Confederation of Indian Industry

Carbon Capture:
Technologies, Economics and Scale-Up Pathways

Enabling Decarbonisation of the Hard-to-Abate Sectors

www.cii.in

Confederation of Indian Industry

Carbon Capture:
Technologies, Economics and Scale-Up Pathways

Enabling Decarbonisation of the Hard-to-Abate Sectors

www.cii.in

Published by

Confederation of Indian Industry (CII),
The Mantosh Sondhi Centre; 23, Institutional Area, Lodi Road, New Delhi 110003, India, Tel: +91 11 45771000;
Email: info@cii.in; Web: www.cii.in

FOREWORD

As the climate crisis intensifies, businesses must urgently reduce greenhouse gas emissions and transition toward more sustainable operations. For the cement sector, this challenge is particularly critical. While the Indian cement industry has made steady progress, measures alone will not be sufficient to achieve deep decarbonisation. Addressing residual emissions will require the deployment of Carbon Capture Utilisation and Storage (CCUS) Technologies.

CII Green Business Centre (CII-GBC), under its World Class Energy Efficiency initiative for the cement sector, has been consistently publishing manuals, case study booklets, and other resources to disseminate information on the latest trends, best practices, and emerging technologies relevant to the industry.

It is my pleasure to present this publication on "Carbon Capture: Technologies, Economics and Scale-Up Pathways" The report provides a comprehensive overview of CCUS technologies pathways, global developments, infrastructure requirements, and deployment opportunities in the Indian context. It is intended to serve as a practical reference for industry leaders, policymakers, and technology providers as they navigate the transition toward low-carbon cement production.

The Indian cement industry is well-positioned to lead this transition, supported by its strong track record in efficiency improvements and technology adoption. However, scaling CCUS will require coordinated efforts across the value chain, including access to low-cost clean energy, development of CO_2 transport and storage infrastructure, supportive policy frameworks, and continued innovation.

This publication aims to support the hard-to-abate sectors in understanding the role of CCUS, evaluating deployment pathways, and enabling informed decision-making for long-term decarbonisation.

I want to express my sincere appreciation to all industry stakeholders, experts, and organisations who have contributed their insights and experiences to this publication. Let us continue to collaborate and accelerate the transition toward a net-zero cement sector.

I warmly invite you to share your feedback on this publication with us at encon@cii.in.

Ajay Kapur
Chairman, Green Cementech 2026 and
Group Chief Executive Officer
Suzlon Energy Ltd

MESSAGE

The cement sector plays a critical role in supporting India's infrastructure growth and economic development. At the same time, it faces the complex challenge of reducing carbon emissions from processes that are inherently carbon-intensive. As the industry progresses toward its sustainability goals, addressing residual emissions will be essential to achieving deep decarbonisation.

Over the years, the Indian cement industry has made commendable progress in improving operational efficiency, increasing the use of alternative fuels, and adopting best-in-class technologies. However, a significant portion of emissions—particularly those arising from clinker production—cannot be eliminated through conventional approaches alone. This underscores the need to explore advanced solutions such as Carbon Capture, Utilisation and Storage (CCUS).

This publication on "Carbon Capture: Technologies, Economics and Scale-Up Pathways" provides a comprehensive perspective on available technologies, global developments, and key considerations for deployment in the Indian context.

Leading industry players have already initiated steps in this direction. UltraTech Cement, for instance, is actively exploring CCUS through pilot initiatives and evaluating pathways for integration as part of its long-term decarbonisation strategy. Such efforts are important in building early experience and accelerating wider adoption across the sector. In the near term, the focus will be on pilot and demonstration projects to validate technologies and optimise costs. Over time, scaling CCUS will require coordinated efforts across industry, government, and technology providers—particularly in developing CO_2 transport and storage infrastructure, ensuring access to affordable clean energy, and establishing supportive policy frameworks.

The insights presented in this publication will help industry stakeholders better understand the opportunities and challenges associated with CCUS and support informed decision-making as the sector moves toward long-term decarbonisation.

I would like to acknowledge the contributions of industry experts, organisations, and stakeholders who have supported the development of this publication. Continued collaboration will be key to accelerating the transition toward a low-carbon cement sector.

I encourage readers to share their feedback at encon@cii.in.

ER Raj Narayanan
Co-Chairman, Green Cementech 2026 and
Business Head and Chief Manufacturing Officer, UltraTech Cement Limited

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AF	Alternative Fuels
AMRUT	Atal Mission for Rejuvenation and Urban Transformation
BITS	Birla Institute of Technology and Science
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation, and Storage
CO_2	Carbon Dioxide
CCTS	Carbon Credit Trading Scheme
EPC	Engineering, Procurement and Construction
GHG	Greenhouse Gases
GJ	Gigajoule
GPP	Green Public Procurement
IISc	Indian Institute of Science
IIT	Indian Institute of Technology
IEAGHG	International Energy Agency Greenhouse Gas Programme
IEA	International Energy Agency
IIP	Indian Institute of Petroleum
IRENA	International Renewable Energy Agency
JV	Joint Venture
KTPA	Kilo Tonnes Per Annum
KWh	Kilowatt-hour
LEILAC	Low Emissions Intensity Lime and Cement
LCOC	Levelized Cost of Carbon
MEA	Monoethanolamine
MT	Million tonnes
MTPA	Million Tonnes Per Annum
NCCBM	National Council for Cement and Building Materials
NDC	Nationally Determined Contributions
NTPC	National Thermal Power Corporation
OPEX	Operating Expenditure
PAT	Perform, Achieve and Trade
PMAY	Pradhan Mantri Awas Yojana
PPP	Public–Private Partnership
PPC	Portland Pozzolana Cement
PSC	Portland Slag Cement
RE	Renewable Energy
SCM	Supplementary Cementitious Materials
SMR	Steam Methane Reforming
TRL	Technology Readiness Level
TSR	Thermal Substitution Rate
VSA	Vacuum Swing Adsorption
WHR	Waste Heat Recovery

ACKNOWLEDGEMENT

CII - Green Business Centre extends its sincere and special gratitude to all experts, industry stakeholders, and practitioners engaged in CCUS and industrial decarbonisation for their continuous support in this initiative by providing valuable data, insights, and technical inputs for this publication, *"Carbon Capture: Technologies, Economics and Scale-Up Pathways,"* thereby enhancing its usefulness for all stakeholders.

We extend our heartfelt thanks to all national and international technical experts, research organisations, and industry associations for generously contributing their time, inputs, and suggestions toward the development of this publication. The interactions and deliberations with industry leaders, technology providers, and sector experts made this entire exercise a truly rewarding experience for CII.

EXECUTIVE SUMMARY

Context and Decarbonisation Imperative

The Indian cement sector is a cornerstone of infrastructure development and economic growth, with production exceeding 453 million tonnes in 2025 and strong projected growth driven by urbanisation, housing, and large-scale infrastructure programmes. Despite relatively low per capita consumption (~300 kg vs global ~540 kg), demand is expected to grow steadily, reinforcing the sector's long-term expansion trajectory.

However, cement production remains inherently carbon-intensive, contributing approximately 285 $MTCO_2$ annually (~8% of India's total emissions). Emissions arise from two primary sources:

- Process emissions from limestone calcination, which are inherent to clinker production
- Energy-related emissions from the use of fossil fuels to achieve high-temperature operations and electrical energy for achieving the required fineness.

While the industry has made measurable progress through energy efficiency improvements, alternative fuels, renewable energy integration, and clinker substitution, these measures alone will not be sufficient to achieve net-zero outcomes. A significant share of emissions, particularly those linked to clinker production, will remain.

Addressing these residual emissions requires the deployment of Carbon Capture, Utilization and Storage (CCUS) Technology, which is essential for achieving India's climate commitments, including its NDCs and net-zero target by 2070.

Purpose and Scope of the Report

This report provides a comprehensive assessment of CCUS technologies as a critical decarbonisation pathway for the Indian cement sector. It covers:

- Carbon capture technologies and their maturity levels
- Plant-level requirements and integration challenges
- Economic implications, including CAPEX, OPEX, and cost of capture
- Global case studies and technology learnings
- Current status, pilots, and opportunities for CCUS deployment in India
- Policy, market, and infrastructure enablers

The analysis integrates global benchmarks with India-specific insights, drawing on research, policy frameworks, pilot projects, and industry developments.

Key Findings

- CCUS is essential for addressing residual emissions in cement, particularly those arising from clinker production.
- Post-combustion capture is currently the most deployable technology, especially for retrofit applications in existing plants.
- Process-integrated technologies, such as direct separation and calcium looping, offer long-term potential for structural cost and energy reduction.
- CCUS introduces significant additional resource requirements, fundamentally altering plant design and utility demand.
- A typical 2 MTPA cement plant may require 8–15 acres of land, 2,500–5,000 m^3/day of water, and 25–40 MW of additional power.

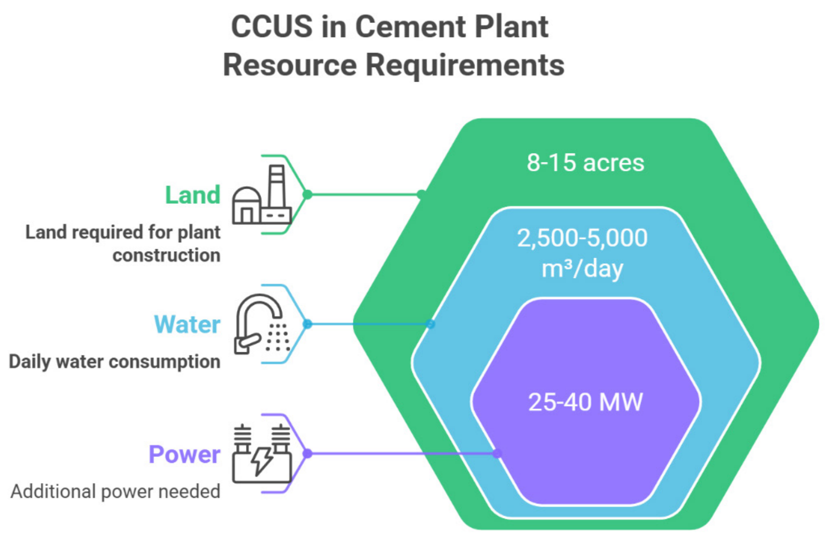

Figure 1: CCUS in Cement Plant-Resource Requirements for a 2 MTPA Plant

- CCUS economics are driven primarily by energy consumption, resulting in capture costs of ₹ 1,800–2,600 per tonne ($40 –120 per tonne). This variation arises due to differences in system boundaries (capture-only vs full CCUS value chain), energy prices and operating conditions, technology assumptions and level of maturity, plant configuration and scale.

The cost estimates presented are based on post-combustion capture using amine-based solvent systems, which currently represent the most mature and deployable technology for cement plants, particularly for retrofit applications.

- Global projects (e.g., Norcem Brevik) confirm technical feasibility but highlight the importance of full value chain integration (capture–transport–storage) and strong policy support.
- Emerging technologies (e.g., LEILAC direct separation) indicate pathways for future cost reduction through process integration.
- In India, CCUS deployment is currently at a pilot and demonstration stage, with increasing policy and industry momentum.
- The most viable pathway for India is retrofit-led deployment in the near term, followed by integration-led optimisation and scale-up.

Key Numbers at a Glance

The implications of CCUS deployment at the plant level can be summarised through the following indicative parameters:

- CO_2 captured (2 MTPA Cement plant): **1.0 – 1.3 million tonnes/year**
- Capture cost: ₹ **1,800 – 2,600 per tonne CO_2**
- Additional power requirement: **25 – 40 MW**
- Thermal energy requirement: **3 – 5 GJ/tCO_2**
- Water requirement: **2,500 – 5,000 m³/day**
- Land requirement: **8 – 15 acres**

Global and Cross-Sector Insights

Global experience demonstrates multiple pathways for CCUS deployment:

- Full-chain CCS projects (e.g., Norcem Brevik) highlight the importance of integrated infrastructure and public–private partnerships
- Process-integrated technologies (e.g., LEILAC) demonstrate potential for lower energy use and simplified systems
- Utilisation-driven approaches (e.g., NTPC Vindhyachal) provide practical entry points where storage infrastructure is limited

Carbon pricing mechanisms (EU ETS, UK ETS, and emerging Indian Carbon Market) play a critical role in enabling CCUS by creating economic incentives, although global markets remain fragmented.

India Perspective

India is currently in a pre-commercial phase of CCUS deployment, characterised by:

- Pilot projects and testbeds across leading institutions and cement companies
- Strong industry–academia–government collaboration
- Early progress in geological CO_2 storage assessment
- Increasing policy support, including ₹ 20,000 crore allocation for CCUS (Union Budget 2026–27)

However, large-scale deployment will depend on:

- development of CO_2 transport and storage infrastructure
- availability of cost-effective energy
- policy and financial support mechanisms
- industry readiness and adoption
- Eco system and demand for greener concrete/cement

The transition is expected to follow a phased pathway: Pilot → Demonstration → Cluster-based deployment → Integrated carbon management systems

In the near term, India's focus will be on scaling pilot and demonstration projects, while long-term deployment will depend on cluster-based infrastructure and policy support mechanisms.

Key Learnings from the Publication

1. CCUS deployment in cement is driven more by process constraints than by energy transition, making it structurally different from other decarbonisation pathways.
2. The economics of CCUS are dominated by energy consumption, making access to low-cost power and heat a critical enabler for deployment.
3. Retrofit feasibility is the primary determinant of near-term adoption, given the large base of existing cement plants in India.
4. Plant scale (⩾2 MTPA) significantly improves CCUS viability, enabling economies of scale in capture, compression, and integration systems.
5. Post-combustion capture is not the most efficient technology, but it is the most deployable, making it the default pathway for early adoption.

6. Process-integrated technologies have the potential to structurally reduce capture costs but require new plant configurations and longer development timelines.
7. CCUS shifts cement production from a fuel-driven to a utility-intensive system, fundamentally altering plant design and operating economics.
8. Standalone capture systems are insufficient; viability depends on the development of transport and storage ecosystems, particularly through cluster-based models.
9. Utilisation-led pathways provide a practical entry point for CCUS in India, especially in the absence of large-scale storage infrastructure.
10. Policy support and carbon markets are decisive enablers for commercialisation.
11. Indigenous R&D and innovation ecosystems are essential to reduce costs and improve efficiency.
12. Strong green products demand and carbon-market ecosystems are needed to enable large-scale adoption of lowcarbon cement.

CCUS represents a core and indispensable pathway for decarbonising the Indian cement sector. While conventional levers will continue to drive near-term reductions, achieving deep and sustained emissions reduction will depend on the timely deployment of CCUS technologies, supported by enabling infrastructure, policy frameworks, and market mechanisms.

The transition to low-carbon cement production is not a single-technology shift but a system-level transformation, requiring coordinated action across technology, energy, infrastructure, and policy ecosystems.

1

INTRODUCTION

INTRODUCTION

The Indian cement industry plays a pivotal role in supporting the country's infrastructure-led growth and economic development. India is currently the second-largest cement producer in the world, with annual production exceeding 453 million tonnes in 2025[1]. The sector comprises 159 large integrated cement plants, 6 clinkerization units, and 128 grinding units across the country.[2]

India's per capita cement consumption stands at around 300 kg, significantly lower than the global average of 540 kg.[3], indicating strong future growth potential as urbanization and infrastructure development accelerate. The industry is expected to grow at a compound annual growth rate of around 5.1% until 2030, with demand likely to rise by 7–8% annually in the near term.[4], driven by housing, transport infrastructure, industrial corridors, logistics parks, and public infrastructure programmes such as PM Gati Shakti, Bharatmala, Smart Cities Mission, AMRUT, and PMAY.

While the cement sector is central to India's growth story, it also presents a major climate challenge. Cement production is inherently carbon-intensive due to both high-temperature thermal processes and process emissions generated during clinker production. Given the expected growth in cement demand, decarbonizing the sector will be essential for achieving India's climate commitments, including its Nationally Determined Contributions (NDCs) and net-zero target by 2070.

1.1 Cement Sector Emissions: India Snapshot

On average, the Indian cement production emits approximately 0.63 tCO_2 per tonne of cement. Based on an estimated cement production of 453 MT in 2025, total sectoral emissions are approximately 285 MT of CO_2, contributing nearly 8% of India's total greenhouse gas emissions.

Cement sector emissions arise from two major sources :

- **Process emissions**, generated during the calcination of limestone in clinker production
- **Energy-related emissions**, arising from the combustion of fossil fuels and electricity use

Emission Intensity by Source (tCO_2e/ton of cement)

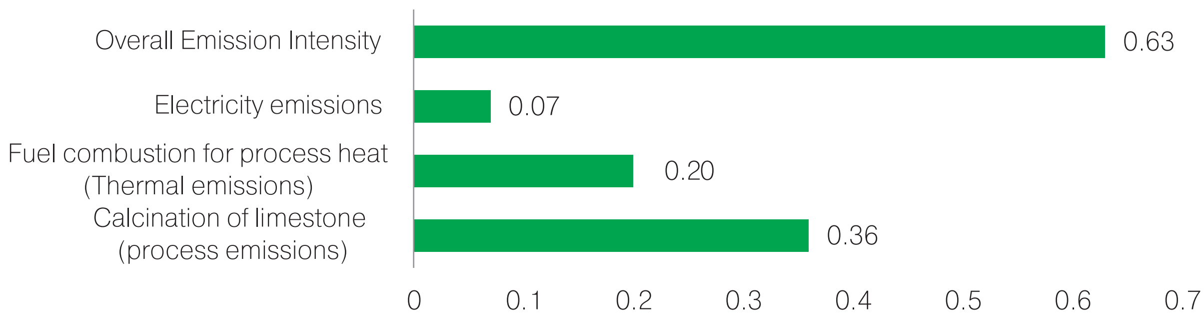

Figure 2 : Emission Intensity of Cement Manufacturing

1 Cement Industry Report Aug 2025 – IBEF
2 Annual Report 2024-25 - DPIIT
3 Annual Report 2024-25 - DPIIT
4 Cement Industry Report August 2025- IBEF

Approximately 56-60% of total CO_2 emissions in cement production are process emissions, which result from the calcination of limestone and cannot be avoided through energy efficiency improvements alone. The remaining emissions come from fuel combustion and power consumption, especially in grinding, raw material preparation, and kiln operations.

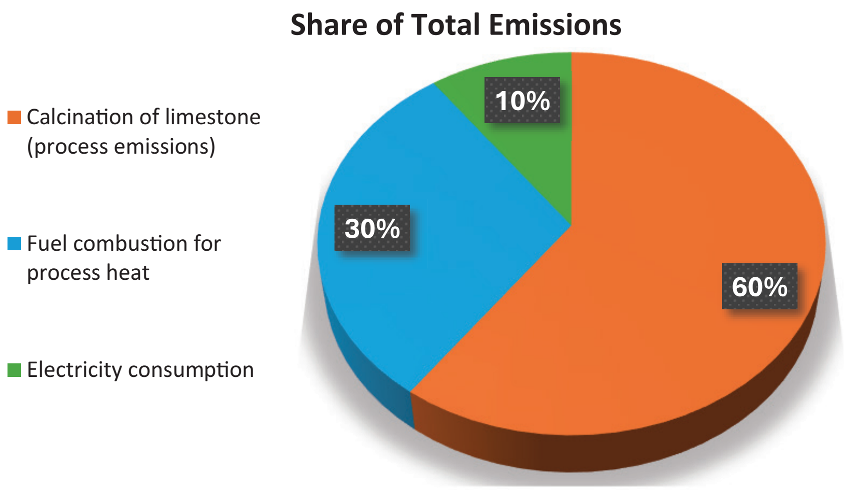

Figure 3 : Source of emissions in cement production

Cement manufacturing requires both thermal and electrical energy, with thermal energy accounting for more than 90% of total energy requirements. The Indian cement industry continues to rely heavily on coal and pet coke as major fuels for clinker production, which further contributes to emissions.

With cement production projected to reach ~660 MT by 2030, emissions under a business-as-usual scenario are expected to rise significantly, reinforcing the need for accelerated decarbonisation efforts.

1.2 Progress and Potential of Existing Decarbonization Levers (SCMs, AFR, Renewable Energy)

The Indian cement industry has made significant progress in reducing its emissions intensity through a range of measures, including energy-efficiency improvements, clinker substitution, and fuel diversification. These measures represent the first line of decarbonisation and continue to offer substantial near- to medium-term mitigation potential.

The key decarbonisation levers and their indicative impact are summarised below:

Table 1 : Emission Reduction Potential of Decarbonization Levers

Decarbonization Lever	Emission Reduction Potential (% of total emissions)	Investment Required	Support Required
Energy Efficiency	~2.5–3%	Low to Medium	• Finance: Primarily self-financed through plant-level retrofits and operational improvements • Policy: Strengthening of CCTS and PAT-type schemes
Alternative Fuels (AF)	~21–24%	Medium	• Finance: Investment support for AFR handling, pre-processing, and feeding infrastructure • Policy: Streamlined co-processing approvals and enabling waste management regulations • Government: Development of robust waste supply chains and municipal partnerships
Clinker Substitution (SCMs)	~10–21%	Low to Medium	• Finance: Largely self-financed through process modifications and blending systems • Policy: Performance-based standards, certification frameworks, and green public procurement (GPP) for increasing demand for low-carbon cement • Government: Strengthening SCM availability and supply chains (fly ash, slag, calcined clay)
Renewable Energy + Waste Heat Recovery (WHR)	~15–20%	Medium	• Finance: Access to green finance, RE incentives, and viability support mechanisms • Policy: Open access frameworks, renewable consumption obligations (RPOs) • Government: Grid integration, infrastructure support, and facilitation of WHR deployment
Green Logistics (Scope 3)	~3%	Medium	• Finance: Incentives for EV adoption, fleet transition, and modal shift investments • Policy: Frameworks for freight electrification and modal shift (rail, waterways) • Government: Development of charging infrastructure and multimodal logistics networks
Carbon Capture (CCUS)	~20–25% (long-term)	Very High	• Finance: Capital subsidies, carbon markets, and risk-sharing mechanisms • Policy: Carbon pricing, CCUS regulations, and long-term offtake frameworks • Government: Development of CO_2 transport and storage infrastructure (clusters/hubs)
Electrification Technologies	~20–30% (long-term)	Very High	• Finance: R&D funding, pilot and demonstration project support • Policy: Incentives for industrial electrification and innovation support • Government: Ensuring access to low-cost renewable power and grid readiness

The Indian cement sector has already demonstrated strong progress across these levers:

- Reduction in electrical specific energy consumption from **88 to ~73 kWh/t of cement**
- Improvement in clinkerization power consumption from **65 to ~50 kWh/t of clinker**
- Average Thermal energy consumption reduced to around **731 kcal/kg clinker**
- Increased Thermal Substitution Rate (TSR), **averaging 7%, with leading plants reaching more than 40%**
- Waste Heat Recovery (WHR) capacity has expanded significantly from **240 MW (in 2014) to 1,345 MW (in 2026)**
- Renewable energy (RE) installed capacity of **~2,000 MW (2026**) & green power procurement through open access
- Increased use of blended cements (PPC, PSC, composite cement share 73%), reducing clinker factor
- Adoption of Industry 4.0 technologies for process optimization

While these measures form the foundation of decarbonisation, they are insufficient to eliminate emissions fully. A significant share particularly process emissions will persist even with aggressive deployment of these levers. Addressing these residual emissions will require the adoption of next-generation technologies such as Carbon Capture, Utilization and Storage (CCUS), which is discussed in the following section.

1.3 Role of CCUS in Cement Decarbonization

Residual emissions from clinker production represent a fundamental challenge in cement decarbonisation. These emissions cannot be eliminated through conventional measures alone, making Carbon Capture, Utilisation and Storage (CCUS) a critical technology pathway.

CCUS enables the capture of CO_2 directly from cement plant exhaust streams, allowing emissions to be either utilised in industrial applications or stored permanently. Global decarbonisation pathways consistently identify CCUS as essential for hard-to-abate sectors such as cement.

International assessments indicate that CCUS could contribute **20–25% of the total emissions reduction** required in the cement sector by 2050, particularly for large integrated plants where clinker production remains unavoidable.

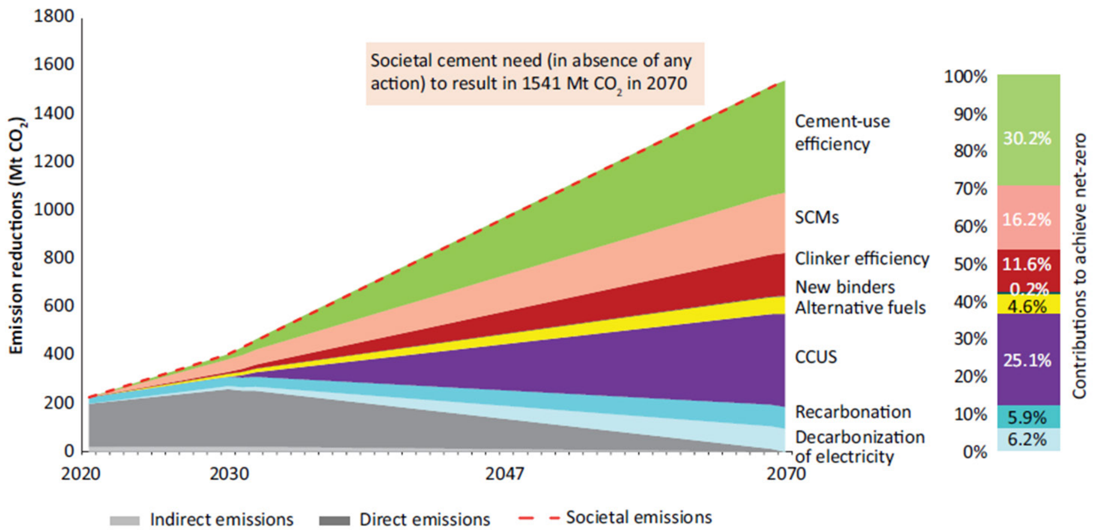

Figure 4 : GCCA Net Zero Roadmap: Net-zero CO_2 2070 pathway for the Indian cement sector[5]

5 Decarbonization Roadmap for the Indian Cement Sector | Net-Zero CO_2 by 2070- GCCA

Table 2 : Global Roadmap Estimates of CCUS Contribution in Cement Decarbonisation

S.No	Organisation / Country	Document / Roadmap	Estimated Emission Reduction Contribution of CCUS (Cement Sector)	Key Context / Notes
1	International Energy Agency (IEA)	Net Zero Roadmap (Cement & Heavy Industry Pathways)	~20–25% by 2050	Identifies CCUS as a critical lever for residual emissions in cement, especially for clinker-related process emissions
2	Global Cement and Concrete Association (GCCA)	2050 Net Zero Roadmap	~20–30% contribution	Positions CCUS as essential alongside clinker substitution and energy efficiency for achieving net-zero cement
3	IPCC	AR6 Mitigation of Climate Change Report	~15–25% (industrial cement mitigation share)	Highlights CCUS as indispensable for hard-to-abate sectors; limited alternatives for process emissions.
4	NITI Aayog (India)	CCUS Policy Framework and Roadmap	~20–25% in cement sector emissions reduction potential	Emphasises CCUS as a key pathway for decarbonising steel and cement in India; supports pilot-to-scale transition
5	European Commission (EU)	EU Industrial Carbon Management Strategy	~20–40% in cement industry decarbonisation mix	CCUS expected to dominate residual emissions reduction under the EU ETS tightening trajectory
6	US Department of Energy (DOE)	Carbon Capture Roadmaps for Industrial Sectors	~20–35% for cement and lime industries	Focus on cost reduction, tax credit (45Q), and deployment of full-chain CCS infrastructure.
7	UK Government (BEIS / DESNZ)	CCUS Deployment Pathway Strategy	~25–30% in cement decarbonisation mix	Strong emphasis on cluster-based CCS deployment (East Coast Cluster model)

While conventional levers will continue to drive near-term reductions, achieving deep decarbonisation in the cement sector will depend on the timely deployment of CCUS technologies. The following chapter explores CCUS pathways, technologies, and global deployment trends relevant to the Indian context.

2

CCUS TECHNOLOGIES

CCUS TECHNOLOGIES

Carbon Capture, Utilisation and Storage (CCUS) comprises a set of technologies that enable the capture of carbon dioxide (CO_2) from industrial sources, followed by its transport and subsequent utilisation or permanent storage. For the cement sector, CCUS provides a critical pathway to address emissions that cannot be reduced through conventional decarbonisation measures.

This chapter outlines key carbon capture technologies applicable to cement plants, their maturity levels, and a comparative assessment to support technology selection.

Overview of the CCUS Process

CCUS consists of three key steps:

- Carbon Capture – Separation of CO_2 from cement plant exhaust gases
- Transport – Movement of captured CO_2 via pipelines, road, or shipping
- Utilisation or Storage – Use of CO_2 in industrial applications or permanent geological storage

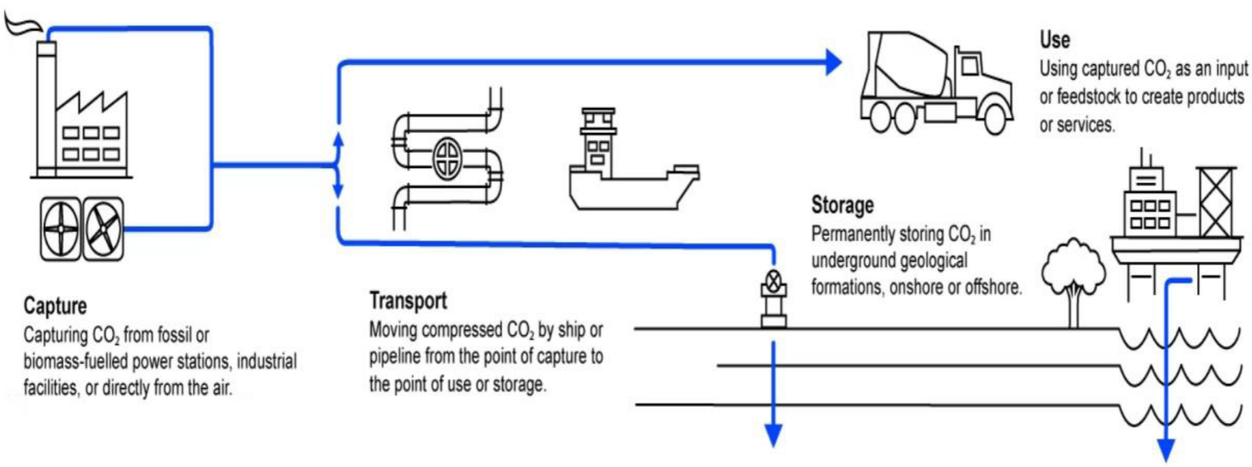

Figure 5 : Steps involved in the CCUS process

Among these, carbon capture is the most complex and cost-intensive stage, accounting for the majority of energy consumption and overall system cost. As a result, the choice of capture technology plays a central role in determining project feasibility.

2.1 Carbon Capture Technologies

A range of carbon capture technologies is being explored for application in the cement sector. These differ in terms of integration requirements, energy consumption, cost, and maturity.

Three Main Technologies for CO_2 Capture

Post Combustion	Pre Combustion	Oxy Fuel Combustion
Capture CO_2 after Fuel Combustion	Capture of CO_2 before Fuel Combustion	Capture after Fuel is burnt with near pure oxygen
Can be retrofitted to existing plants	Less used/developed than Post combustion	Early stage of development
Can be applied to all type of facilities	Can only be applied to power plants and limited facilities	Can be applied to power plants and other processes involving combustion

Figure 6 : Technologies for CO_2 Capture

Among the three capture pathways, pre-combustion technology has limited applicability in the cement sector due to the absence of a gasification-based process route. It is therefore not considered a primary pathway for deployment.

2.1.1 Post-Combustion Capture

Post-combustion capture involves separating CO_2 from flue gases after the combustion process. This is typically achieved using chemical solvents (e.g., amine-based systems).

- Can be retrofitted to existing plants
- Most mature and widely demonstrated technology
- Suitable for near-term deployment

However, it involves relatively high energy consumption, particularly for solvent regeneration.

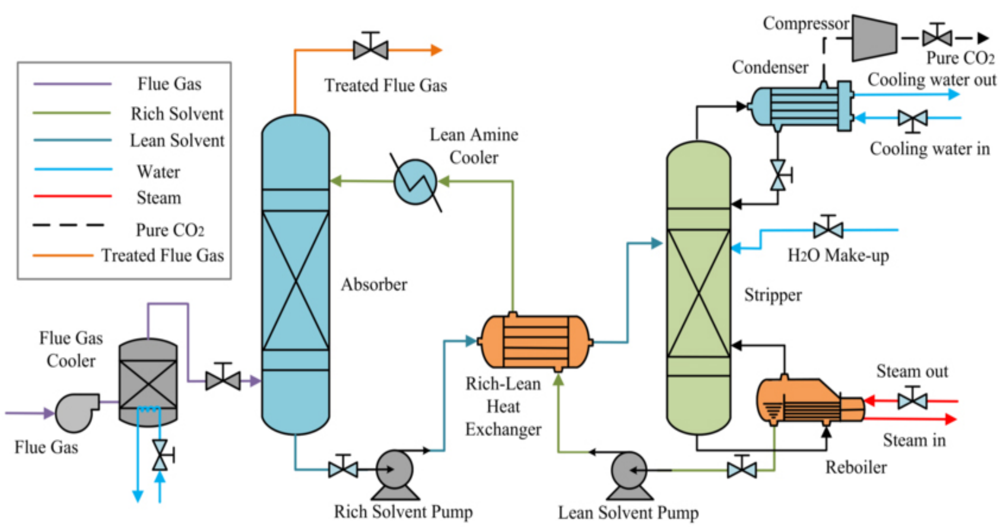

Figure 7 : A general schematic diagram of the post-combustion CO_2 capture process based on MEA.

The presence of acidic gases and trace contaminants such as SOx, NOx, HCl, VOCs, and other impurities in cement kiln flue gases can significantly impact solvent performance and operating economics in solvent-based capture systems. These contaminants may lead to solvent degradation, irreversible reaction, corrosion, and increased solvent make-up requirements. As a result, efficient flue gas pre-treatment systems become critical for maintaining solvent stability, improving capture efficiency, and reducing long-term operating costs.

2.1.2 Oxy-Fuel Combustion

In oxy-fuel systems, fuel is combusted in pure oxygen instead of air, resulting in a flue gas stream with less nitrogen and a high CO_2 concentration.

- Produces a concentrated CO_2 stream, simplifying capture
- Requires major modification to kiln and combustion systems
- Suitable for new plants or major retrofits

This technology offers strong long-term potential but requires significant capital investment.

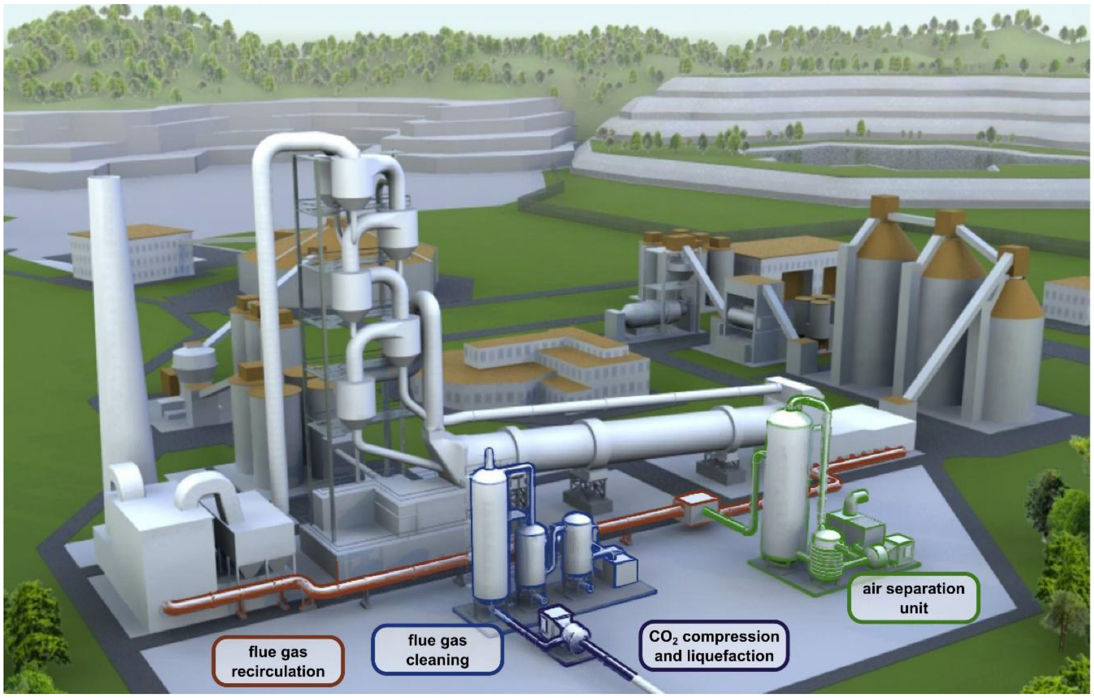

Figure 8 : A general schematic diagram of the oxy - fuel combustion CO_2 capture process

2.1.3 Direct Separation (Calciner-Based Technologies)

These technologies separate process emissions directly during clinker production, often using indirect heating or modified calcination processes.

- Specifically targets process emissions
- Lower energy penalty compared to post-combustion
- Requires new process configurations

Examples include indirect calcination and electrified calciners (e.g., LEILAC).

The purity of CO_2 obtained through direct separation or electrified calcination pathways can also be influenced by minor constituents present in raw materials and alternate fuels, including sulphur, chlorine, and phosphorus compounds in limestone. Depending on process configuration and operating conditions, these impurities may influence downstream gas purification requirements, material compatibility, and suitability for utilisation applications. Effective gas cleaning and impurity management systems will therefore be important considerations for commercial deployment of such technologies.

2.1.4 Calcium Looping (CaL)

Calcium looping uses calcium oxide as a sorbent to capture CO_2 in a cyclic process.

- High capture efficiency potential
- Can be integrated with cement process chemistry
- Still at pilot/demonstration stage

2.1.5 Emerging and Hybrid Technologies

New approaches under development include:

- Electrified kilns with integrated capture
- Membrane-based separation
- Cryogenic separation
- Hybrid systems combining multiple capture techniques

These technologies are currently at early development stages but may offer improved efficiency and lower costs in the long term.

2.2 Technology Readiness Levels (TRLs) and Commercial Status

CCUS technologies for cement are at varying stages of maturity, ranging from commercially available solutions to early-stage innovations.

- Commercial / Near commercial: Post-combustion capture
- Demonstration stage: Oxy-fuel combustion, calcium looping
- Pilot / early-stage: Direct separation technologies, electrified processes

Globally, several pilot and demonstration projects are underway, with a gradual transition towards early commercial deployment expected over the next decade.

Technology selection will depend on:

- Plant configuration
- Scale of operation
- Integration feasibility
- Cost considerations

2.3 Comparative Assessment of Key CCUS Technologies

The table below provides a comparative assessment of the most relevant CCUS technologies for the cement sector.

Table 3 : Comparison of CCUS Technologies

Technology	Efficiency	CAPEX (USD/tCO_2)	Additional Energy Requirement	Retrofit Suitability	Key Advantage	Key Challenge
Post-Combustion Capture	85–95%	\$70–120/tCO_2	High	High	Mature, deployable today	High energy + OPEX
Oxy-Fuel Combustion	90–95%	\$90–140/tCO_2	Medium-High	Low-Medium	High CO_2 purity	High CAPEX, oxygen cost
Pre-Combustion Capture	85–95%	\$100–150/tCO_2	Medium	Low	High efficiency	Not suited for cement kilns
Calcium Looping	85–95%	\$80–130/tCO_2	Medium-High	Medium	Good integration with cement	Still at the pilot stage
Direct Separation	Up to 95%	\$100–150/tCO_2	Medium	Low	Targets process emissions	Early-stage deployment

Cost ranges are indicative and may vary depending on plant configuration, scale, energy prices, and integration approach.

Key Insights

- Post-combustion capture is the most mature and suitable for near-term deployment, especially for retrofit applications
- Oxy-fuel and direct separation technologies offer strong long-term potential but require significant process modifications
- Calcium looping presents a promising pathway due to its compatibility with cement chemistry
- Technology selection will be plant-specific, depending on technical feasibility and economic considerations

2.4 Emerging Technologies and Future Outlook

Future developments in CCUS for cement are focused on CO_2 removal efficiency, reducing energy consumption, and lowering costs.

Key areas include:

- Electrification of calcination processes
- Integration of CCUS with renewable energy systems
- Development of modular and scalable capture systems
- Hybrid solutions combining capture with process redesign

For India, **post-combustion capture remains the most viable near-term solution**, particularly for retrofitting existing plants. In the long term, process-integrated technologies such as direct separation and electrified calciners may offer transformative pathways for deep decarbonisation.

2.5 Key Technology Providers for CCUS in Cement

The deployment of CCUS technologies in the cement sector is supported by a range of global technology providers offering capture systems, process integration solutions, and engineering services.

Table 4 : Key CCUS Technology Providers (Global and India)

Technology	Provider	Country	Website
Post-Combustion Capture	SLB Capturi	Norway	https://www.slb.com/capturi
	Shell CANSOLV	Canada	https://www.shell.com
	Mitsubishi Heavy Industries	Japan	https://www.mhi.com
	Carbon Clean	UK/India	https://www.carbonclean.com
Oxy-Fuel Combustion	Air Liquide	France	https://www.airliquide.com
	Linde	Germany	https://www.linde.com
Calcium Looping	Calix	Australia	https://www.calix.global
Direct Separation	Calix	Australia	https://www.calix.global
Engineering and Integration	Technip Energies	France	https://www.technipenergies.com
	Fluor	USA	https://www.fluor.com
	Larsen & Toubro	India	https://www.larsentoubro.com
Indian Technology & R&D Ecosystem	National Council for Cement and Building Materials	India	https://www.ncbindia.com
	Indian Institute of Technology Bombay		https://www.iitb.ac.in
	Indian Institute of Technology Madras		https://www.iitm.ac.in
	CSIR-Indian Institute of Petroleum		https://www.iip.res.in

The above list is indicative and includes major global and Indian stakeholders involved in CCUS technology development, deployment, and research. Technology selection depends on plant configuration, scale, and project-specific requirements.

3

PLANT-LEVEL REQUIREMENTS AND INTEGRATION

PLANT-LEVEL REQUIREMENTS AND INTEGRATION

The deployment of Carbon Capture, Utilization and Storage (CCUS) technology in cement plants requires the addition of dedicated systems for CO_2 capture, compression, and handling. These systems significantly increase the plant's resource requirements and must be carefully integrated with existing operations.

The plant-level requirements are derived from global CCUS techno-economic studies (IEA, IEAGHG, IRENA) and scaled to a 2 MTPA cement plant based on standard emission and capture assumptions.

3.1 Typical CCUS Configuration for Cement Plant

A CCUS-enabled cement plant typically includes the following components:

- **Flue Gas Collection and Conditioning:-** Collection of exhaust gases from kiln, preheater, and calciner
- **CO_2 Capture Unit:-** Separation of CO_2 using selected technology
- **Regeneration / Separation System:-** Recovery of CO_2 and recycling of solvents/sorbents
- **CO_2 Compression System:-** Compression of CO_2 to ~100–120 bar
- **CO_2 Handling and Dispatch:-** Temporary storage and transfer for transport

The capture system is the most energy-intensive component and drives the overall increase in plant utilities.

3.2 Land, Water, Energy Requirements for 2 MTPA Plant

The integration of CCUS significantly increases plant-level resource requirements. Indicative values are provided below.

Table 5 : Typical Resource Requirements for CCUS Deployment

Parameter	Typical Range	Unit	Remarks
CO_2 Captured	1.0 – 1.3	Million tonnes of CO_2/year	Based on 85–90% capture
Land Requirement	8 – 15	Acres	Capture island + utilities
Water Requirement	2,500 – 5,000	m^3/day	Cooling + solvent systems
Additional Power Requirement	25 – 40	MW	Capture + compression
Thermal Energy Requirement	3 – 5	GJ/t of CO_2	For solvent regeneration
Additional Energy Requirement	20 – 30%	Increase	Additional plant load
CO_2 Compression Pressure	100 – 120	Bar	Transport requirement

Note: The above values are indicative planning estimates for a 2 MTPA integrated cement plant and are derived from plant output, emission intensity, capture rate, and technology-specific utility factors based on global techno-economic studies. Actual values will vary depending on clinker factor, capture technology, cooling configuration, integration design, and site conditions.

1. **Average Emission intensity** for a typical cement plant = 0.60 to 0.75 MT of CO_2/t of cement
2. **Annual CO_2 emitted** = 2.0 × (0.60 to 0.75) = 1.2 to 1.5 MT of CO_2/year

3. **A capture rate of 85–90%.**

   So, CO_2 captured = annual CO_2 emitted × capture rate

   - Low case: 1.2 × 0.85 = 1.02 MT of CO_2/year
   - High case: 1.5 × 0.90 = 1.35 MT of CO_2/year

4. **Hourly CO_2 flow**

   Assuming 8,000 operating hours/year.

   Hourly CO_2 flow = annual captured CO_2 / operating hours

   = 1.0 MT/year ÷ 8,000 h = 125 t of CO_2/h

   = 1.3 MT/year ÷ 8,000 h = 162.5 t of CO_2/h

   ~125–160 t of CO_2/hour

   This is useful for checking the compressor, absorber, and piping size.

5. **Thermal energy requirement**

   For a solvent-based post-combustion system, the typical regeneration duty is around 3–5 GJ per tonne of CO_2captured.

   Thermal energy = captured CO_2 × specific thermal demand

   = 1.0 million t × 3 GJ/t = 3.0 million GJ/year

   = 1.3 million t × 5 GJ/t = 6.5 million GJ/year

   This is a technology factor, not something derived from plant output alone.

6. **Additional power requirement**

   Power is needed for flue gas fans, pumps, solvent circulation, CO_2 compression, auxiliaries, etc.

   Typical electrical load for capture + compression is often around 80–150 kWh/t of CO_2

   Then the annual electricity demand becomes:

   - Low case: 1.0 million t × 80 kWh/t = 80 GWh/year
   - High case: 1.3 million t × 150 kWh/t = 195 GWh/year

   Convert to MW using 8,000 hours/year:

   - 80 GWh ÷ 8,000 h = 10 MW
   - 195 GWh ÷ 8,000 h = 24 MW

   If we include wider plant integration loads, steam system auxiliaries, cooling, and conservative design margin, the range often used for a 2 MTPA retrofit becomes ~25–40 MW additional load.

7. **Water requirement**

   Water is mainly required for cooling, solvent makeup & regeneration systems and utility systems.

   A practical basis for estimating is 1–3 m^3 of water per tonne of CO_2 captured for a broad planning estimate, depending on the cooling configuration and technology.

   If captured CO_2 is roughly 1.0–1.3 MT of CO_2/year, and the annual water requirement will be:

   - 1.0 million × 1 = 1.0 million m^3/year
   - 1.3 million × 3 = 3.9 million m^3/year

Convert to daily:

- 1.0 million ÷ 365 = ~2,740 m^3/day
- 3.9 million ÷ 365 = ~10,685 m^3/day

That broad range is often too wide for report tables, so for a practical, conservative planning range for an efficient cement CCUS setup, ~2,500–5,000 m^3/day.

8. Land requirement

Land is estimated from the footprint of absorber & stripper columns, heat exchangers, tanks, compression trains, cooling systems, electrical and control systems, access roads and safety clearance.

For a 2 MTPA cement plant, a planning allowance of ~8–15 acres is usually a layout-based estimate derived from conceptual engineering and project analogues.

9. Energy penalty

Energy penalty is the increase in total plant energy demand due to CCUS.

Energy penalty = additional CCUS energy / original plant energy consumption.

Key Observations

- Energy requirement is the most critical parameter, driving both operational complexity and cost.
- Water demand increases significantly, particularly for solvent-based systems
- Land constraints are critical for retrofit plants
- CCUS introduces a substantial additional utility load, requiring plant-level redesign

Energy demand emerges as the primary constraint for CCUS deployment, influencing both technical feasibility and overall cost. These additional resources and integration requirements translate directly into cost implications, discussed in Chapter 4.

4

ECONOMICS OF CCUS IN CEMENT INDUSTRY

ECONOMICS OF CCUS IN CEMENT INDUSTRY

4.1 CAPEX AND OPEX Overview

The cost of CCUS in cement plant can be broadly divided into:

- **Capital Expenditure (CAPEX)**, covering the capture island, gas conditioning systems, solvent regeneration or separation systems, CO_2 compression, utilities, and plant integration
- **Operating Expenditure (OPEX)**, including energy, solvent or sorbent replacement, water, maintenance, labour, and auxiliary power consumption :

According to the NITI Aayog CCUS Policy Framework, the cost of carbon capture varies across industrial sectors depending on process conditions and CO_2 concentration levels. For the Indian cement sector, estimates from NITI Aayog indicate

- **Capital charge: ₹ 800–1,000 per tonne of CO_2 captured**
- **Operating cost: ₹ 1,050–1,600 per tonne of CO_2 captured**
- **Total cost of capture: ₹ 1,800 – 2,600 per tonne of CO_2**

Table 6 : Sector-wise Typical Carbon Capture Cost[6]

Industry name	Ref. Plant capacity	CCU capacity (mtpa)	Capital Costs, ₹ crores	Capital Charges (A), ₹/Tco2	Cash Cost (B), ₹/Tco2	Total Capture Cost (A+B), ₹/Tco2
Gasification based production	70 ktpa H_2	1 mtpa	₹ 80–100 Crore	90–120	250–300	340–420
NG based SMR for H_2 production	130 ktpa H_2	0.7 mtpa	₹ 700–800 Crore	900–1,200	1,150–1,400	2,050–2,600
Cement	2.5 mtpa clinker	2 mtpa	₹ 1,600–1,800 Crore	800–1,000	1,050–1,600	1,800–2,600
Iron and Steel	2.0 mtpa BF-BOF based ISP	2 mtpa	₹ 1,600–2,000 Crore	1,000–1,300	1,900–2,300	2,900–3,600
Refinery (CDU & FCC)	5 mtpa crude processing	1 mtpa	₹ 1,100–1,300 Crore	1,200–1,400	2,700–3,100	3,900–4,500
Coal-based power	800 MW	5 mtpa	₹ 3,500–4,000 Crore	700–1,000	2,100–2,500	2,800–3,500

This indicates that operating expenditure accounts for the larger share of the total cost of capture, mainly due to the high energy requirements associated with CO_2 separation and compression. Thermal energy for solvent regeneration and additional electrical load for fans, pumps, and compression systems are key cost drivers.

CCUS fundamentally alters the cost structure of cement production, shifting it from a fuel-driven to an energy- and capital-intensive system. At current cost levels, large-scale CCUS deployment in India will require targeted policy and financial support mechanisms.

4.2 Levelized Cost of Carbon (LCOC)

The Levelized Cost of Carbon (LCOC) represents the average cost of capturing one tonne of CO_2 over the life of the project, accounting for both capital recovery and operating expenditure.

Global benchmarks from the International Energy Agency indicate that the cost of CO_2 capture for cement and other dilute industrial streams typically ranges between USD 40 – 120 per tonne of CO_2.

6 CCUS-Report-Niti Aayog.pdf

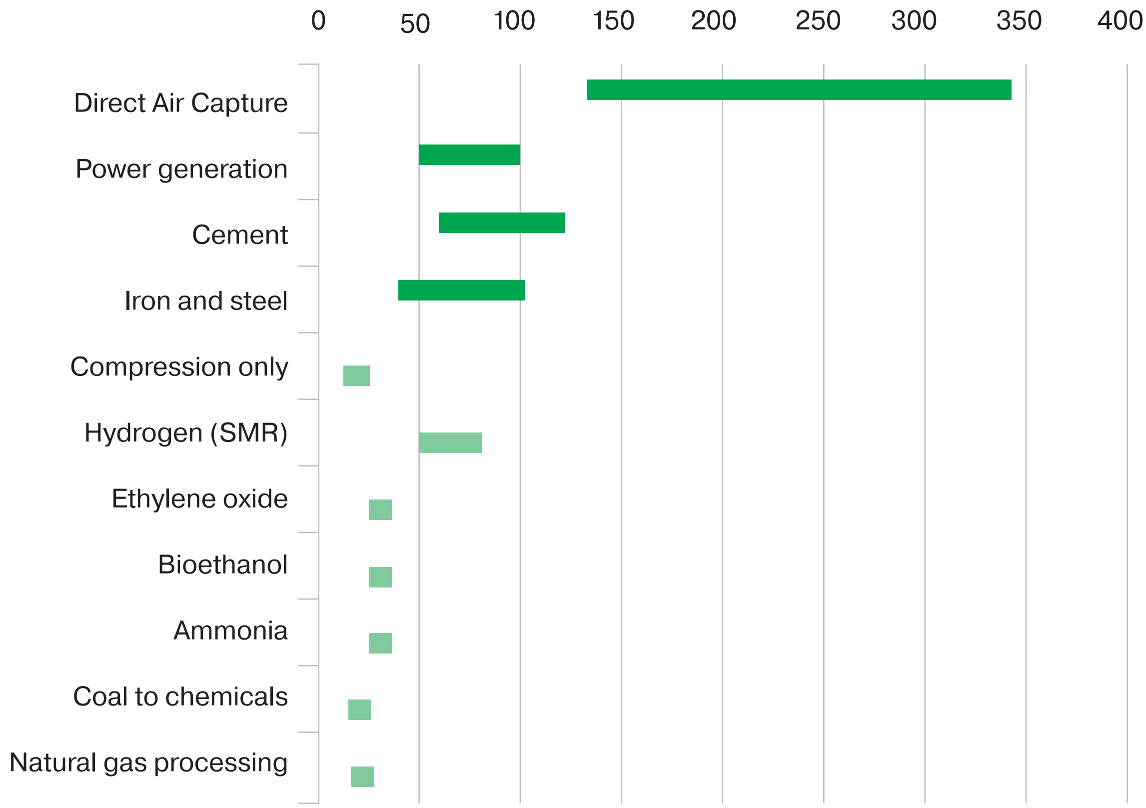

Figure 9 : Levelised cost of CO_2 capture by sector and initial CO_2 concentration, 2019[7],

However, India-specific estimates indicate a comparatively lower cost range of:

₹ 1,800 – 2,600 per tonne of CO_2

This variation arises due to differences in:

- system boundaries (capture-only vs full CCUS value chain)
- energy prices and operating conditions
- technology assumptions and level of maturity
- plant configuration and scale

Despite these differences, both global and India-specific estimates consistently indicate that CO_2 capture in the cement sector is relatively cost-intensive.

This is primarily due to the low concentration of CO_2 in cement plant flue gases, which increases the energy required for separation and compression. As a result, the LCOC for cement is higher compared to sectors with concentrated CO_2 streams, reinforcing its classification as a hard-to-abate sector**.**

4.3 Cost Comparison Across Technologies

The cost of CO_2 capture in cement varies significantly across technology pathways, depending on energy requirements, the level of process integration, and deployment maturity. While the indicative cost ranges (₹/tCO_2) provide a useful comparison, the economic attractiveness of each technology is determined by how these costs evolve over time and across plant configurations.

7 https://www.iea.org/data-and-statistics/charts/levelised-cost-of-co2-capture-by-sector-and-initial-co2-concentration-2019

Table 7 : Indicative Cost Comparison Across Technologies[8]

Technology	Typical Cost Range (₹/tCO_2)	Economic Characteristics
Post Combustion Capture	2,000 – 2,600	Most mature, lower technical risk, higher energy cost
Oxy Fuel Combustion	1,800 – 2,400	High capital requirement, potential efficiency gains from high CO_2 concentration
Calcium Looping	2,000 – 2,800	Integration advantage with the cement process is still evolving
Direct Separation	2,200 – 3,000	Targets process emissions directly, early-stage deployment

Cost competitiveness across technologies is expected to evolve as systems scale and integration improves, particularly for process-integrated solutions.

4.4 Enabling Financial and Policy Support for CCUS Deployment

The commercial deployment of CCUS in the cement sector will require targeted financial and policy support during the initial phases, given the high capital investment and energy-intensive nature of capture systems. Under current market conditions, CCUS projects are not economically viable on a standalone basis, particularly in the absence of a mature carbon pricing framework and stable demand for low-carbon cement products.

To enable early-stage deployment and reduce investment risks, a combination of support mechanisms will be required, including capital subsidies, concessional finance, carbon markets, and risk-sharing frameworks. In parallel, policy measures such as carbon pricing, CCUS-specific regulations, and long-term offtake mechanisms for low-carbon products will be critical to establish stable revenue streams. The development of shared CO_2 transport and storage infrastructure through cluster-based approaches will further support cost reduction and large-scale deployment.

At the same time, scaling CCUS will require significant investments in breakthrough technologies and innovative utilisation pathways for captured CO_2. Advancing these solutions will depend on strong collaboration between industry, academia, and research institutions to accelerate technology development, improve process efficiency, and enable viable end-use applications.

These combined efforts will be particularly important during the initial deployment phase, until carbon markets mature, carbon pricing signals strengthen, and demand for green cement products becomes established. Over time, as market mechanisms stabilise and scale is achieved, the dependence on direct financial support is expected to reduce, enabling CCUS to transition toward commercially viable deployment pathways.

4.5 Technology Cost Positioning

1. **Near-Term Deployment**

   Post-combustion capture is currently the most deployable option due to its compatibility with existing plants and lower implementation risk. It is particularly suited for early adoption and pilot-scale deployment across the existing fleet of cement plants.

2. **Medium-Term Optimization (Balanced Cost Potential)**

   Oxy-fuel combustion offers potential efficiency advantages through higher CO_2 concentration, which can reduce downstream capture requirements. However, its deployment is more suited to new plants or major upgrades due to the need for significant process modifications.

8 Cost ranges are indicative and are compiled from the International Energy Agency, NITI Aayog, IEAGHG and published literature. Actual costs vary depending on plant configuration, energy prices, technology maturity, and system boundaries.

Implications for India

For the Indian cement sector, technology selection will be shaped by a combination of cost, scalability, and implementation feasibility.

- Near-term deployment is likely to rely on technologies that can be retrofitted to existing plants, given the large installed base of operating cement capacity.
- Energy cost sensitivity will be a key factor, as capture economics are heavily dependent on power and thermal energy availability.
- Large plant sizes in India (2–3 MTPA and above) provide an advantage for achieving economies of scale in CCUS deployment.
- Over the longer term, integrated and process-based technologies may become more attractive as new plants are designed with CCUS readiness.

Transition pathway: Retrofit-led deployment in the near term → Integration-led optimization in the long term

Key Insight: In the Indian context, the most viable CCUS pathway will be determined not just by cost, but by retrofit feasibility, energy availability, and scale of deployment.

To understand how these technologies perform under real-world conditions, global case studies are examined in the following chapter.

5

GLOBAL CASE STUDIES AND TECHNOLOGY LEARNINGS

GLOBAL CASE STUDIES AND TECHNOLOGY LEARNINGS

5.1 Case Study: Norcem Brevik CCS Project (Norway)

Figure 10: Norcem cement plant at Brevik, Norway, integrated with carbon capture facilities.

Image courtesy : Heidelberg cement

The **Norcem Brevik Carbon Capture and Storage (CCS) project in Norway**[9] represents a landmark development in industrial decarbonization. Located at a cement plant in Brevik (Porsgrunn), the project is part of the national Longship CCS project Norway initiative, which aims to demonstrate a complete CCS value chain—from capture to permanent geological storage.

Operated by Heidelberg Materials (formerly HeidelbergCement)**,** Brevik is widely recognized as the **world's first full-scale CCS facility in the cement industry**, targeting one of the most difficult sectors to decarbonize.

The project captures approximately 400,000 tonnes of CO_2 annually, equivalent to nearly 50% of the plant's emissions, and integrates seamlessly with downstream transport and storage via the Northern Lights CO_2 transport and storage project in Norway.

5.1.1 Technical Configuration and Value Chain

The Brevik CCS project is notable for implementing a full-chain CCS architecture, consisting of four integrated components:

1. **Capture (Onsite – Brevik Cement Plant)**
   - Technology: Post-combustion capture using amine-based solvent systems
   - Capture rate: ~400,000 tCO_2/year
   - Source: Cement kiln flue gas (process + fuel emissions)
2. **Conditioning and Liquefaction**
   - CO_2 is purified, compressed, and liquefied at ~–25°C
   - Stored in intermediate tanks before export
3. **Transport (Shipping + Pipeline)**
   - Liquefied CO_2 is transported via dedicated CO_2 carrier ships
   - Delivered to the Øygarden terminal on Norway's west coast
   - Further transported via offshore pipeline (~100 km)
4. **Storage (Offshore – North Sea)**
   - Injection into a deep saline aquifer (~2.5–3 km below seabed)
   - Managed by Northern Lights JV (Equinor, Shell, TotalEnergies)
   - Permanent geological sequestration with monitoring systems

Table 8 : Norcem Brevik Project Timeline and Development Pathway[10]

Phase	Timeline	Key Activities
Early R & D	2005-2016	Pilot testing and feasibility studies
Concept Selection	2016-2018	Front-end engineering design (FEED)
Investment Decision	2020	Norwegian Parliament's approval of Longship
Construction	2021-2024	Capture plant integration and infrastructure build
Commissioning	2024	Mechanical completion and testing
Operations	June 2025	Commercial-scale CO_2 capture and storage

9 World premiere: CCS cement facility opens in Norway | Heidelberg Materials

10 https://www.brevikccs.com/en/
CCUS: more future with less CO_2 | Heidelberg Materials
Brevik CCS | SLB Capturi
CCS Project 'Longship' – Policies - IEA

5.1.2 Cost Structure and Financing Model

The Brevik project is embedded within the broader Longship framework:

- **Total Longship investment:** ~NOK 30–34 billion (€2.6–3.4 billion)
- **Government contribution:** ~65–80% (reflecting first-of-a-kind risk)
- **Brevik capture facility CAPEX cost:** ~€350–400 million (approx.)
- **Capture cost:** ~€80–100 per tonne CO_2 (indicative early-stage cost)

The project exemplifies a public–private partnership (PPP) model, where government support enables the commercialization of early-stage CCS technologies.

Table 9 : Norcem Brevik Project - Key Providers and Stakeholders[11]

Segment	Key Players	Role
Plant Owner	Heidelberg Materials	Cement production & capture host
Capture Technology	Aker Carbon Capture / Capturi JV	CO_2 capture system
EPC & Integration	Multiple contractors	Plant construction & integration
Transport & Storage	Northern Lights CO_2 transport and storage project, Norway	CO_2 logistics & sequestration
Storage Operators	Equinor, Shell, TotalEnergies	Offshore storage

5.1.3 Providers and Project Delivery

The carbon capture system at Brevik is delivered by SLB Capturi, a joint venture between SLB and Aker Carbon Capture. The solution is based on modular, amine-based post-combustion capture technology, designed for industrial scalability.

The provider operates under an EPC (Engineering, Procurement, and Construction) and integration model, delivering the capture facility as a turnkey system while ensuring seamless integration with existing cement plant operations. This approach reflects a broader industry shift toward standardized, end-to-end CCS solutions aimed at reducing project complexity and enabling replication across industrial sectors.

Transport and storage are managed through the Northern Lights CO_2 transport and storage project in Norway, a joint venture between Equinor, Shell, and TotalEnergies.

5.1.4 Position in the Global CCS Landscape

The Norcem Brevik project represents a first-of-a-kind deployment within the global CCS ecosystem:

- First industrial-scale CCS application in cement
- One of the first fully integrated CCS value chains globally
- Demonstrates ship-based CO_2 transport, enabling flexible infrastructure
- Serves as a model for cluster-based decarbonization systems

The project expands CCS beyond power generation into hard-to-abate industrial sectors, setting a precedent for future deployments worldwide.

5.1.5 Key Learnings and Future Outlook

Full Value Chain Integration is Critical: The Norcem Brevik project demonstrates that full-chain CCS deployment is technically and commercially viable for hard-to-abate sectors such as cement. A central insight is that integration across the entire value chain—capture, transport, and storage—is critical; isolated development of capture technology alone is insufficient without parallel infrastructure for CO_2 logistics and sequestration.

11 Northern Lights Project (https://norlights.com), TotalEnergies (https://totalenergies.com), Equinor (https://www.equinor.com)

Role of Government Support: The project highlights the importance of strong government support in enabling first-of-a-kind (FOAK) projects, where high capital costs and technological risks would otherwise limit private investment. Public funding under the Longship programme has been instrumental in de-risking deployment and establishing a foundation for future commercialization.

Standardization and Scalable Delivery Models: From a technological and delivery perspective, the use of modular capture systems and EPC-based execution models demonstrates a pathway toward standardization and scalability, which are essential for reducing costs and accelerating replication across industrial sites.

CCS as a Core Decarbonization Lever for Cement: The Brevik case also reinforces that CCS is indispensable for cement decarbonization, as a significant share of emissions arises from process chemistry rather than energy use. This positions CCS as a core mitigation pathway for achieving long-term net-zero targets in the sector.

Cost Reduction and Infrastructure Development: Looking ahead, costs are expected to decline through learning effects, standardization, and economies of scale. The development of shared infrastructure, particularly through the Northern Lights CO_2 transport and storage project, enables a hub-and-cluster model that can support multiple emitters and accelerate large-scale deployment.

Blueprint for Global Replication: Overall, the Norcem Brevik project establishes a replicable blueprint for industrial CCS deployment, demonstrating how coordinated policy support, integrated project delivery, and scalable infrastructure can enable the transition toward commercial carbon management systems.

5.2 Emerging Case Study: LEILAC PROJECT (Europe)

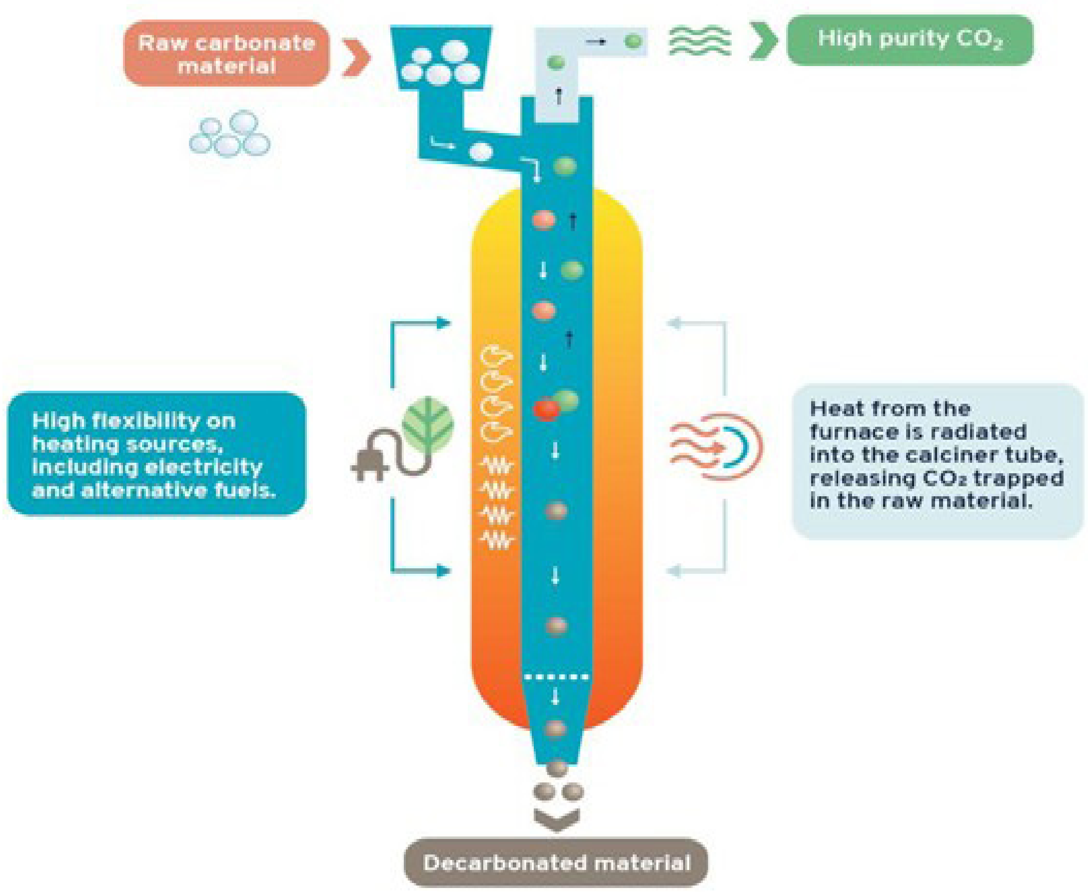

Figure 11 : LEILAC direct separation technology illustrating indirect calcination and its integration within a cement plant for process CO_2 capture

The **LEILAC (Low Emissions Intensity Lime and Cement)** project represents an innovative approach to carbon capture in the cement sector by targeting emissions directly at the source of generation—limestone calcination.

Developed under the European Union's Horizon 2020 programme, the project demonstrates a direct separation technology that fundamentally differs from conventional carbon capture approaches. Instead of capturing CO_2 from flue gas after combustion, LEILAC isolates process emissions during calcination itself, preventing dilution with combustion gases.

The project has been implemented in phases:

- **LEILAC-1 (Belgium):** Pilot-scale demonstration (~25,000 tCO_2/year)[12]
- **LEILAC-2 (Germany):** Large-scale demonstration (~100,000 tCO_2/year)[13]

The technology is designed to capture >95% purity CO_2 from calcination, which accounts for nearly 60% of total cement plant emissions.

5.2.1 Technology Concept and Configuration

At the core of the LEILAC system is a Direct Separation Reactor (DSR) based on indirect calcination.

- Limestone is heated externally within a reactor tube
- Combustion gases are kept separate from calcination gases
- CO_2 released during calcination is captured as a high-purity stream (~95%)

12 Project Leilac-1 - CO_2 Process Emissions Research | Leilac

13 Project Leilac-2 - Capturing 100,000tpa of CO_2 Emissions | Leilac

Key System Features

- No requirement for chemical solvents, absorption–desorption systems and complex gas separation units
- Simplified process chain: CO_2 can be directly cooled, compressed, and transported
- Compatibility with alternative fuels, electrified heating systems, and future low-carbon process configurations.

This represents a process-integrated capture approach, rather than an add-on system.

5.2.2 Project Development and Scale-Up

The LEILAC project has followed a structured development pathway:

Table 10 : Development and Scale-Up of LEILAC Project

Phase	Location/Plant	Operator	Key Outcome
LEILAC-1 (Belgium)	Lixhe Cement Plant	Heidelberg Materials	Validated direct separation concept at pilot scale
LEILAC-2 (Germany)	Hannover Cement Plant	Heidelberg Materials	Industrial-scale demonstration (~100,000 tCO_2/year)

LEILAC-1: Pilot Validation

The LEILAC-1 pilot plant, operational since 2019, successfully demonstrated the technical feasibility of direct separation carbon capture under real operating conditions.

Key outcomes include:

- Effective indirect calcination of limestone and raw meal
- Direct separation of process CO_2 emissions with ~95% purity
- Stable and safe reactor performance at high temperatures
- No requirement for additional chemicals or downstream processing
- No impact on clinker production or host plant operations
- Comparable energy performance to conventional cement processes
- No significant material build-up or operational degradation over time

LEILAC-2: Industrial Demonstration and Scale-Up

Building on pilot success, LEILAC-2 represents the transition toward industrial-scale deployment.

Key design features include:

- Target capture capacity of ~100,000 MT of CO_2/year at >95% purity
- Multi-tube reactor configuration (four calciner tubes in a single furnace chamber)
- Integration of a preheater string for improved heat recovery
- Full heat integration with the host cement plant
- Fuel flexibility:
  - ➢ natural gas
  - ➢ biomass
  - ➢ potential for full alternative fuel (AF) operation
- Use of standard cement plant equipment, enabling easier integration, operation, and maintenance

A critical innovation is the development of a replicable multi-tube module, which enables scaling from pilot to commercial deployment.

The involvement of Heidelberg Materials as an industrial partner highlights the relevance of LEILAC technology for future cement plant integration and scale-up. The project is being developed in collaboration with technology provider Calix and European research partners, with a focus on validating scalability, operational reliability, and integration with cement plant operations.

This modular and collaborative approach provides a strong foundation for large-scale replication across the cement sector.

5.3 Key Insights, Current Status and Future Outlook

The LEILAC project demonstrates that process-integrated carbon capture is technically feasible without disrupting cement plant operations, marking a significant departure from conventional capture approaches.

A key insight is that CO_2 can be separated at source with high purity, eliminating the need for solvent-based systems and reducing process complexity. The pilot results further indicate that such systems can operate with energy requirements comparable to conventional processes, strengthening the long-term case for cost reduction.

However, the technology is still in the demonstration phase, and several aspects remain under validation:

- long-term operational performance at scale
- integration with large commercial plants
- cost competitiveness relative to established technologies

From an implementation perspective, the requirement for process-level integration means that deployment is more suited to new plants or major upgrades, rather than simple retrofits.

Looking ahead, the modular multi-tube design offers a clear pathway for scale-up, enabling:

- replication across large cement plants
- integration with low-carbon fuels and electrification
- gradual transition toward next-generation cement production systems

Overall, LEILAC establishes a strong foundation for future low-cost, process-integrated carbon capture, but requires further scale-up and validation before widespread commercial deployment.

While Norcem Brevik demonstrates full-chain commercial feasibility, the LEILAC project represents a pathway for reducing capture cost through process integration. Several other cement companies are also evaluating carbon capture technologies through pilot and demonstration projects across Europe, North America, and Asia. These projects are helping to develop technical expertise, optimise capture technologies, and better understand the economic and operational requirements of CCUS deployment in cement plants.

Building on global experience, the next chapter assesses India's current status and opportunities for CCUS deployment.

5.4 Global CCUS Projects – Capture Capacity, Technology & Policy Drivers

Table 11 : Global CCUS Projects – Capture Capacity, Technology & Policy Drivers

Project	Sector	Company / Group	Country	CO_2 Captured ($MtCO_2$/yr)	Capture (%)	Commiss-ioned (Year)	Key Stakeholders	Funding	Capex / Technology Provider	Technology Type	Policy Driver	Applicability in India
Al Reyadah CCS	Steel	Emirates Steel / ADNOC	UAE	0.8	25–30%	2016	ADNOC, Masdar	Govt / NOC	~$1 bn; Mitsubishi Heavy Industries	Post-combustion absorption	EOR-linked	Medium
Steelanol – Ghent	Steel	ArcelorMittal	Belgium	0.125	~15%	2023	LanzaTech, Primetals, EU partners	EU + Private	€200 m; LanzaTech	Gas fermentation (CCU)	EU ETS	High
Norcem Brevik CCS	Cement	Heidelberg Materials	Norway	0.4	~50%	2025	Govt Norway, Northern Lights	~85% public	~€350–400 m (capture); Aker Carbon Capture	Post-combustion absorption	Carbon tax + CfD	Very High
Quest CCS	Hydrogen / Refining	Shell	Canada	1.0–1.1	~70%	2015	Shell, Chevron, CNRL, Govt Alberta	~65% public	~$1.35 bn; Shell (ADIP-X)	Pre-combustion (SMR) + storage	Carbon tax	High
Shute Creek (LaBarge)	Gas Processing	ExxonMobil	USA	~7	~65%	1986	ExxonMobil	Private	Proprietary	Acid gas removal	US 45Q	Medium
ACTL	Multi-sector	Enhance Energy	Canada	~1.8	—	2020	Nutrien, NWR	Govt + Private	~$1.2 bn	Transport + storage	Carbon tax	Very High
Boundary Dam Unit-3	Power	SaskPower	Canada	~0.6–0.8	~60%	2014	SaskPower, Govt Canada	Public	~$1.2–1.5 bn; Shell Cansolv	Post-combustion amine	Carbon tax	High
Petra Nova	Power	NRG / JX Nippon	USA	~1.0	~90%	2017	NRG, JX Nippon	Private	~$1 bn	Post-combustion	US 45Q + EOR	Medium
Sleipner CO_2 Storage	Gas Processing	Equinor	Norway	~1.0	~100%	1996	Equinor, Norwegian Govt	Operator funded	~$100 m	Gas processing + saline storage	CO_2 tax + EU ETS	Medium
Gorgon CCS	LNG / Gas	Chevron (JV)	Australia	~3–4	~40–50%	2019	Chevron, Exxon, Shell	Private	>$3 bn	Reservoir CO_2 reinjection	Regulatory compliance	Medium
Illinois Industrial CCS	Bio-ethanol	ADM	USA	~1.0	~100%	2017	ADM, US DOE	Govt + Private	~$200 m	Fermentation CO_2 + storage	DOE + 45Q	High

6

STATUS AND OPPORTUNITIES FOR CCUS IN INDIA

STATUS AND OPPORTUNITIES FOR CCUS IN INDIA

The development of Carbon Capture, Utilization and Storage (CCUS) in India is currently at an early but rapidly evolving stage, with increasing policy focus, pilot-scale deployments, and cross-sector engagement. While large-scale commercial deployment has not yet been achieved, recent initiatives indicate a clear transition from research and pilot phase toward demonstration and scale-up.

India's approach is characterised by a combination of policy support, institutional initiatives, and industry–academia collaboration, laying the foundation for future CCUS deployment in hard-to-abate sectors such as cement.

6.1 Current Status, Pilots and MoUs

6.1.1 Policy and Institutional Framework

India's industrial decarbonisation strategy is supported by a combination of national policies and financial mechanisms aimed at reducing emissions while sustaining economic growth.

Recognising the importance of carbon capture technologies for industrial sectors, in the Union Budget 2026–27[14], the Government of India has made a significant budgetary provision to accelerate decarbonisation technologies in hard-to-abate industrial sectors, including cement. The budget proposed an outlay of ₹ 20,000 crore (₹200 billion) over the next five years specifically for Carbon Capture, Utilisation and Storage (CCUS) technologies and related initiatives.

At the policy level, the NITI Aayog has released a national CCUS roadmap outlining technology pathways, financing mechanisms, and regulatory considerations for hard-to-abate sectors such as cement, steel, power, and refining. This roadmap outlines coordinated action across government, industry, and academia to accelerate CCUS deployment. India has an estimated 600 billion tonnes of geological CO_2 storage capacity in depleted oil and gas fields, saline aquifers, and unmineable coal seams, making it one of the largest potential storage bases globally. CCUS technology is essential for decarbonizing 56% of emissions from the steel and cement sectors that cannot be mitigated through conventional renewable energy approaches.

6.1.2 Pilots and Demonstration Projects in Cement

India's CCUS ecosystem is transitioning from pilot-scale experimentation to early-stage deployment, supported by policy initiatives, industry participation, and cross-sector learnings.

The Department of Science and Technology (DST) has established multiple CCU testbeds in collaboration with cement companies and research institutions to validate technologies under real plant conditions.

Table 12 : CCU Testbeds in Cement Sector

Testbed	Institute / Partners	Technology	Capacity
Testbed-1	National Council for Cement and Building Materials (Ballabhgarh) + JK Cement	Oxygen-enhanced calcination with CO_2 capture and utilisation (lightweight blocks, olefins)	~2 TPD CO_2
Testbed-2	IIT Kanpur + JSW Cement	Carbon-negative mineralisation (CO_2 to solid minerals)	Pilot scale
Testbed-3	IIT Bombay + Dalmia Cement	Catalyst-driven CO_2 capture at plant scale	Pilot/demo scale
Testbed-4	CSIR-Indian Institute of Petroleum, IIT Tirupati, IISc Bangalore + JSW Cement	Vacuum Swing Adsorption (VSA) for CO_2 separation and utilisation	Pilot scale
Testbed-5	IIT Madras & BITS Pilani, Goa + UltraTech Cement	Advanced carbon reduction & utilisation interventions	Pilot scale

14 Union Budget 2026 - The Hindu

These testbeds represent India's first coordinated effort to transition CCUS technologies from laboratory research to plant-level demonstration, with a strong focus on:

- CO_2 utilisation pathways
- process integration
- technology validation under real operating conditions

6.1.3 Industry Initiatives and International Collaborations

1. **Adani Cements Indo-Swedish Pilot**

   Adani Cements has received an Indo-Swedish grant funding under the LeadIT Industry Transition Partnership to conduct a pioneering CCU pilot in collaboration with the Indian Institute of Technology Bombay and a Swedish technology partner. This initiative focuses on capturing CO_2 from cement operations and converting it into value-added products such as calcium carbonate and green methanol, helping to validate the technical and economic feasibility of CCU in the sector.

2. **Geological CO_2 Storage Drilling**

   In 2025, India completed its first geological CO_2 storage test drilling in Jharkhand's coalfields, led by NTPC and IIT-Bombay. This project evaluates underground storage potential and monitoring, marking a significant step toward developing full-scale geological storage capabilities. Early findings suggest notable storage potential for millions of tonnes of CO_2 over a decade.

Overall Status Assessment

- Predominantly pilot and demonstration stage
- Strong focus on CO_2 utilisation pathways
- Early progress in geological storage assessment
- Increasing industry–academia–government collaboration

India is currently in a pre-commercial phase, with growing momentum toward scale-up and integrated CCUS deployment.

The next phase of CCUS deployment in India will depend on scaling pilot initiatives into integrated, cluster-based systems supported by policy, infrastructure, and market mechanisms.

6.1.4 Industry Initiatives and International Collaborations

In addition to storage-focused pathways, CO_2 utilisation (CCU) presents an important opportunity to create value from captured emissions in the Indian context. While large-scale geological storage infrastructure is still under development, utilisation pathways can serve as a practical entry point for early CCUS deployment, particularly in sectors with established demand for CO_2 or CO_2-derived products.

India already has significant industrial consumption of products such as urea, methanol, soda ash, and speciality chemicals, for which CO_2 can either be used directly or converted into value-added products. In several of these applications, CO_2 is combined with hydrogen or ammonia, linking CCU deployment with the broader transition toward green hydrogen and low-carbon industrial systems.

Utilisation pathways offer the following advantages:

- Enable early-stage deployment of carbon capture systems without waiting for full CCS infrastructure
- Create revenue streams that partially offset capture costs
- Support industrial decarbonisation across multiple sectors (fertilizers, chemicals, fuels)
- Provide flexibility in regions where CO_2 transport and storage networks are not yet developed

However, CCU also has inherent limitations. The total market size for CO_2 utilisation is relatively smaller compared to the total cement sector emissions. In many cases, CO_2 is re-emitted after product use (e.g., fuels), limiting long-term climate benefits compared to permanent storage. As a result, CCU should be viewed as a complementary pathway, particularly for early deployment, rather than a complete substitute for CCS.

The table below provides an indicative overview of key CO_2 utilisation pathways in India, along with their market size, cost context, and key input requirements.

Table 13 : Indicative CO_2 Utilisation Pathways and Market Linkages in India

Application / Product	Annual Production / Consumption (India)	Indicative Cost (USD/tonne) (Domestic / Imported)	End Use	Key Additional Inputs
Methanol	~0.3 MT	400 / 340	Chemicals, fuel blending	Hydrogen
Urea	~44 MT	514 / 950	Fertilizer	Ammonia
Dimethyl Ether (DME)	~0.67 MT	510 / 630	LPG substitute, clean fuel	Hydrogen
Soda Ash	~4.6 MT	~265	Glass, detergents	CO_2 (~30 USD/tCO_2 input cost)
FMCG – Soft Drinks	~0.1 MT CO_2 use	~950	Carbonation (≈6.5 g/L; ~12 L per capita/ year)	Food-grade CO_2
Pharmaceuticals	~1,5 MT (est.)	~526	APIs, chemical synthesis	Hydrogen
Synthetic Methane	Emerging	NA	Fuel, grid injection	Hydrogen

The utilisation of captured CO_2 for the production of chemicals such as urea and methanol is gaining increasing attention as a potential pathway for supporting early-stage CCUS deployment. However, the economic viability of such applications depends on the cost competitiveness of captured CO_2 relative to conventionally sourced CO_2 streams currently used in industrial processes. While CCUS-derived CO_2 can support decarbonisation objectives, its large-scale adoption will depend on advancements in capture technologies, the availability of low-cost clean energy, and the development of supportive policy and market mechanisms.

In addition to chemical applications, biological utilisation pathways such as algae cultivation using captured CO_2 are also emerging as potential opportunities. Algae can convert CO_2 into biomass that may be further processed into biofuels, chemicals, animal feed, or other value-added products. Although currently at an early stage of commercial deployment, such pathways offer long-term potential for integrating carbon utilisation with circular bioeconomy approaches.

6.2 Global Context and Carbon Market Landscape

Global greenhouse gas emissions are highly concentrated among a limited number of economies, driven by industrial activity, energy consumption patterns, and production scale. Understanding the distribution of emissions across countries is essential for assessing where decarbonisation efforts, including CCUS deployment, can have the greatest impact.

Table 14 : Top 10 High Emitting Countries – CO_2 Emissions Share

Rank	Area / Jurisdiction	CO_2 Emissions 2024 (Gt CO_2/year)	Approximate % CO_2 Emissions Share
1	China	~13.1	33.1%
2	United States	~4.6	11.7%
3	India	~3.1	8.0%
4	European Union (EU27)	~2.5 – 3.0	6.4%
5	Russia	~2.0	5.1%
6	Japan	~1.0	2.5 %
7	Iran	~0.8	2.1%
8	Indonesia	~0.8	2.0%
9	Saudi Arabia	~0.7	1.7%
10	South Korea	~0.6	1.5%

While emissions are concentrated in a few major economies, the extent to which these emissions are regulated through carbon pricing mechanisms varies significantly across regions. This has direct implications for CCUS deployment, as such mechanisms create the economic incentives required for carbon capture and storage investments.

Carbon pricing mechanisms, including emissions trading systems and voluntary markets, play a critical role in shaping the economic viability of CCUS technologies by assigning a cost to emissions and enabling market-based decarbonisation pathways.

Table 15: Global Carbon Pricing Mechanisms – Coverage and Market Overview[15]

Name of the Scheme/ system	Country / Region applicable	Approx Emissions 2024 (Gt CO_2/year)	Mandatory / Voluntary	In operation since	2026 carbon price USD / ton CO_2	Applicable sectors	Remarks
Indian Carbon Market ICM	India	3.1	Mandatory (phased)	Expected 2026	9 - 13 (expected)	9 high-emission sectors, including cement, steel	Under Implementation
European Union Emissions Trading System (EU ETS):	EU	2.5-3.0	Mandatory	2005	80-100	Power, industry, aviation, etc.	Most mature global ETS
UK ETS	United Kingdom	0.4-0.5	Mandatory	2021	70-100	Power, industry, aviation, etc.	Post-Brexit EU ETS successor
Swiss Emissions Trading System (ETS)	Switzerland	0.04	Mandatory	2008	80-90	Energy-intensive industries	Linked to the EU ETS

15 Compiled from World Bank Carbon Pricing Dashboard, ICAP ETS Database, IEA reports, and public market disclosures. Prices are indicative and vary with market conditions.

Name of the Scheme/ system	Country / Region applicable	Approx Emissions 2024 (Gt CO_2/year)	Mandatory / Voluntary	In operation since	2026 carbon price USD / ton CO_2	Applicable sectors	Remarks
China Emissions Trading System (China ETS)	China	13.1	Mandatory	2021	10-12	Power sector (expanding to industry)	World's largest by volume
California Cap-and-Trade	USA-California	0.35-0.4	Mandatory	2012	25-35	Power, transport, industry	Linked with Quebec
Regional Greenhouse Gas Initiative (RGGI)	USA (East Coast states)	0.2-0.3	Mandatory (regional)	2009	15-25	Power sector	Regional cap-and-trade system
South Korea Emissions Trading Scheme (K-ETS)	South Korea	0.6-0.7	Mandatory	2015	6-10	Power, industry, aviation	Mature Asian ETS
Quebec - ETS	Canada	0.08-0.1	Mandatory	2013	25-30	Power, buildings, transport	Linked with California
Canada - Federal (OBPS + Carbon Pricing)	Canada	0.7	Mandatory	2019	50-65	Industry and fuels	Hybrid system (tax + trading)
GX-ETS (Green Transformation Emissions Trading System)	Japan	1.0-1.1	Voluntary →Mandatory	Transition phase (2023)	10-30	Large emitters (>100 $ktCO_2$/yr)	Mandatory from 2026
New Zealand ETS	New Zealand	0.07-.08	Mandatory	2008	35-50	Industry, forestry	One of the oldest ETS systems
The Brazilian Emissions Trading System (SBCE)	Brazil	1.2-1.3	Mandatory (phased)	Framework (2024), not fully operational	5-40	Energy, industry, transport	Full rollout expected ~2030
Verified Carbon Standard (VCS)	Global	NA	Voluntary	Operational	5-15	Forestry, energy, industry	Largest voluntary market
Gold Standard	Global	NA	Voluntary	Operational	8-20	Renewable community projects	Premium credits
American Carbon Registry (ACR)	USA	NA	Voluntary	Operational	10-25	Industry, forestry	Established registry
Climate Action Reserve (CAR)	USA, Mexico	NA	Voluntary	Operational	5-15	Forestry, waste, O&G	North America-focused
Global Carbon Council (GCC)	Global (Middle East)	NA	Voluntary	Operational	5-12	Energy, infrastructure	Emerging market

Global carbon pricing systems show significant fragmentation, with mature markets such as the EU and UK ETS exceeding USD 70–100/tCO_2, while emerging economies remain largely below USD 15/tCO_2. This disparity highlights the transitional challenge for developing economies such as India in establishing effective carbon pricing mechanisms for industrial decarbonisation.

Emissions coverage values represent the share of emissions within each jurisdiction covered by the respective scheme. Approximate global shares are indicative and derived from national emission profiles and scheme coverage; these should be interpreted as directional estimates.

Despite the expansion of carbon pricing mechanisms, no single system currently covers more than ~13% of global emissions. This highlights the fragmented nature of carbon markets and reinforces the need for broader, more coordinated adoption to enable large-scale deployment of CCUS technologies.

6.3 Cross-Sector Case Snapshot: Power Sector (NTPC)

Figure 12 : NTPC Vindhyachal Super Thermal Power Station, India (host site for carbon capture and utilization project)

The NTPC Vindhyachal Carbon Capture Project in India is an early demonstration of Carbon Capture and Utilization (CCU) at a coal-based power plant. The project is located at the Vindhyachal Super Thermal Power Station, operated by NTPC Limited.

The facility captures approximately 20 tonnes of CO_2 per day (~7,000 MT of CO_2/year) from flue gas using amine-based post-combustion capture technology. Unlike storage-focused CCS projects, the captured CO_2 is utilized for methanol production, demonstrating a value-added pathway for emissions management.

Technically, the project integrates three key elements:

(i) post-combustion CO_2 capture from coal-fired units,

(ii) purification and compression of CO_2, and

(iii) catalytic conversion to methanol, supported by external hydrogen input. The system is designed as a retrofit solution, highlighting the feasibility of deploying carbon capture on existing thermal power infrastructure.

Figure 13 : Carbon capture and CO_2-to-methanol demonstration unit at NTPC Vindhyachal.

Commissioned around 2021, the project operates at a pilot-to-demonstration scale, with the primary objective of validating CCU technologies under Indian operating conditions rather than achieving large-scale emissions reduction.

From a global perspective, the Vindhyachal project represents a utilization-driven carbon management pathway, particularly relevant for emerging economies where CO_2 transport and storage infrastructure is limited. While the scale is modest compared to large CCS projects, it provides critical insights into integration, operability, and product-based carbon economics.

The key takeaway is that CCU can serve as an entry point for carbon capture deployment, especially in coal-dependent systems. However, long-term scalability depends on the availability of low-cost hydrogen, market demand for methanol, and overall process economics.

6.4 Concluding Insights

The analysis across global case studies, carbon market developments, and India-specific initiatives highlights that there is no single pathway for carbon capture deployment in the cement sector. Instead, implementation is shaped by technology maturity, infrastructure availability, policy frameworks, and regional priorities.

Global experience demonstrates that carbon capture is transitioning from pilot-scale validation to early-stage commercialization, supported by integrated project delivery models, public funding, and industrial partnerships. At the same time, carbon pricing mechanisms are emerging as a critical enabler by creating economic signals necessary to support large-scale CCUS investments, although global markets remain fragmented and uneven in coverage.

In the Indian context, early-stage pilots, industry–academia collaborations, and policy initiatives indicate growing momentum. However, large-scale deployment will depend on the development of enabling ecosystems, including carbon markets, transport and storage infrastructure, and access to low-carbon energy.

Across all geographies, common success factors include strong policy support, standardization of technologies, and collaboration across the value chain. Key challenges remain around cost competitiveness, scalability, and system integration.

Looking ahead, CCUS is expected to evolve toward integrated carbon management systems, where capture, transport, utilization, and storage function as interconnected components. Achieving meaningful decarbonisation in the cement sector will require a portfolio approach combining multiple technologies, business models, and policy instruments tailored to regional conditions.

GLOSSARY OF TERMS (CCUS DEFINITIONS AND EXAMPLES)

This glossary provides definitions of key technical terms used in Carbon Capture, Utilization and Storage (CCUS), with brief contextual explanations relevant to the cement sector. The glossary is intended to support both technical and non-technical readers in understanding key CCUS concepts used throughout this report.

Carbon Capture, Utilization and Storage (CCUS)

A set of technologies that enable the capture of carbon dioxide (CO_2) from industrial sources, followed by its utilisation in products or permanent storage in geological formations.Example: Capturing CO_2 from cement kiln exhaust and either using it to produce chemicals or storing it underground.

Carbon Capture (CC)

The process of separating CO_2 from flue gases or process streams generated during industrial operations. Example: Removing CO_2 from kiln exhaust gases in a cement plant using solvent-based systems.

Carbon Utilization (CCU)

The use of captured CO_2 as a feedstock for producing value-added products such as fuels, chemicals, or building materials. Example: Converting captured CO_2 into calcium carbonate or methanol.

Carbon Storage (CCS)

The long-term storage of captured CO_2 in deep geological formations such as saline aquifers, depleted oil and gas fields, or unmineable coal seams.Example: Injecting CO_2 into offshore saline formations in the North Sea.

Post-Combustion Capture

A capture method where CO_2 is separated from flue gases after fuel combustion, typically using chemical solvents such as amines.Example: Retrofitting a cement plant with an amine-based absorption system.

Oxy-Fuel Combustion

A process where fuel is burned in pure oxygen instead of air, producing a flue gas stream with a high concentration of CO_2, making capture easier.Example: Modifying a kiln to operate with oxygen to simplify downstream CO_2 capture.

Direct Separation (Indirect Calcination)

A process-integrated technology that captures CO_2 directly during limestone calcination by separating combustion gases from process emissions.Example: LEILAC reactor capturing high-purity CO_2 during clinker production.

Calcium Looping (CaL)

A cyclic process that uses calcium oxide (CaO) as a sorbent to capture CO_2, which is later released and concentrated for storage or use.Example: Integrating CaL reactors with cement kilns to capture process emissions.

Capture Rate

The percentage of total CO_2 emissions that are captured by the system.Example: A 90% capture rate means 90% of emitted CO_2 is captured before release.

CO_2 Purity

The concentration of CO_2 in the captured stream is typically expressed as a percentage. Example: Direct separation technologies can produce CO_2 streams with >95% purity.

Levelized Cost of Carbon (LCOC)

The average cost of capturing one tonne of CO_2 over the lifetime of a project, including capital and operating costs. Example: In India, cement capture costs are estimated at ₹1,800–2,600 per tonne CO_2.

Energy Penalty

The increase in energy consumption of a plant due to the addition of carbon capture systems.Example: A cement plant with CCUS may experience a 20–30% increase in total energy demand.

CO_2 Compression

The process of increasing the pressure of captured CO_2 (typically to 100–120 bar) for transport and storage. Example: Compressing CO_2 before pipeline transport or liquefaction.

CO_2 Transport

The movement of captured CO_2 from the capture site to utilisation or storage locations via pipelines, ships, or trucks. Example: Shipping liquefied CO_2 from a cement plant to an offshore storage site.

Geological Storage

The injection and long-term containment of CO_2 in underground formations. Example: Storage of CO_2 in deep saline aquifers at depths greater than 1 km.

Cluster / Hub Model

A shared infrastructure approach where multiple industrial emitters connect to common CO_2 transport and storage systems.Example: Multiple cement and steel plants connecting to a regional CO_2 pipeline network.

Hard-to-Abate Sector

Industries where emissions are difficult to eliminate due to process constraints or high energy requirements. Example: Cement, steel, and chemicals.

Process Emissions

CO_2 emissions are generated from chemical reactions during production, rather than from fuel combustion. Example: CO_2 released during limestone calcination in cement manufacturing.

Flue Gas

The exhaust gas is produced during combustion processes in industrial plants. Example: Gas stream from cement kiln containing CO_2, nitrogen, and other gases.

Solvent Regeneration

The process of recovering solvents used in CO_2 capture by releasing the absorbed CO_2 using heat. Example: Heating amine solutions to release captured CO_2 for compression.

First-of-a-Kind (FOAK) Project

An initial commercial-scale project using new technology, typically involving higher costs and risks. Example: The Norcem Brevik CCS project is a FOAK cement CCS plant.

Technology Readiness Level (TRL)

A scale used to assess the maturity of a technology, ranging from early-stage research (TRL 1) to full commercial deployment (TRL 9).Example: Post-combustion capture is at TRL 8–9, while direct separation is at lower TRLs.

CO_2 Concentration (Flue Gas)

The percentage of CO_2 present in flue gas streams, which affects capture efficiency and cost. Example: Cement plants have relatively low CO_2 concentration (~20–30%), making capture more energy-intensive.

Absorber and Stripper Columns

Key equipment in solvent-based capture systems:

- Absorber: CO_2 is captured from flue gas
- Stripper: CO_2 is released from the solvent using heat

Example: Used in post-combustion amine systems.

Amine-Based Solvents

Chemical solvents (e.g., MEA – Monoethanolamine) are used to absorb CO_2 from flue gases. Example: Most commercial post-combustion systems use amine solvents.

Compression and Liquefaction

Processes used to prepare CO_2 for transport:

- Compression increases pressure
- Liquefaction reduces volume for shipping

Example: CO_2 is liquefied at ~–25°C for marine transport.

Enhanced Oil Recovery (EOR)

A process where CO_2 is injected into oil fields to increase oil extraction, while storing CO_2 underground. Example: Used in the US and the Middle East.

Decarbonisation Pathway

A structured approach outlining how emissions are reduced over time using a combination of technologies and strategies. Example: Combining efficiency, SCMs, and CCUS to reach net-zero.

Capture Island

The section of the plant dedicated to CO_2 capture systems, including absorbers, regenerators, and compressors. Example: Additional infrastructure added to existing cement plants.

Operational Expenditure (OPEX)

Ongoing costs associated with running CCUS systems, including energy, maintenance, and consumables.

Capital Expenditure (CAPEX)

An initial investment is required for installing CCUS infrastructure and systems.

Carbon Neutral

A condition in which net carbon dioxide (CO_2) emissions are zero, achieved by reducing emissions as far as possible and balancing remaining emissions through carbon removal or offsets.

Example: An industrial facility that runs on renewable electricity and offsets its remaining CO_2 emissions through afforestation projects can be considered carbon neutral.

Net Zero

A state in which total greenhouse gas (GHG) emissions are reduced as close to zero as possible, with only unavoidable residual emissions balanced through carbon removal.

Roadmap

A strategic plan that outlines actions, timelines, and milestones required to achieve a defined goal over a period.

Pilot

A smallscale implementation of a new technology, policy, or practice conducted to test its feasibility, performance, and viability before wider deployment.

Testbeds

Controlled realworld environments where new technologies or solutions are tested under practical operating conditions.

CII - Green Business Centre Initiatives

CII - Green Business Centre (CII – GBC), as part of its efforts to promote environmentally sustainable development of Indian industry and demonstrate that green makes good business sense, is playing a catalytic role in promoting World Class Energy Efficiency and Decarbonization initiatives in the cement industry with the support of all stakeholders.

CII - GBC has been working with all the major cement plants in the country on the energy efficiency and sustainable front, resulting in significant benefits being achieved and reported by these units. Some of these activities include:

- Development of a technology roadmap to make the Indian cement industry pursue a low-carbon growth path by 2050.
- Facilitating cement plants in achieving PAT (Perform, Achieve and Trade program of BEE) targets in a cost- effective manner.
- Developing of energy benchmarking web tool.
- Developing a website to accelerate the net-zero transition in the industry.
- Reducing carbon emissions from the sector by facilitating the electrification of trucks used by the sector.
- Conducting detailed energy audits and energy benchmarking studies to identify the potential and opportunities for improving the performance and reducing the energy consumption.
- Supporting cement plants in increasing alternative fuel consumption by identifying the waste generators and waste availability.
- Creating awareness on application specific cement.
- Greenhouse gas (GHG) Inventorization and lifecycle assessment (LCA) studies.
- Green product (GreenPro) certification and green company (GreenCo) assessment services.
- Organising national and international missions to facilitate the industry to achieve excellence in energy and environment.
- Organising an annual international conference “Green Cementech” to provide a platform for knowledge dissemination for the benefit of the cement industry.

About CII Green Business Centre

The CII – Green Business Centre (CII – GBC) is CII's Developmental Institute for Green Practices and Businesses, focused on offering world-class advisory services dedicated to the conservation of natural resources. Its mission is to help India emerge as a global leader in green business by 2030.

The Green Business Centre in Hyderabad, Telangana, is housed in one of the greenest buildings in the world. Established in 2004, the Green Business Centre was inaugurated by His Excellency, the late Dr. A. P. J. Abdul Kalam, the then President of India, on 14 July 2004.

The Centre promotes sustainable practices and supports businesses through a comprehensive range of services, including Green Buildings (IGBC), Energy Management Initiatives, Energy Efficiency Initiatives, GreenPro Certification, GreenCo Rating System, Green Entrepreneurship Council (GEC), Council on Green Mobility, Green Cooling Council, Solar Vendor Rating Program (VRP) etc.

The Green Business Centre has registered over 19,150 green building projects (through the Indian Green Building Council - IGBC), certified more than 14,500 GreenPro products, conducted over 2,200 energy audits globally, registered more than 1,500 manufacturing facilities under GreenCo, and engaged with 300 cleantech startup Across India, Sweden, Australia, Ethiopia, Bangladesh & Japan.

CII GBC with all its councils has contributed to reducing 55 million tons of CO_2 emissions, saving 198 billion litres of water and 65 billion kWh of energy annually.

Learn more by logging on to - https://greenbusinesscentre.com/

Conclusion

We feel that this publication on “Carbon Capture: Technologies, Economics and Scale-Up Pathways” has provided useful insights and practical perspectives on CCU technologies and their role in industrial decarbonisation and will help advance informed decision-making and implementation efforts across the sector.

We welcome your valuable feedback, suggestions, and inputs for any corrections or improvements to be incorporated in future updates of this publication.

Contact Details:

Mr P. V. Kiran Ananth
Deputy Executive Director
Confederation of Indian Industry
CII-Sohrabji Godrej Green Business Centre
Survey No. 64, Kothaguda Post,
Near HITEC City, Hyderabad- 500084, India.
Phone: +91 40 4418 5152
e-mail: kiran.ananth@cii.in
W: www.cii.in / www.greenbusinesscentre.com

NOTES

NOTES

Confederation of Indian Industry

The Confederation of Indian Industry (CII) works to create and sustain an environment conducive to the development of India, partnering Industry, Government and civil society through advisory and consultative processes.

CII is a non-government, not-for-profit, industry-led and industry-managed organisation, with around 9,700 members from the private as well as public sectors, including SMEs and MNCs, and an indirect membership of over 365,000 enterprises from 318 national and regional sectoral industry bodies.

For 130 years, CII has been engaged in shaping India's development journey and works proactively on transforming Indian Industry's engagement in national development. CII charts change by working closely with the Government on policy issues, interfacing with thought leaders, and enhancing efficiency, competitiveness, and business opportunities for industry through a range of specialised services and strategic global linkages. It also provides a platform for consensus-building and networking on key issues.

Through its dedicated Centres of Excellence and Industry competitiveness initiatives, promotion of innovation and technology adoption, and partnerships for sustainability, CII plays a transformative part in shaping the future of the nation. Extending its agenda beyond business, CII assists industry to identify and execute corporate citizenship programmes across diverse domains, including affirmative action, livelihoods, diversity management, skill development, empowerment of women, and sustainable development, to name a few.

For 2025-26, CII has identified "Accelerating Competitiveness: Globalisation, Inclusivity, Sustainability, Trust" as its theme, prioritising five key pillars. During the year, CII will align its initiatives to drive strategic action aimed at enhancing India's competitiveness by promoting global engagement, inclusive growth, sustainable practices, and a foundation of trust.

With 70 offices, including 12 Centres of Excellence, in India, and 9 overseas offices in Australia, Egypt, Germany, Indonesia, Singapore, UAE, UK, and USA, as well as institutional partnerships with about 250 counterpart organisations in almost 100 countries, CII serves as a reference point for Indian industry and the international business community.

Confederation of Indian Industry
The Mantosh Sondhi Centre
23, Institutional Area, Lodi Road, New Delhi – 110 003 (India)
T: 91 11 45771000
E: info@cii.in • W: www.cii.in

Follow us on

cii.in/facebook cii.in/twitter cii.in/linkedin cii.in/youtube