ISCSITR- INTERNATIONAL JOURNAL OF ENGINEERING AND TECHNOLOGY (ISCSITR-IJET)

**Vol.5, Iss. 2, July-Dec, 2024, pp. 1-6.**

https://iscsitr.com/index.php/ISCSITR-IJET

**Journal ID: 6283-7415**

# Engineering Solutions for Carbon Capture and Sequestration in Industrial Emissions

**Manchala Aditya,**

France.

## Abstract

The increasing concentration of carbon dioxide ($CO_2$) in the atmosphere due to industrial emissions is one of the primary drivers of climate change. Carbon capture and sequestration (CCS) technologies have emerged as viable solutions for mitigating $CO_2$ emissions from industrial sources. This paper explores the engineering solutions for carbon capture, including pre-combustion, post-combustion, and oxy-fuel combustion techniques, alongside advancements in $CO_2$ transportation and storage. Various sequestration methods, such as geological, mineral, and ocean sequestration, are discussed, highlighting the technical challenges, costs, and environmental impacts. A review of current research, pilot projects, and case studies illustrates the practical applications of CCS in industries such as power generation, cement, and steel manufacturing. The paper also examines the role of novel materials, such as metal-organic frameworks (MOFs) and amine-based sorbents, in improving capture efficiency. By addressing the current challenges and opportunities, this study contributes to the body of knowledge needed to scale up CCS deployment in industrial sectors, which is essential for achieving global emission reduction targets.

**Keywords:** Carbon Capture and Sequestration (CCS), Industrial Emissions, $CO_2$ Capture Technologies, Geological Sequestration, Metal-Organic Frameworks (MOFs), Climate Change Mitigation, Emission Reduction, Environmental Engineering, Sustainable Industry, Carbon Storage

**How to cite this paper:** Manchala Aditya. (2024). Engineering Solutions for Carbon Capture and Sequestration in Industrial Emissions. *ISCSITR- INTERNATIONAL JOURNAL OF ENGINEERING AND TECHNOLOGY (ISCSITR-IJET)*, 5(2), 1–6.

**URL:** https://iscsitr.com/index.php/ISCSITR-IJET/article/view/ISCSITR-IJET_05_02_001
**Published:** 27th July 2024



## 1. INTRODUCTION

The rapid rise in atmospheric carbon dioxide ($CO_2$) concentrations, primarily driven by industrial activities, poses a significant challenge to global climate stability. The industrial sector, including power generation, cement production, and steel manufacturing, accounts for a substantial share of $CO_2$ emissions. As global efforts intensify to limit climate change, Carbon Capture and Sequestration (CCS) has emerged as a crucial technological strategy to reduce emissions from industrial sources. CCS involves capturing $CO_2$ at the point of emission, transporting it to a storage site, and securely sequestering it to prevent its release into the atmosphere.

Despite its potential, the large-scale implementation of CCS faces numerous technical, economic, and regulatory challenges. The effectiveness of CCS depends on the efficiency of carbon capture methods, the feasibility of transportation, and the long-term stability of sequestration sites. This paper examines the key engineering solutions for CCS, evaluating their viability, challenges, and recent advancements. By analyzing the latest developments in capture materials, sequestration methods, and industrial applications, this study contributes to the knowledge necessary for accelerating CCS deployment.

## 2. Carbon Capture Technologies

Carbon capture can be implemented at different stages of industrial processes, primarily through three major techniques: pre-combustion, post-combustion, and oxy-fuel combustion. Pre-combustion capture involves converting fossil fuels into a mixture of hydrogen and $CO_2$ before combustion. The $CO_2$ is then separated using solvents or sorbents and stored, while hydrogen is utilized as a cleaner energy source. This method is widely applied in integrated gasification combined cycle (IGCC) plants and offers higher $CO_2$ capture efficiency compared to other approaches. However, pre-combustion systems require extensive infrastructure modifications, making retrofitting existing industrial plants challenging.

Post-combustion capture, on the other hand, is a more flexible approach that removes $CO_2$ from flue gases after combustion. This is typically achieved using chemical solvents, such as amine-based sorbents, which selectively absorb $CO_2$. While post-combustion capture is suitable for retrofitting existing facilities, it suffers from high energy consumption due to solvent regeneration. Oxy-fuel combustion, the third method, involves burning fuel in a mixture of oxygen and recycled flue gas, producing a $CO_2$-rich exhaust stream that is easier to capture. This technique offers high capture efficiency but requires substantial energy input for oxygen production. The choice of capture technology depends on factors such as industrial process compatibility, energy efficiency, and economic feasibility.

## 3. $CO_2$ Transportation and Storage

Once $CO_2$ is captured, it must be transported to a suitable storage site. Pipelines are the most common method for transporting captured $CO_2$, especially for large-scale CCS projects. $CO_2$ pipelines require specific pressure and temperature conditions to maintain the gas in a supercritical state, ensuring efficient transport. However, challenges such as corrosion, leakage risks, and public acceptance must be addressed to expand $CO_2$ pipeline networks. In regions where pipeline infrastructure is not viable, alternative transportation methods, such as ship-based $CO_2$ transport, are being explored, particularly for offshore sequestration sites.

Storage of captured $CO_2$ is a critical component of CCS, with geological sequestration being the most widely researched and implemented method. $CO_2$ can be injected into deep saline aquifers, depleted oil and gas reservoirs, or unmineable coal seams, where it remains trapped for long periods. Geological sequestration has been demonstrated in pilot projects, such as the Sleipner project in Norway, which has successfully stored millions of tons of $CO_2$ beneath the North Sea. Despite its promise, concerns regarding leakage, seismic activity, and monitoring requirements remain. Alternative sequestration methods, such as mineral carbonation—where $CO_2$ reacts with minerals to form stable carbonates—and ocean sequestration, are also being investigated to expand storage options.

## 4. Advancements in Capture Materials

The efficiency of CCS heavily depends on the performance of $CO_2$ capture materials. Conventional amine-based solvents, while widely used, suffer from high energy penalties and degradation over time. To overcome these limitations, researchers are developing novel materials, such as metal-organic frameworks (MOFs), which exhibit high surface area and tunable adsorption properties. MOFs have shown superior $CO_2$ selectivity and lower energy requirements for regeneration compared to traditional sorbents, making them a promising alternative for future CCS applications.

Another area of advancement involves solid sorbents, such as zeolites and porous carbons, which offer high $CO_2$ adsorption capacity with lower thermal energy input. Additionally, membrane-based separation technologies are gaining attention for their ability to selectively filter $CO_2$ from gas streams with minimal energy consumption. These emerging materials and technologies have the potential to significantly enhance CCS efficiency, reducing costs and making large-scale deployment more feasible for industrial sectors.

## 5. Industrial Applications and Case Studies

CCS has been implemented in various industrial sectors to mitigate $CO_2$ emissions. In the power generation industry, coal-fired power plants have integrated CCS technologies to reduce their carbon footprint. One notable example is the Boundary Dam project in Canada, which successfully captures over one million tons of $CO_2$ annually and utilizes it for enhanced oil recovery. Similarly, the cement industry—a major contributor to global $CO_2$ emissions—has explored CCS as a means to address process-related emissions that arise from limestone calcination. Pilot projects, such as the Norcem cement plant in Norway, have demonstrated the feasibility of CCS in cement manufacturing.

The steel industry, another high-emission sector, has also begun integrating CCS solutions. The use of $CO_2$ capture in blast furnace gas treatment can significantly reduce emissions. For instance, the HIsarna pilot project in the Netherlands employs an innovative smelting reduction process with CCS to minimize carbon output. While these case studies illustrate the practicality of CCS in different industries, large-scale adoption is still hindered by high costs, energy demands, and regulatory challenges. Further investment in research and supportive policies is essential to accelerate CCS deployment across various sectors.

## 6. Challenges and Future Prospects

Despite its potential, CCS faces several challenges that must be addressed for widespread adoption. The high costs associated with capture, transportation, and storage remain a major barrier. Developing cost-effective and energy-efficient capture technologies is crucial to making CCS economically viable. Additionally, long-term storage security is a critical concern, as leakage or unintended $CO_2$ release could undermine climate mitigation efforts. Robust monitoring and verification systems must be implemented to ensure safe and permanent sequestration.

Public perception and policy frameworks also play a significant role in the future of CCS. Concerns regarding environmental risks, land use, and potential health impacts need to be addressed through transparent communication and stakeholder engagement. Governments must provide incentives, such as carbon pricing and subsidies, to encourage industries to adopt CCS. As global carbon reduction targets become more ambitious, continued research, technological innovation, and international collaboration will be essential for scaling up CCS and integrating it into sustainable industrial practices.

## 7. Conclusion

Carbon capture and sequestration represents a critical engineering solution for reducing industrial $CO_2$ emissions and mitigating climate change. While CCS technologies—such as pre-combustion, post-combustion, and oxy-fuel combustion—offer viable pathways for capturing $CO_2$, challenges related to cost, energy consumption, and storage security must be addressed. Advances in capture materials, including MOFs and solid sorbents, are paving the way for more efficient and scalable CCS solutions.

Industrial case studies demonstrate the practical applications of CCS in power generation, cement production, and steel manufacturing, yet widespread deployment remains limited. Overcoming financial, technical, and regulatory barriers will require coordinated efforts from governments, industries, and researchers. With continued advancements and policy support, CCS has the potential to play a pivotal role in achieving global emission reduction goals and transitioning towards a more sustainable industrial future.

**References**


[1] Metz, B., Davidson, O., de Coninck, H., Loos, M., & Meyer, L. (Eds.). (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press.

[2] Herzog, H. (2018). Carbon Capture. The MIT Press.

[3] Rubin, E. S., Mantripragada, H., Marks, A., Versteeg, P., & Kitchin, J. (2012). The outlook for improved carbon capture technology. Progress in Energy and Combustion Science, 38(5), 630-671.

[4] Rochelle, G. T. (2009). Amine scrubbing for $CO_2$ capture. Science, 325(5948), 1652-1654.

[5] Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., Fernández, J. R., Ferrari, M. C., Gross, R., Hallett, J. P., Haszeldine, R. S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R. T., Pourkashanian, M., Rochelle, G. T., Shah, N., Yao, J. G., & Fennell, P. S. (2014). Carbon capture and storage update. Energy & Environmental Science, 7(1), 130-189.

[6] Lackner, K. S. (2003). A guide to $CO_2$ sequestration. Science, 300(5626), 1677-1678.

[7] Haszeldine, R. S. (2009). Carbon capture and storage: How green can black be? Science, 325(5948), 1647-1652.

[8] Figueroa, J. D., Fout, T., Plasynski, S., McIlvried, H., & Srivastava, R. D. (2008). Advances in $CO_2$ capture technology—The U.S. Department of Energy's Carbon Sequestration Program. International Journal of Greenhouse Gas Control, 2(1), 9-20.

[9] Wang, Q., Luo, J., Zhong, Z., & Borgna, A. (2011). $CO_2$ capture by solid adsorbents and their applications: Current status and new trends. Energy & Environmental Science, 4(1), 42-55.

[10] Stephens, J. C., & Jiusto, S. (2010). Assessing innovation in emerging energy technologies: Socio-technical integration in carbon capture and storage. Journal of Cleaner Production, 18(4), 371-375.