucknow, India*
[3] *Assistant Professor, uGDX, ATLAS SkillTech University, Mumbai, India*
[4] *Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh, India*
[5] *Assistant Professor, Department of Civil Engineering, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India*
[6] *Assistant Professor, Department of Chemical, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India*
[7] *Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India*
**Corresponding author E-mail: t.ramachandran@jainuniversity.ac.in*

Received: May 2, 2025, Accepted: May 31, 2025, Published: July 7 2025

Abstract

Human behaviors have resulted in a significant rise in emissions of carbon dioxide (CO2), a principal greenhouse gas (GHG) that is exacerbating climate change (CLC), leading to a global temperature increase above 2°C compared to levels before industrialization. This work assessed the primary methods used for carbon capture (CC). The article outlines the progress in CC, storage, and use for climate change mitigation (CCM). This research aggregated data on GHG emission mitigation activities, including CC and storage (CC&S) and usage, contemporary technical advancements in CC&S, and their financial, ecological, and social ramifications. The potential of CC&S technology for CCM has also been examined. CC&S procedures need reduced energy use, making them more economically viable for CCM. CC&S for CCM has problems, and the public view of these programs seems intricate or unsatisfactory for the implementation of significant initiatives, obstructing the achievement of emissions reduction objectives across different states. A single migration seems insufficient for achieving an economy without emissions. Stringent regulations, monetary benefits, stakeholder engagement, and technical advancements are essential for migration; nevertheless, these technological innovations and regulatory measures must be validated via a comprehensive sustainability assessment to mitigate the risks associated with capital and CLC.

Keywords: *Greenhouse Gas; Carbon Capture; Climate Change; Storage; Ecology.*

1. Introduction

Green energy sources have advanced significantly during the last 10 years. The average power price for sunlight and wind power technologies has decreased by 65% and 86%, respectively [1]. The average solar electricity price was almost five times greater before 10 years. Notwithstanding the rapid advancement of renewable technology, nations depend on oil and gas to meet worldwide power demands [4]. The worldwide energy demand is projected to be mostly satisfied by fossil fuels, accounting for 80% by 2045. While awaiting the complete maturation of green energy to supplant fossil fuels, CC&S and coal-based emissions are essential during this transitional phase [11]. The combined combustion cycle (CCC) is a prevalent method associated with CC&S in green energy source facilities. Transport and electricity production in developing nations account for 50% of the nation's total GHG releases [3].

Moreover, coal is considered the present and future energy source in developing nations, with overall reserves estimated at roughly 165 gigatons. Consequently, the CCC method, in conjunction with CC, becomes essential. Worldwide, coal is the predominant form of energy for power production and the second-biggest supply for electricity generation [12]. Currently, the worldwide emissions of CO2 rate and atmospheric CO2 levels over 410 ppm have resulted in almost 1.5°C of CLC compared to the pre-industrial era, with an extra 0.5°C attributable to coal combustion [5] [2].

Consequently, examining CC technology is crucial since it is the only method to reduce CO2 releases from industrial-scale power production facilities, potentially decreasing these releases by 55% in 2055 [6]. The expense of mitigating CO2 releases would escalate if CC&S technologies are disregarded [13].

The International Energy Agency (IEA) also forecasted the necessary sector modifications to attain the CO2 emission reduction objective [7]. To achieve the CLC objective by 2055, CO2 emission reductions must be 20% for CC&S, 18% for green energy, 7.5% for atomic power effectiveness, 6% for power production efficiency, 16% for final consumer energy shifting, and 40% for final usage effectiveness.

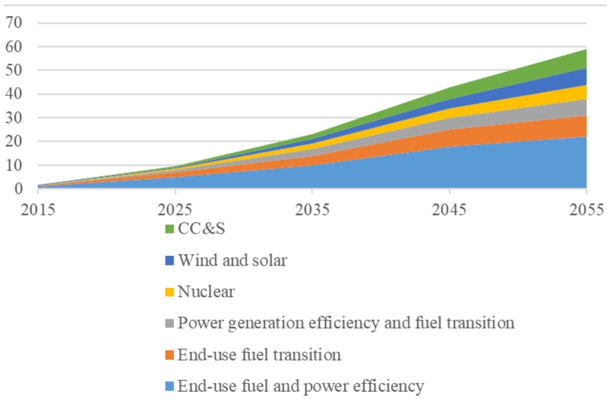

Fig. 1: Projected Emission Reductions by Technology (2015–2055).

Fig. 1 illustrates the emission reductions achieved via various technology modifications from 2015 to 2055. Despite extensive endeavors to implement CC&S, its financial, ecological, and social potential remains underdeveloped [14] [10]. This research aggregated data on GHG release reduction projects, including CC&S, while examining current technical advancements in these areas and their financial, ecological, and social ramifications [8]. Due to the fact that climate change is a global concern, carbon capture and storage within CC&S has become a major focus in the energy transition strategy worldwide. In prior sections, we discussed emission reduction pathways, mitigation contributions, and other factors of emissions. Now we will shift our attention to the technology which makes these reductions possible. Carbon capture and storage technologies will not only help achieve long-term climate goals but also enable more effective deployments by understanding scientific mechanisms and current advancements . This enables the classification of these approaches into chemical, biological or emerging frameworks thus providing an overall assessment of their operational feasibility.

In the first section of this document we discuss fossil fuels as a persistent source of energy worldwide with emphasis on CC&S. We further build upon Chapter two concentrates on transfer mechanisms discussing trade offs pertaining to article efficiency then concludes claiming chapters four five and six being devoted towards describing renewable hydrogen policies advanced materials such as MOFs while illustrating public perception through communication platforms as basic components helping drive forward even supported structural pillars.The paper claims CCS can be achieved with creative technologies and policies that meet climate ambitions through innovation.

2. Carbon capture and storage (CC&S)

CC&S includes CC, segregation, contraction, transportation, storage, and usage, and is acknowledged as an appealing technique for emission reduction. Diverse methodologies are employed or suggested within the CC&S attempts for CCM like reforestation, harvesting biomass for biological energy or biological substance generation, direct atmospheric CC, the immediate release of technological carbon into oceanic or underground lakes and rivers, and exploitation of collected carbon from different sectors, yielding distinct outcomes like chemical compounds, energy sources, plastic items, or algal blooms. Research that included industrial carbon capture and storage into a worldwide, multi-regional, multi-sector power business framework also validated the potential for CO2 reduction in business sectors, particularly in the chemical, iron, and construction sectors [15].

Biological energy CC&S, reforestation, and land utilization administration are acknowledged as the primary negative carbon techniques. Nevertheless, CLC was shown to be a superior alternative to CC&S, exhibiting more acceptability [17]. Conversely, the CC&S strategy is recognized for its practicality and adaptability in tackling global CLC concerns. CC&S for CCM is acknowledged as an appropriate substitute for mineral preservation and generating goods with additional value [16].

For instance, pollutants from steel plants and gasified biomass waste have been instantly transformed into nonethylene glycol (MEG) via oxidation utilizing an engineered bacteria as a precursor for diverse polymer goods, including resins, fibers, and containers; however, the requirement for CO2 as a raw material for different outcomes is observed to be lower than the worldwide emissions of CO2. Nonetheless, CC&S is recognized as resource-intensive (20 times more than other processes when H2 is created), mostly due to elevated power use in H2 synthesis. Conversely, the bio-route (where biomass is cultivated and treated to produce chemicals) demands 40 times more land than CC&S procedures for CCM.

Examining different CCS methods brings out important trade-offs associated with each. Algae-based capture systems, for example, CO_2 fixing while concurrently producing biomass have capture efficiencies of 50-70%. Furthermore, they require extensive land and sunlight which hinders their scalability potential. On the other hand, amine scrubbing performs chemical absorption with greater than 90% capture efficiency and is already used at an industrial scale. However, these systems incur hefty operating costs of 40−40−120 per ton of CO_2 captured alongside significant energy penalties of up to 3.5 GJ/ton CO_2 scrubbed. Amine scrubbing dominant usage in industry demonstrates its maturity and near term economic viability, while biological approaches hold promise for long-term sustainability but require additional refinement to improve cost effectiveness along with efficiency [11].

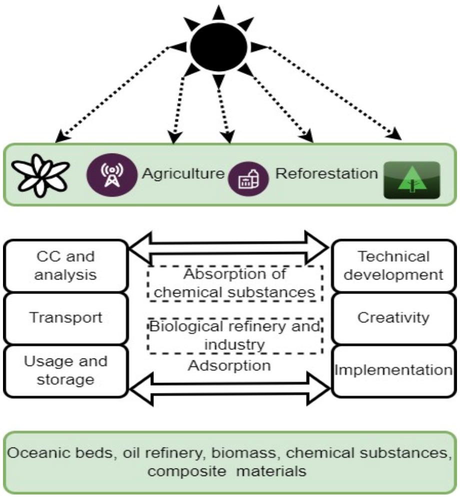

Fig. 2: A Summary of CC&S Methods for CCM.

Sophisticated methods and systems may facilitate CLC without reforming the chemical sector for CC&S, such as H2 synthesis from collected carbon; nonetheless, the authors observed that each method had distinct advantages and disadvantages, resulting in no definitive superior option. While numerous options exist for industrial carbon reduction, CC&S is recognized as the most cost-effective solution for the cement and iron sectors. Modern fossil fuel stations need around 27% of power per net kW/h production for CC. In a sophisticated chemical procedure, industrial carbon is sequestered and transformed into artificial solid carbonated substances to diminish the carbon impact of power plants. Furthermore, CO2 may be generated using rapid carbonation while managing solid waste processes, which possess recycling possibilities.

A summary of CC&S methods has been given in Fig. 2. Carbon can be extracted from energy production, industrial sectors, or the natural environment, utilizing chemical-based intake, segregation, or adsorption methods. It is then concentrated at elevated temperature, shipped to inshore or far away reservoirs or saline waterways, and subsequently administered to storage facilities. On the other hand, carbon from the air may be sequestered by sunlight and transformed into diverse biological products. Successful deployment of CC&S requires technology advancements and stakeholder engagement for CCM.

Various advanced segregation methods are used via the combustion procedure for the CO2 extraction from the exhaust gases. The approaches include intake, small algae, membrane division, adsorption, and freezing (Fig. 3). Assimilation is a well-established CO2 segregation method used in the chemical and oil industries to date. Assimilation is categorized into two types: (1) physical, which depends on humidity and pressure (occurring at extreme pressures and reduced temperatures), and (2) chemical-based, where CO2 uptake is contingent upon an acid-base neutralization reaction [9]. Notable among the preferred solvents are amino acids, ammonium solutions, and fluorinated solutions. Ionized fluids are a prevalent contemporary addition, demonstrating outstanding potential in CO2 uptake and exhibiting eco-friendliness.

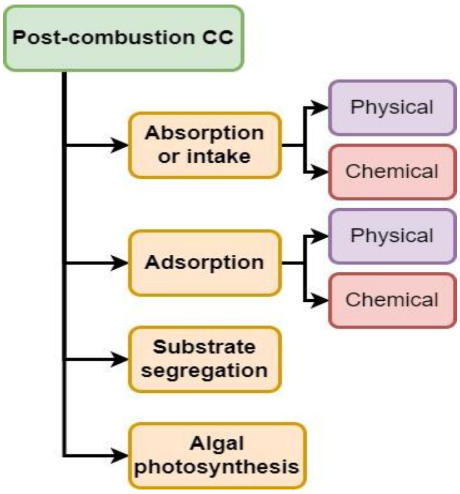

Fig. 3: Flue Gas CO_2 Capture Methods

Algal cell biological fixation is an effective method for removing CO2 from exhaust gases. This approach requires using organisms that photosynthesize for human-induced CC&S for CCM. Maritime phytoplankton are posited to possess greater possibilities due to their superior carbon stabilization rates compared to terrestrial plants. Algae cultivation is expensive, yet the method generates many high-value compounds that may be used for revenue generation. Algae respiration facilitates the dissolution of calcium dioxide, which may serve as a long-term carbon store.

The division of compounds via walls relies on the differences in relations among gases and the cell wall materials, which are tailored to allow selective transport of certain components into the barrier. Substrates provide exceptional efficacy in CO2 removal for both pre-combustion CC and post-combustion CC. A wide array of varied substrate materials and techniques is available, some of which are used in industry and may be pertinent to CO2 isolation. The implementation of substrate separation methods and the associated expenses for substantial CO2 collection mostly depend on the substrate substances.

Adsorptive extraction is an integrated separation method based on the differences in adsorption and the components' removal characteristics. The frozen CO2 separation process employs the principles of liquid phase thermal and pressure fluctuations in the constituent molecules of the exhaust gas. This process involves the cooling and precipitation of CO2, which is then collected from the exhaust gases.

3. Conclusion

The article delineates carbon capture, storage, and utilization advancements for climate change mitigation. This study collected data on GHG mitigation initiatives, including CC&S and use, recent technological breakthroughs in CC&S, and their financial, ecological, and social implications. The capabilities of CC&S technology for CCM have also been analyzed. CC&S methods need diminished energy consumption to enhance CCM's economic viability.

Although several hurdles persist in enhancing its general effectiveness, the initial combustion technique has promise for CC. The solution rejuvenation temperature must be maintained at a lower level than now used to prevent solvent degradation. The exploration of innovative air segregation technologies, including ion-transport and oxygen-transport barriers and biochemical looping techniques, is crucial in the combustion of the oxygen fuel process. Both classic and innovative approaches for CC have been assessed. The post-combustion technique necessitates unique solutions with advantageous characteristics, including high cycle capacities, cheap manufacturing costs, minimal corrosion, reduced deterioration, fewer by-products, and diminished ecological impact. Simultaneously, other obstacles are linked to substrate segregation, including condensation of moisture on the substrate, a fast decline in choice and permeability during execution, and the passage of pollutants through the substrate.CC&S for CCM has challenges, and The negative perception people have about carbon capture and storage mortally handers its adoption. This is often caused by safety concerns and lack of awareness. A good example of this is the Barend Recht project in Netherlands. These problems are a direct relation to why communication strategies fail capturing the attention from stakeholders. Local trust and participation, social license to operate, and open communication are primary for endorsement as well as building confidence for social acceptance. Their focus should shift on MOFs: Metal organic frameworks with high CO_2 selectivity and efficiency. Safety studies post long term storage also seem to be critical alongside techno-economic assessments on sectors that are hard to decarbonize like cement or steel CCS integration. In terms of climate mitigation a large scale deployment of CCS could be enhanced using policy tools such as carbon credits, subsidies or creating emission trading systems.

References

[1] Al Hajri, N. H., Al Harthi, R. N., Pasam, G. K., & Natarajan, R. (2024). IoT and machine learning based green energy generation using hybrid renewable energy sources of solar, wind and hydrogen fuel cells. In *E3S Web of Conferences* (Vol. 472, p. 01008). EDP Sciences. https://doi.org/10.1051/e3sconf/202447201008.

[2] Zümrütdal, E., Zarifi, F., Yiğittekin, E. S., İstifli, E. S., Mertoğlu, T. Ş., Türüt, N., ... & Kılınççeker, G. (2022). Effect of Activated Carbon in Yogurt Production. *Natural and Engineering Sciences, 7*(1), 1-21. https://doi.org/10.28978/nesciences.1098648.

[3] Arehart, J. H., Hart, J., Pomponi, F., & D'Amico, B. (2021). Carbon sequestration and storage in the built environment. *Sustainable Production and Consumption, 27,* 1047-1063. https://doi.org/10.1016/j.spc.2021.02.028.

[4] Anita Lakshmi, N., Rekha, S., & Surendar. (2015). Multi Port DC-DC Converter for Standalone PV System. *International Journal of Advances in Engineering and Emerging Technology, 6*(4), 196–206.

[5] Hasse, C., Debiagi, P., Wen, X., Hildebrandt, K., Vascellari, M., & Faravelli, T. (2021). Advanced modeling approaches for CFD simulations of coal combustion and gasification. *Progress in Energy and Combustion Science*, *86*, 100938. https://doi.org/10.1016/j.pecs.2021.100938.

[6] Saidova, K., Abdullayeva, S., Yakubova, D., Gudalov, M., Abdurahmonova, K., Khudoykulova, H., Mukhammadova, G., & Zokirov, K. (2024). Assessing the Economic Benefits of Climate Change Mitigation and Adoption Strategies for Aquatic Ecosystem. *International Journal of Aquatic Research and Environmental Studies, 4*(S1), 20-26. https://doi.org/10.70102/IJARES/V4S1/4.

[7] Uvarajan, K. P. (2024). Advanced modulation schemes for enhancing data throughput in 5G RF communication networks. SCCTS Journal of Embedded Systems Design and Applications, 1(1), 7-12. https://doi.org/10.31838/ESA/01.01.02.

[8] Christian, J., Paul, M., & Alexander, F. (2025). Smart traffic management using IoT and wireless sensor networks: A case study approach. Journal of Wireless Sensor Networks and IoT, 2(2), 45-57.

[9] Osman, A. I., Deka, T. J., Baruah, D. C., & Rooney, D. W. (2020). Critical challenges in biohydrogen production processes from the organic feedstocks. *Biomass Conversion and Biorefinery,* 1-19. https://doi.org/10.1007/s13399-020-00965-x.

[10] Shimazu, S. (2024). Intelligent, Sustainable Supply Chain Management: A Configurational Strategy to Improve Ecological Sustainability through Digitization. *Global Perspectives in Management, 2*(3), 44-53.

[11] Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M., & Rooney, D. W. (2021). Recent advances in carbon capture storage and utilisation technologies: a review. *Environmental Chemistry Letters, 19*(2), 797-849. https://doi.org/10.1007/s10311-020-01133-3.

[12] Habib, M. A., & Khan, R. (2021). Environmental impacts of coal-mining and coal-fired power-plant activities in a developing country with global context. *Spatial modeling and assessment of environmental contaminants: risk assessment and remediation,* 421-493. https://doi.org/10.1007/978-3-030-63422-3_24.

[13] Wei, Y. M., Kang, J. N., Liu, L. C., Li, Q., Wang, P. T., Hou, J. J., ... & Yu, B. (2021). A proposed global layout of carbon capture and storage in line with a 2 C climate target. *Nature Climate Change, 11*(2), 112-118. https://doi.org/10.1038/s41558-020-00960-0.

[14] Shu, D. Y., Deutz, S., Winter, B. A., Baumgärtner, N., Leenders, L., & Bardow, A. (2023). The role of carbon capture and storage to achieve net-zero energy systems: Trade-offs between economics and the environment. *Renewable and Sustainable Energy Reviews*, *178*, 113246. https://doi.org/10.1016/j.rser.2023.113246.

[15] Kanwal, F., & Torriero, A. A. (2022). Biohydrogen—A green fuel for sustainable energy solutions. *Energies*, *15*(20), 7783. https://doi.org/10.3390/en15207783.

[16] Osman, A.I., Hefny, M., Abdel Maksoud, M.I.A. et al. *Recent advances in carbon capture storage and utilisation technologies: a review*. Environmental Chemistry Letters, 19, 797–849 (2021). https://doi.org/10.1007/s10311-020-01133-3.

[17] Haszeldine, R.S., Flude, S., Johnson, G., & Scott, V. (2018). *Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments*. *Philosophical Transactions of the Royal Society A*, 376: 20160447. https://doi.org/10.1098/rsta.2016.0447.

[18] Madhanraj. (2025).AI-Powered Energy Forecasting Models for Smart Grid-Integrated Solar and Wind Systems.National Journal of Renewable Energy Systems and Innovation, 1-7.