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# Carbon Capture, Utilization, and Storage Technologies for Net-Zero Industrial Emission Pathways

Arjun Sen[1*] Hiba Rashid[2*] Nikhil Joshi[3*]

[1]Department of Industrial Engineering, Central University of Karnataka, Kalaburagi, India
[2]Department of Computer Science, Islamic University of Science and Technology, Awantipura, India
[3]Department of Mechanical Engineering, Rajasthan Technical University, Ahmedabad, India
email: arjun.Sen@cukr.ac.in, hiba.r@iust.ac.in, nikhil.j@rti.ac.in

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**Abstract:** Achieving net-zero emissions requires deep decarbonization of industrial sectors such as cement, steel, chemicals, refining, and power generation, where process emissions and high-temperature energy demands are difficult to eliminate through electrification alone. Carbon capture, utilization, and storage (CCUS) technologies have emerged as a critical pathway for reducing industrial carbon dioxide emissions while enabling transitional and long-term climate strategies. This paper investigates CCUS technologies for net-zero industrial emission pathways. It examines capture methods including post-combustion, pre-combustion, oxy-fuel combustion, adsorption, membranes, and direct air capture. It further analyzes carbon utilization routes such as synthetic fuels, chemicals, mineralization, enhanced materials, and biological conversion, alongside geological storage in depleted reservoirs, saline aquifers, and basalt formations. Particular attention is given to techno-economic feasibility, lifecycle emissions, infrastructure requirements, policy incentives, and integration with hydrogen and renewable energy systems. Benefits include mitigation of hard-to-abate emissions, preservation of industrial competitiveness, and support for circular carbon economies. Major barriers include high capital cost, energy penalties, transport network limitations, storage verification, public acceptance, and regulatory uncertainty. A future roadmap is proposed involving low-cost solvents, modular capture systems, carbon hubs, digital monitoring, and market mechanisms rewarding negative or avoided emissions. The paper concludes that CCUS is not a standalone substitute for broader decarbonization, but an essential complement for sectors where direct elimination of carbon emissions remains technologically or economically constrained.

**Keywords:** Carbon Capture, CCUS, Net-Zero Emissions, Industrial Decarbonization, Carbon Storage

## 1. Introduction

Climate change mitigation requires rapid reduction of greenhouse gas emissions across energy, transport, agriculture, and industry. While renewable electricity and energy efficiency can decarbonize many sectors, heavy industries face more difficult challenges. Cement releases carbon dioxide through limestone calcination. Steelmaking often depends on carbon-intensive reducing agents. Chemical production and refining involve complex thermal and process emissions. In such sectors, complete elimination of emissions through conventional measures alone is difficult in the near term [1]. Carbon capture, utilization, and storage has therefore gained strategic importance. CCUS refers to technologies that capture carbon dioxide from industrial streams or the atmosphere, then either use it in valuable products or store it permanently underground. It is particularly relevant for hard-to-abate sectors where process emissions cannot be fully avoided [2]. Interest in CCUS has expanded because many national net-zero strategies now recognize that some residual emissions will remain even after aggressive efficiency and renewable deployment. This paper examines how CCUS technologies can support industrial emission pathways consistent with long-term climate goals.

## 2. Sources of Industrial Carbon Emissions

Industrial emissions arise from both fuel combustion and chemical processes. Combustion emissions result from burning coal, gas, oil, or other fuels to generate heat and power. Process emissions occur when chemical transformations inherently release carbon dioxide. In cement production, calcination of limestone produces $CO_2$ regardless of fuel source. In steelmaking, blast furnaces use coke to remove oxygen from iron ore. Ammonia, methanol, and hydrogen production also generate concentrated carbon streams depending on feedstocks [3]. Because these sources vary in concentration, pressure, and contamination level, capture technologies must be tailored to specific industrial contexts.

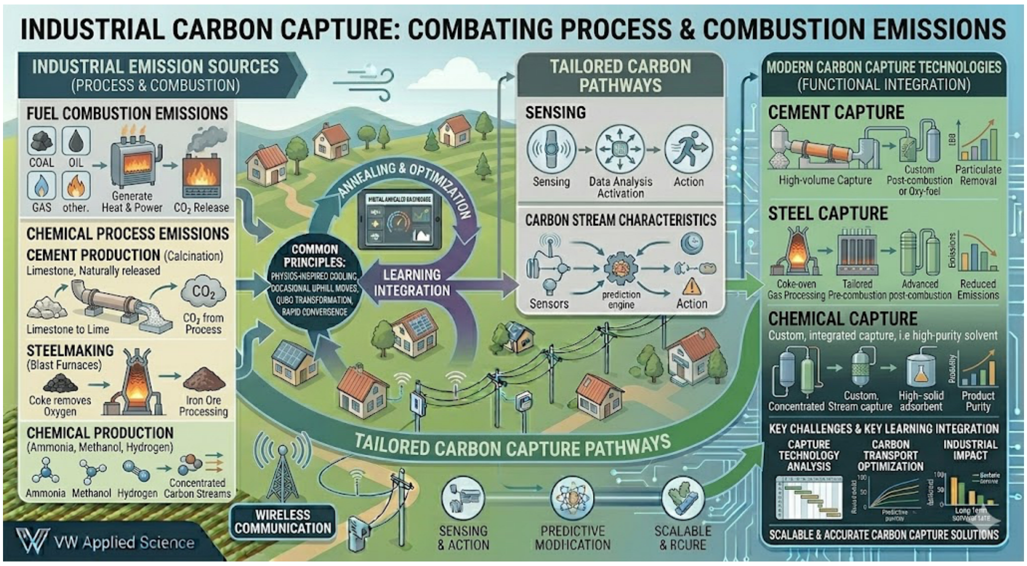

Fig 1

## 3. Post-Combustion Carbon Capture

Post-combustion capture removes $CO_2$ from flue gases after fuel combustion. It is attractive because it can often be retrofitted to existing plants. The most established approach uses chemical solvents such as amines that selectively absorb carbon dioxide and release it during regeneration. This method has been demonstrated in power and industrial facilities, but solvent regeneration requires significant energy, reducing overall efficiency. Corrosion, solvent degradation, and water demand also affect economics [4]. Research focuses on improved solvents, process intensification, heat integration, and modular systems that reduce operational penalties.

## 4. Pre-Combustion and Oxy-Fuel Capture

Pre-combustion capture converts fuels into synthesis gas containing hydrogen and carbon monoxide, then shifts carbon monoxide into $CO_2$ for separation. Because the resulting $CO_2$ stream is often concentrated and pressurized, separation can be efficient. This route is relevant in gasification and hydrogen production systems. Oxy-fuel combustion burns fuel in oxygen rather than air, producing exhaust rich in $CO_2$ and water vapor. After condensation, a concentrated $CO_2$ stream remains. However, oxygen production itself consumes energy and adds cost [5]. These methods may be advantageous in new-build facilities designed around integrated capture systems.

## 5. Adsorption and Membrane Separation

Solid adsorbents such as zeolites, activated carbon, and metal-organic frameworks can selectively bind carbon dioxide. Pressure swing or temperature swing cycles then regenerate the material. Adsorption systems may reduce solvent-related issues and enable compact designs. Membrane systems separate gases based on permeability differences. They are modular, scalable, and potentially lower maintenance. Advanced membranes are being developed for high selectivity and durability under industrial conditions [6]. Both approaches are promising, especially where space constraints or flexible operation are important.

## 6. Direct Air Capture

Direct air capture removes $CO_2$ directly from ambient air rather than concentrated industrial streams. Because atmospheric concentration is low, energy demand is high. However, this approach can address distributed emissions and generate negative emissions when paired with permanent storage. Direct air capture may become increasingly valuable for balancing residual emissions from aviation, agriculture, or legacy infrastructure. It also decouples capture location from emission source, allowing siting near storage resources or renewable energy availability [7]. Current costs remain high, but innovation and scale may improve competitiveness over time.

## 7. Carbon Utilization Pathways

Captured carbon dioxide can be used rather than discarded. Utilization pathways include production of synthetic fuels, methanol, urea, polymers, aggregates, carbonates, and specialty chemicals. Mineralization converts $CO_2$ into stable solids through reaction with alkaline materials. Some uses provide temporary storage, while others create long-term sequestration in construction products. The climate value of utilization depends on lifecycle assessment, energy source, and displacement of conventional products [8]. Utilization is most effective when markets are genuine, scalable, and supported by low-carbon energy inputs.

## 8. Geological Carbon Storage

Permanent storage is central to large-scale decarbonization because product markets alone cannot absorb all captured $CO_2$ . Geological storage injects compressed carbon dioxide into deep underground formations such as saline aquifers, depleted oil and gas reservoirs, or reactive basalt formations.

At suitable depths, $CO_2$ remains trapped through structural, residual, solubility, and mineral mechanisms. Monitoring technologies such as seismic surveys, pressure sensing, and well integrity testing help verify containment [9]. Decades of experience in subsurface engineering provide a strong foundation, though site-specific assessment is essential.

## 9. CCUS in Cement, Steel, and Chemicals

Cement is one of the highest-priority sectors for CCUS because process emissions are unavoidable in clinker production. Capture units can be integrated into kiln systems to significantly reduce emissions intensity. Steel decarbonization may involve hydrogen-based routes, scrap recycling, and CCUS for blast furnaces or direct reduced iron processes during transition periods. Chemical sectors can often provide relatively pure $CO_2$ streams, improving capture economics. Cluster approaches where multiple industries share transport and storage infrastructure may reduce cost and accelerate deployment [10].

## 10. Energy Penalty and Economic Considerations

A major challenge of CCUS is the additional energy required for capture, compression, transport, and storage. If powered by high-carbon energy, climate benefits are reduced. Therefore, integration with renewable electricity, waste heat recovery, or low-carbon fuels is important. Capital costs include capture units, pipelines, compressors, monitoring systems, and injection wells. Economic viability often depends on carbon pricing, tax incentives, contracts for difference, or premium markets for low-carbon products [11]. As technologies mature and infrastructure scales, costs are expected to decline.

## 11. Infrastructure and Carbon Hubs

Large-scale CCUS requires transport and storage networks. Pipelines are often the most efficient option for continuous large volumes, while ships may serve coastal or international routes. Carbon hubs aggregate emissions from multiple facilities and connect them to shared storage sites. This reduces duplication and enables smaller emitters to participate. Industrial clusters with ports, refineries, cement plants, and chemical complexes are ideal candidates. Coordinated planning is essential because capture facilities cannot scale without confidence in downstream transport and storage availability.

## 12. Policy, Regulation, and Public Acceptance

Government policy strongly influences CCUS deployment. Clear rules are needed for permitting, liability, storage rights, monitoring standards, and cross-border transport. Long investment horizons require stable policy signals. Public acceptance depends on trust, safety assurance, and transparent communication. Communities may support projects when local jobs, environmental safeguards, and long-term benefits are clearly demonstrated [12].

CCUS should be framed as part of a broader decarbonization portfolio rather than an excuse to delay clean energy transition.

## 13. Future Directions

Next-generation CCUS will likely feature advanced solvents, low-energy sorbents, AI-optimized process control, modular capture units, and integrated carbon management platforms. Coupling with green hydrogen may enable synthetic fuels and cleaner industrial heat. Digital monitoring systems using sensors, satellites, and predictive analytics can improve verification and reduce operational risk. Carbon removal markets may expand demand for durable negative emissions. International cooperation will be important because storage resources, industrial centers, and renewable potential are unevenly distributed.

## 14. Conclusion

Carbon capture, utilization, and storage is an essential component of net-zero industrial strategies, especially for sectors where process emissions and high-temperature operations remain difficult to decarbonize fully. By capturing carbon at source, converting it into useful products, or storing it permanently underground, CCUS can significantly reduce emissions from cement, steel, chemicals, refining, and related industries. However, CCUS is not a universal solution. It must complement energy efficiency, renewable deployment, electrification, material efficiency, and circular economy approaches. With supportive policy, robust infrastructure, continued innovation, and transparent governance, CCUS can play a decisive role in enabling credible industrial transition pathways.

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