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NITI Aayog

Roadmap for CEMENT SECTOR DECARBONISATION

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Roadmap for

CEMENT SECTOR DECARBONISATION

January 2026

Preface

India's pursuit of sustainable and inclusive growth demands a delicate balance between economic advancement and environmental responsibility. Among the key sectors driving this progress, the cement industry holds a vital position as a backbone of the nation's infrastructure and economic development. As the world's second-largest producer of cement, India is on the cusp of significant growth, with production expected to rise nearly sevenfold by 2070, from 391 million tons in 2023. However, this rapid expansion brings with it a considerable environmental challenge, as emissions from the sector are projected to increase from 246 million tons of CO_2 equivalent ($MtCO_2e$) in 2023 to 945 $MtCO_2e$ in 2047 to 1,323 $MtCO_2e$ annually by 2070 under a Business-As-Usual scenario.

This dual challenge of meeting growing demand while addressing environmental concerns underscores the need for a forward-looking strategy that aligns industrial growth with climate action. Recognising this imperative, the report, ***'Road Map for Cement Sector Decarbonisation'***, provides a comprehensive framework to guide the sector toward a sustainable future. It outlines a phased, long-term approach to significantly reduce emissions while ensuring the sector's continued contribution to India's economic progress. At the heart of this roadmap are three transformative solutions: scaling up carbon capture, utilisation, and storage (CCUS) technologies, increasing the use of clinker substitutes, and developing a robust supply chain for alternative fuels. This combination of technological, market-driven, and policy-enabled interventions offers a practical, adaptable, and cost-effective pathway to deep decarbonisation.

By 2030, the proposed measures have the potential to deliver measurable impacts, including significant reductions in cumulative emissions, mobilisation of private capital, creation of green jobs, and enhanced fiscal contributions. These outcomes demonstrate that decarbonisation is not merely an environmental necessity but also a transformative economic opportunity, enabling the cement sector to thrive in a low-carbon economy.

The roadmap is not just a strategy for emissions reduction; it is a vision for a thriving and sustainable cement industry in a low-carbon economy. It equips the sector to foster innovation, lower costs, and enhance its global competitiveness in an increasingly sustainability-driven market. This report marks a bold step in turning ambition into action and strategy into measurable outcomes, positioning India's cement industry as a global benchmark for sustainable industrial development.

We hope this report serves as a valuable guide for policymakers, industry leaders, and stakeholders, encouraging collaborative efforts to build a resilient and sustainable future for the cement sector and the nation. Together, we can embark on this journey to shape a sustainable and prosperous future for generations to come.

Foreword and Acknowledgement

The cement industry is central to India's infrastructure and economic development, yet it faces a pressing imperative to reconcile rapid growth with deep decarbonisation. The Roadmap for Cement Sector Decarbonisation draws on a wide body of technical evidence, extensive stakeholder inputs, and practical field observations to outline a phased, implementable pathway for the sector's low-carbon transition.

I would like to acknowledge the guidance and support of Shri B.V.R. Subrahmanyam, Chief Executive Officer, NITI Aayog, whose confidence in the Working Committee enabled this exercise. My sincere thanks to Dr. Anshu Bharadwaj, Programme Director (Energy, Green Transition & Climate Change), and Shri Rajnath Ram, Adviser (Energy), NITI Aayog, for their strategic advice and continual oversight during the preparation of this report.

This roadmap benefited substantially from the subject-matter expertise and constructive engagement of the Working Committee members and peer reviewers. I am grateful to Dr. L.P. Singh, Director General, National Council for Cement & Building Materials (DPIIT), and Shri Vivek Negi, Joint Director, Bureau of Energy Efficiency, for their technical inputs. I also extend my appreciation to industry leaders and association representatives- Ms. Aparna Dutt Sharma, Secretary General, Cement Manufacturers Association; Shri Kaustubh Phadke, India Head, Global Cement & Concrete Association- India; Dr. Raju Goyal, Executive President & CTO, Ultratech Cement; Shri S. Dakshinamoorthy, Vice President, The India Cements; Shri Ashwin Raykundalia, Chief Sustainability Officer, ACC/Ambuja; and Shri Anupam Badola, Deputy Chief Sustainability Officer, Dalmia Cement for sharing practical insights on plant operations, fuel substitution and material markets.

The study's empirical foundation was strengthened by more than 20 stakeholder consultations, reviews of 30+ national and international datasets and reports, and a field visit to the Indore municipal solid waste and material recovery facilities to validate the feasibility of RDF value chains. I thank the Bureau of Energy Efficiency, the Cement Manufacturers Association, GCCA-India, and other partner organisations for their time and evidence-based contributions during these consultations.

This report was developed with technical support from WRI India. I acknowledge the exceptional contribution of Ms. Ankita Gangotra, Mr. Deepak Krishnan, Ms. T. S. Gowthami, Ms. Kajol, Mr. NGR Kartheek and Ms. Shivani Shah, whose analytical inputs and drafting support were indispensable. Their collaboration ensured rigorous analysis across the technical, economic and policy dimensions of the roadmap.

I would like to recognise the dedication of the NITI Aayog research and coordination team. Special thanks to Shri Manoj Kumar Upadhyaya, Member Secretary of the Working Committee, and to Ms. Poonam Kapur, Research Officer; Shri Anurag Pandey, Young Professional; and Shri Saksham Agarwal, Young Professional, for their sustained effort in organising stakeholder consultations, collating data, and shaping the content of the report.

I also appreciate the contributions of other colleagues across NITI Aayog, whose support in peer review, logistics and quality assurance improved the final output.

Several government departments, state governments, research institutions, technology providers, financing bodies and civil society organisations provided critical inputs. I am grateful to all the experts, practitioners, and officials who participated in workshops and bilateral discussions, as well as to the industry and service-provider representatives who took the time to review the draft findings.

This roadmap represents a collective effort to identify pragmatic, scalable interventions, ranging from alternative fuel supply chains and clinker substitution to CCUS pilots,that can materially reduce emissions while maintaining the sector's competitiveness. I hope it serves as a pragmatic guide for policymakers, industry and finance partners to accelerate the cement sector's transition to a resilient, low-carbon future.

ISHTIYAQUE AHMED

Programme Director, Industry, & Foreign Investment

Chairman, Technical Working Committee on Decarbonisation Roadmap for Cement Sector

NITI Aayog

Technical Working Committee Order is at Annexure-1

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Message

The cement industry is a cornerstone of our nation's infrastructure development and economic growth. At the same time, it faces the imperative of transforming its production processes to meet rising environmental expectations and climate commitments. This report provides a timely and rigorous assessment of the sector's pathway towards a low carbon future.

Drawing on technical insights from more than thirty national and global databases, complemented by site visits and structured engagements with industry stakeholders, the report presents a comprehensive and data driven analysis of the current performance of the cement sector. It identifies key opportunities for decarbonisation while carefully balancing the need to sustain production with the responsibility to protect the environment.

The study, *Roadmap for Cement Sector Decarbonisation*, examines critical levers for transition, including the increased use of low carbon materials, the scaling up of carbon capture and utilization technologies, and the expanded adoption of alternative fuels. Through robust quantitative analysis and detailed evaluations, the report sets out a practical roadmap with actionable recommendations to drive technological innovation, enable regulatory reform, and strengthen collaboration across industry, government, and research institutions.

This framework is intended not merely as an analytical exercise, but as a call to action for policymakers and industry leaders. The insights presented here will support the design of forward looking policies that catalyse investment in green technologies and sustainable practices. By fostering an enabling ecosystem for innovation and market transformation, the report outlines a clear pathway for the cement sector to emerge as a global exemplar of sustainable industrial development.

The recommendations contained in this document aim to ensure that the cement industry continues to meet growing domestic and international demand while significantly reducing its environmental footprint. Their implementation will contribute meaningfully to emissions reduction, in alignment with national climate commitments and broader global sustainability objectives. Through coordinated and sustained action, the cement sector can build a resilient and sustainable future and offer valuable lessons for emerging economies worldwide.

(Suman Bery)

Place- New Delhi
Dated- 16th December 2025

राजीव गौबा
Rajiv Gauba
Member
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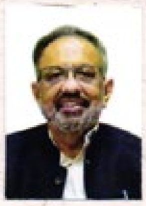

Message

The cement industry occupies a central place in Indian economic and infrastructural aspirations, while facing a strategic imperative that is to reconcile rapid growth with deep decarbonization. This roadmap presents a rigorous, evidence-based pathway to do precisely that: balancing industrial competitiveness with social development and ambitious climate outcomes. With the sector emitting roughly 246 $MtCO_2e$ in 2023, and demand projected to rise steeply in the coming decades, prompt, coordinated action is needed.

To this end, the report identifies three high-impact levers: scaled use of RDF from municipal solid waste, accelerated deployment of clinker substitutes, and piloting and scaling of CCUS that, when combined, could unlock the greatest abatement. Practical targets such as achieving around 20% thermal substitution through RDF could yield cumulative reductions of 70-80 $MtCO_2e$, while the wider adoption of clinker substitutes and CCUS will help reduce hard-to-abate process emissions over the medium to long term. Moreover, it points out that shifting standards from prescriptive inputs toward performance-based criteria would make widespread adoption of low-carbon cements possible, without affecting quality or safety.

Realizing this transition will require a supportive policy and institutional environment that incentivizes innovation, builds confidence in industry, and ensures consistent regulatory signals. Clear standards, better inter-agency coordination, and stable investment conditions will be required to guide the sector through this transformation.

The report is thus an appeal for concerted and timely action. It crystallizes the need for close collaboration at the level of central ministries, state governments, industry, and financial institutions in translating these recommendations into quantifiable progress. Alignment of policies, institutions, and markets will enable the cement sector to pursue low-carbon pathways in a way that keeps the economic and infrastructure growth on track.

I commend the working group for developing a clear and actionable roadmap and urge its swift operationalization. Under sustained policy leadership, continuous cross-sector collaboration, and with determination, India's cement industry can achieve a balance between meeting growing demand and setting an example for sustainable industrial transformation globally.

(Rajiv Gauba)

New Delhi
12th December 2025

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MESSAGE

Decarbonizing the cement sector is a formidable task due to its energy-intensive processes and reliance on fossil fuels, which account for 97% of its fuel consumption, and the inherent CO_2 emissions from limestone calcination. However, it is also an opportunity to innovate and lead in sustainable practices. The *'Roadmap for Cement Sector Decarbonization'* outlines key levers such as alternative fuels, decarbonization of electricity, and carbon capture technologies that are essential for reducing the sector's carbon footprint, projected to rise from 246 million tonnes of CO_2e in 2023 to 1,323 million tonnes by 2070 under a business-as-usual scenario.

The report underscores the potential of using refuse-derived fuel (RDF) from municipal solid waste, targeting a 20% thermal substitution rate by 2030, which could reduce emissions by 73 million tonnes of CO_2e cumulatively. It also advocates increasing the adoption of clinker substitutes like calcined clay, which could cut emissions by 7-15% by 2070, leveraging India's already low clinker-to-cement ratio of 67.5%. Additionally, the approach to piloting and scaling CCUS technologies is crucial for addressing the sector's hard-to-abate emissions, with CCUS potentially reducing 35-50% of emissions. The report recognizes the technical and economic challenges associated with scaling up these technologies and emphasizes the importance of pilot projects to demonstrate feasibility and reduce costs.

The roadmap also highlights the urgency of revising BIS standards to accommodate performance-based criteria and low carbon cement. With 436 million tonnes of MSW projected by 2050, integrating circular economy principles into urban and industrial policy is non-negotiable.

This report is a call to action for policymakers, industry leaders, and innovators. Aligning with initiatives like the Swachh Bharat Mission for RDF supply chains will be critical. As we move forward, NITI Aayog remains committed to fostering cross-ministerial collaboration, advancing regulatory frameworks, and incentivizing R&D to position India as a global leader in sustainable cement production.

(Dr. V.K. Saraswat)

New Delhi
16.12.2025

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Chief Executive Officer

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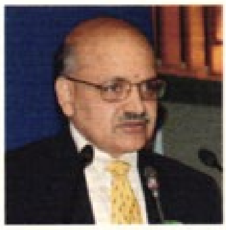

MESSAGE

India's aspiration of *Viksit Bharat* by 2047 will require large-scale expansion of infrastructure, including roads, bridges, ports and housing, all of which rely on a strong domestic cement industry. India is clearly the world's second-largest cement producer, with an installed capacity exceeding 620 million tons and an annual production of about 430 million tons. Cement production is projected to rise to 1,750 million tons by 2047 and 2,100 million tons by 2070.

However, cement sector is also a major greenhouse gas (GHG) emitter. Cement sector contributes around 6% of India's total GHG emissions, with an average emission intensity of 0.63 tonnes of CO_2 per tonne of cement produced. Emissions arise primarily from two sources: process emissions from calcination and energy-related emissions from the use of fuel and electricity. Process emissions alone account for roughly 60% of total emissions.

In the last few years, significant efforts have been made by the cement industry to improve energy efficiency. India introduced the Perform, Achieve and Trade (PAT) mechanism in 2012, setting mandatory energy-efficiency targets for designated consumers, including cement plants, which has helped lower the sector's energy intensity. Specific thermal energy consumption in cement manufacturing is now approximately 13% lower than the global average. Building on this progress, the PAT framework is now being transitioned into a broader Carbon Credit Trading Scheme that shifts compliance from energy-consumption-based targets to facility-level greenhouse-gas emission-intensity targets. Going forward, much more needs to be done to align cement industry with India's Net Zero pledge.

In this context, the **Roadmap for Cement Sector Decarbonisation** sets out a data-driven blueprint for the industry's low-carbon transition. It prioritizes three high-impact strategic solutions: strengthening supply chains for refuse-derived fuel from municipal solid waste; increasing the use of clinker substitutes to reduce process emissions; scaling up Carbon Capture, Utilisation and Storage (CCUS). Together, these interventions provide a scalable pathway to align the cement sector's growth with national climate commitments.

I commend the collaborative efforts of research institutions, industry stakeholders, government bodies and the NITI Team in shaping this forward-thinking framework. I thank Shri Ishtiyaque Ahmed, Programme Director (Industry), who chaired the working group, and appreciate the support provided by the Green Transition, Energy & Climate Change division under Dr. Anshu Bharadwaj, Programme Director, and all working group members. I also thank our knowledge partners, World Resources Institution (WRI) for their excellent efforts.

Dated: 15th January, 2026

[B.V.R. Subrahmanyam]

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Message

The report is a transformative blueprint for one of India's most essential industries. It presents a strategic pathway to reduce the sector's carbon intensity from an emission intensity of 0.63 tCO_2e per tonne to a projected reduction of emissions to 198-252 $MtCO_2e$ by 2070 demonstrating a clear route to a net-zero future. The report identifies key economic and technical levers, including the scaling up of cost-effective RDF usage to achieve a 20% thermal substitution rate, the increased integration of clinker substitutes to reduce the clinker-to-cement ratio, and the advanced deployment of CCUS technologies, which alone can mitigate up to 50% of process emissions. This comprehensive, data-driven approach not only outlines actionable recommendations but also underscores the importance of collaboration among policymakers, industry stakeholders, and research institutions to ensure a sustainable, resilient future for the cement sector.

I commend the dedication of the working group, industry stakeholders, and experts whose insights have shaped this vital document. Their collective expertise has ensured that this roadmap provides a clear, actionable pathway for policymakers and industry leaders to transition the cement sector toward a sustainable, low-carbon future. NITI Aayog remains steadfast in fostering innovation and collaboration to realise these ambitious targets.

Dr Anshu Bharadwaj
Programme Director (Energy, Green Transition & Climate Change)

India's per capita cement consumption is about 260 kg as compared to global average of 540 kg. With rapid urbanisation and infrastructure growth, the cement consumption is expected to double by 2030. The cement sector contributes roughly 7% of GHG emissions, of which about 55% comes from limestone calcination, 33% from on-site fuel combustion, and the remaining 12% from electricity use. Therefore, scaling up low carbon technologies, alternate fuels and green electricity will be crucial to decarbonise the Cement sector.

This report provides a robust policy recommendations and actionable steps to overcome the regulatory, technological and financial challenges. I extend gratitude to the Working Group for their rigorous analysis and providing inputs for shaping the critical recommendations of the report.

Sh. Rajnath Ram
Adviser (Energy)

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Cement Report Message

India's path to sustainable and resilient growth relies on balancing economic progress with environmental responsibility. Decarbonising hard-to-abate sectors is both an urgent necessity and a strategic opportunity. The cement industry serves as a fundamental pillar of India's infrastructure and economic growth. As the world's second-largest producer of cement, India is poised for significant growth across multiple sectors, with cement production projected to increase nearly sevenfold by 2070 from 334 million tons in 2023. However, this growth trajectory comes with a steep environmental cost, as the sector's emissions are expected to rise from 246 million tons of CO_2 equivalent ($MtCO_2e$) in 2023 to 1,319 $MtCO_2e$ annually by 2070 in the Business-As-Usual Scenario. This scale of growth underscores the urgent need for a forward-looking strategy that harmonises industrial expansion, development with climate action.

The report, *'Road Map for Cement Sector Decarbonisation'*, outlines a phased, long-term strategy aligned with India's net-zero targets, providing a clear pathway for the cement industry to achieve significant reductions in net emissions over time. Central to this roadmap are four impactful solutions: leveraging public procurement to drive demand for low-carbon cement, scaling up carbon capture, utilisation, and storage (CCUS), increasing the use of clinker substitutes in cement production, and establishing a robust supply chain for alternative fuels.

The proposed interventions have the potential to deliver significant, measurable impacts across various dimensions by 2030 and can substantially reduce cumulative emissions, attract large-scale private investments into the sector, create green jobs throughout the value chain, and boost fiscal revenues through increased tax contributions.

This strategy of the roadmap is not just about reducing emissions; it is about enabling the cement sector to thrive in a low-carbon economy. It empowers the industry to, unlock innovation and compete in an increasingly sustainability-conscious market, demonstrating that decarbonisation is not a trade-off but a transformative economic opportunity. This roadmap is a bold step toward that vision, converting ambition into action and strategy into measurable impact.

(Madhav Pai)
CEO, WRI India

WRI India, is an independent charity legally registered as the India Resources Trust (IRT).

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Abbreviations

AF	Alternate Fuels
AFR	Alternate Fuels and Raw Materials
AR	Alternate Raw Materials
ASTM	Advancing Standards Transforming Markets
BAT	Best Available Technology
BAU	Business as Usual
BEE	Bureau of Energy Efficiency
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BIS	Bureau of Indian Standards
BREF	Best Available Techniques Reference
CPP	Captive Power Plants
CCU	Carbon Capture and Utilisation
CCS	Carbon Capture and Storage
CCTS	Carbon Credit and Trading Systems
CCUS	Carbon Capture Utilisation and Storage
CEA	Central Electricity Authority
CEEW	Council on Energy Environment and Water
CIDC	Construction Industry Development Council
CII	Confederation of Indian Industry
CMA	Cement Manufacturers Association
CO	Carbon Monoxide
CPCB	Central Pollution Control Board
CPWD	Central Public Works Department
CSA	Calcium-Sulpho-Aluminate
Cr	Crore
DPIIT	Department for Promotion of Industry and Internal Trade
DST	Department of Science and Technology
ECBC	Energy Conservation and Building Code
ECRA	European Cement Research Academy
EE	Energy Efficiency
EN	European Standard
EIA	Environmental Impact Assessment
ESP	Electrostatic Precipitator
EPD	Environment Product Declaration
EPR	Extended Producer Responsibility
EU	European Union
FMC	First Movers Coalition
FY	Fiscal Year
GCCA	Global Cement and Concrete Association

GCF	Green Climate Fund
GDP	Gross Domestic Product
GeM	Government e Marketplace
GHG	Greenhouse Gas
GJ	Giga Joules
GRIHA	Green Rating for Integrated Habitat Assessment
GSI	Geological Survey of India
Gt	Giga Ton
$GtCO_2e$	Giga Ton of Carbon Dioxide Equivalent
GPP	Green Procurement Policy
GVA	Gross Value Addition
HEP	High Emission Plant
IBEF	India Brand Equity Foundation
IBM	Indian Bureau of Mines
IDDI	Industrial Deep Decarbonisation Initiative
IEA	International Energy Agency
IGBC	Indian Green Building Council
IMC	Inter Ministerial Committee
IPPU	Industrial Processes and Product Use
INR	Indian Rupee
IS	Indian Standard
LC3	Limestone Calcined Clay Cement
LEP	Low Emission Plant
LULUCF	Land Use, Land Use Change and Forestry
MACC	Marginal Abatement Cost Curve
MBT	Mechanical-biological Treatment
MoEFCC	Ministry for Environment, Forest and Climate Change
MoHUA	Ministry of Housing and Urban Affairs
MoRTH	Ministry of Road Transport and Highways of India
MSME	Micro Small and Medium Enterprises
MSW	Municipal Solid Waste
Mt	Million Tons
MTPA	Million Tons Per Annum
$MtCO_2e$	Million Tons of Carbon Dioxide Equivalent
NITI	National Institution for Transforming India
NHAI	National Highways Authority of India
NOx	Nitrogen Oxide
OPC	Ordinary Portland Cement
PAT	Perform Achieve Trade
PIB	Press Information Bureau

PMAY	Pradhan Mantri Awas Yojana
PCC	Portland Composite Cement
PDC	Portland Dolomitic Limestone Cement
PLC	Portland Limestone Cement
PPP	Public Private Partnership
PoPaP	Polluter Pays Principle
PPC	Portland Pozzolana Cement
PSC	Portland Slag Cement
RDF	Refuse Derived Fuel
RE	Renewable Energy
RE RTC	Renewable Energy- Round-The-Clock
RMI	Rocky Mountain Institute
SCMs	Supplementary Cementitious Materials
SDG	Sustainable Development Goals
SEC	Specific Energy Consumption
SIA	Social Impact Assessment
SRF	Solid Recovered Fuel
TERI	The Energy and Resources Institute
TPD	Tons Per Day
TPY	Tons Per Year
TSR	Thermal Substitution Rate
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
ULBs	Urban Local Bodies
VGF	Viability Gap Funding
VRM	Vertical Roller Mill
WBCSD	World Business Council for Sustainable Development
WEF	World Economic Forum
WHR	Waste Heat Recovery
WRI	World Resources Institute

EXECUTIVE SUMMARY

Executive Summary

India is the world's second-largest cement producer after China, contributing about 13% of global annual cement output. As per the Cement Manufacturers Association (CMA), the country has an installed capacity of around 622 million tonnes per annum (Mtpa), and in FY 2024 it produced 427 million tonnes of cement. India's per capita cement consumption is about 260 kg a year, much lower than the global average of 540 kg and the demand is fueled by the construction of new highways and metro systems, the expansion of urban areas, and ongoing investments in rural housing and infrastructure projects. There are 333 cement manufacturing units in India comprising 159 integrated, large cement plants; 116 grinding units; 62 mini cement plants; and five clinkerization units (DPIIT 2024).

Globally, cement production is also a significant source of carbon emissions. In 2023, cement manufacturing contributed roughly 2.4 $GtCO_2e$ of Scope 1 and 2 emissions worldwide. India's production of about 391 Mt of cement results in roughly 246 $MtCO_2e$ of emissions (PIB 2024) around 6% of national greenhouse gas emissions. Despite this sizeable footprint, the Indian cement industry has already made notable progress in bringing down its emissions intensity. Many cement plants in India now operate at energy-efficiency levels comparable to those of the best performers worldwide. This has been achieved mainly through investment in modern equipment and better plant operation. The wider use of high-efficiency kilns with pre-heaters and pre-calciners has reduced the energy required per tonne of cement, helping cut fuel use and related emissions.

Decarbonisation Roadmap - A Strategic Blueprint for India's Cement Sector

To support the shift toward cleaner energy and net-zero emissions, NITI Aayog has formed specialised working groups to prepare decarbonisation roadmaps for the cement, aluminium and MSME sectors. These documents are intended as practical planning tools, outlining how each sector can move step by step toward more sustainable, lower-carbon modes of production.

The Cement Sector Decarbonisation working group assessed twenty-two recommendations grouped under four categories of solutions, i.e. Immediate (e.g, energy efficiency initiatives); economically viable solutions that may require regulatory support; solutions that can become economically viable in the long run with government policy & regulatory support, and initiatives that may have limited impact on decarbonisation.

Out of the twenty-two recommendations, seven solutions were prioritised, which required regulatory and policy support from the government. The seven solutions were consolidated into three high-impact solutions i.e.

(i) Increased usage of **Refuse Derived Fuel** (RDF) from municipal solid waste for substituting thermal heating from coal.

(ii) Increased usage of **Supplementary Cementitious Materials / Clinker Substitutes**.

(iii) Scaling up **Carbon Capture, Utilisation and Storage** (CCUS) in the cement industry for capturing CO2 in process emission.

These solutions were selected for their scalability and potential for significant impact, even though their full benefits may only be realised in the long term. By using these three solutions, Indian cement sector may reduce 80-85% GHG emission by 2070.

Table 1: Evaluation of the Twenty-two Recommendations for Decarbonising the Cement Sector

<table>
<tr><th colspan="2">Group A</th><th>Group B</th><th>Group C</th><th colspan="2">Group D</th></tr>
<tr><td colspan="2">Solutions industries can implement independently</td><td>Economically viable solutions, which require regulatory support for implementation</td><td>Economically viable solutions, which require policy support from the government</td><td colspan="2">Deprioritised solutions</td></tr>
<tr><td rowspan="9">Economically viable energy efficient initiatives</td><td>1. Improve refractory materials</td><td>8. Transition from input-based standards to performance-based standards</td><td>13. Development of supply chains for green and alternative fuels</td><td>15. Public procurement to drive the usage of low carbon cement</td><td rowspan="5">Solutions deprioritised due to limited impact and/or low implementation feasibility.</td></tr>
<tr><td>2. Kiln Combustion Improvement Systems</td><td>9. Mapping of new clinker substitutes in India</td><td rowspan="8">14. Scaling of CCUS for the cement industry</td><td>16. 100% fly ash and pond ash generated in the country to be allocated to cement manufacturing</td></tr>
<tr><td>3. Efficient clinker coolers</td><td>10. Blending to increase adoption of alternatives to fly ash and slag</td><td>17. Implementation of polluter pays principle</td></tr>
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<tr><td rowspan="3">7. Heat rate reduction in captive power plants</td><td>20. Ban on the export of clinker substitutes, which have a high decarbonisation potential</td></tr>
<tr><td>21. Propagation of pre-cast structures for the efficient use of cement</td></tr>
<tr><td>22. Consideration of WHR as RE for the purpose of RPOs</td></tr>
</table>

Increased Usage of Refuse Derived Fuel (RDF) from Municipal Solid Waste (MSW)

The country generates approximately 62 Mt of MSW annually, a figure projected to rise to 165 Mt by 2031 and 436 Mt by 2050 (CMA 2021). This surge in waste generation is expected to strain the capacity of ULBs in collecting, transporting, treating and scientifically disposing of MSW. Table 2 summarises the findings and recommendations for increased usage of RDF from MSW as alternate fuel in cement sector.

Table 2: Increased use of RDF from Municipal Solid Waste (MSW)

Potential emission reduction through greater use of RDF from MSW in the cement sector	Increasing the use of RDF from MSW to achieve 20% thermal substitution rate by 2030 could result in a cumulative emission reduction of approximately 80 $MtCO_2e$ (10% reduction in energy emissions compared to BAU by 2030)[1].
Key challenges in using MSW for thermal substitution in the Indian cement sector	**Low calorific value and high ash content**: RDF from MSW has a low calorific value and high moisture content, which leads to inefficient kiln operations.
	Contaminants in RDF: The presence of sediment, stones, and glass in RDF can damage kiln equipment and reduce shredder lifespan.
	Inconsistent RDF supply: Supply disruptions caused by seasonal variability and short-term contracts limit the availability of RDF for cement plants.
	High infrastructure costs: Significant investment is required to develop specialised RDF handling and processing infrastructure at cement plants.
	Operational Issues: Low-quality RDF increases the use of energy consumption, necessitates the use of high-grade limestone, and causes odor and combustion challenges.
Interventions to scale up the use of RDF from MSW in the cement sector	**Run three to five pilots** in cities to replicate learnings from Indore and Goa on building municipal discipline**.**
	Selection of pilot cities: Prioritise cities within a 100-150 km radius of cement plants, with a focus on those with strong waste management infrastructure and substantial waste generation capacity.
	Stakeholder engagement and capacity building: Engage local governments, NGOs, and municipal workers through city profiling, workshops, and public awareness campaigns to ensure efficient waste segregation at the source.
	Long-term agreements: A PPP model based long-term agreement among ULBs and vendors/MSW collection & sorting groups, RDF producers and cement plants needs to be established through policy initiative by MoHUA. The agreement will not only ensure assured offtake of the RDF by cement plants but it will also ensure the continuous MSW supply to RDF producer. This type of the model will offset high capital investment costs for RDF production and reduce the RDF price for cement plants, making the thermal heating substitution by RDF technically & financially viable for cement plants.
	Transportation cost coverage: Ensure that ULBs may bear transportation and logistics costs for delivering RDF to cement plants in lieu of the disposing of the MSW of their area or provide free of cost land and charge zero royalty or free or revenue from RDF produce to offset the sorting of waste, transporting of the RDF and other miscellaneous cost incurred upon RDF producer.
	RDF standards and compliance: Establishment of the third-party audit authorised/licensed by BIS to ensure RDF quality, technical specifications (e.g., calorific value, moisture, and ash content) of RDF aligned with BIS norms. a Cement plants may have the right to reject option for non-compliant RDF shipments.

1 subject to feasibility studies and relevant technical standard

Project cost/ Investment	**It is estimated that the cost of the interventions can be approximately INR 4,100 crore,** which can eventually be offset through the implementation of user charges and fines for non-compliance.
Socio-economic benefits of scaling up the use of RDF from MSW India	Interventions to increase the use of RDF from MSW- thereby the thermal substitution rates- could lead to **additional capital investment of approximately INR 15,000 crore and generate employment of approximately 65,000 people.**

Increased Use of Supplementary Cementitious Materials/Clinker Substitutes in Cement Production

The Indian cement industry has pioneered the transition to green products by producing blended cement using alternative raw materials. The extent to which clinker can be substituted in the final cement product largely depends on the properties of the alternative raw material and the intended application of the cement. According to the International Energy Agency (IEA), displacing one tonne of clinker can save approximately 3.7 GJ of energy and avoid 0.83 tonnes of CO_2 emissions. India's clinker-to-cement ratio- approximately 67.5%- is already lower than global average of 77% and can be further reduced. SCMs /clinker substitutes are essential for decarbonising the cement sector, with the potential to reduce emissions by seven to fifteen percent by 2070[2]. Higher clinker content leads to higher limestone consumption and increased GHG emissions during cement production. However, regulatory challenges hinder broader adoption, as existing standards often impose strict compositional requirements limit the use of clinker substitutes. Addressing these challenges is essential for promoting the use of alternative materials in the cement industry. Currently, using clinker substitutes is economically viable, providing savings of approximately INR 1600/tCO2. Moreover, incorporating materials like calcined clay and bio-ash enhances effective waste management. The circular economy framework this supports can actively help in creating waste to wealth streams. Table 3 summarises the proposed interventions and their expected impact.

Table 3: Increased usage of Supplementary Cementitious/Materials Clinker Substitutes

Clinker substitutes are important for cement sector decarbonisation	Clinker substitutes can address 7-15%[2] of cement sector emissions by 2070
	Usage of clinker substitutes is **economically viable at present (saving of ~USD 20/tCO_2 i.e. ~INR 1,600/tCO_2).**
	Usage of Supplementary Cementitious Materials (SCM) like Hydraulic (granulated blast furnace slag) and pozzolanic (calcined clay) materials and bio-ash can **boost circular economy** and helps in **effective waste management.**
	Clinker to cement ratio in India **is approximately 67.5%** currently and it can go to **approximately 62%** if key bottlenecks are addressed.
Key bottlenecks in greater usage of clinker substitutes	**Limited availability**: Availability of major clinker substitutes like fly ash and slag will decline post 2050 due to phasing down of coal and BF-BOF steel.
	Regulatory bottlenecks: Existing standards may not adequately support widespread adoption of clinker substitutes due to specific prescribed composition of cements.

2 subject to feasibility studies and relevant technical standards

Proposed interventions	**The transition from inputs-based standards to performance-based standards** to allow for greater usage of blended cement while focusing on quality. It is recommended that BIS frame standard accordingly.
	Definition of standards for CSA (Calcium-Sulpho-Aluminate) cement to encourage adoption of low carbon CSA cement with clear guidelines for production and application. Also, other cement types such as Portland Limestone Cement (PLC), Hydraulic cement, and Increased fly ash to 40% (more than 35%) in blended cement can be considered [3]. It is recommended that BIS frame definition of standard accordingly.
	As the availability of major clinker substitutes like fly ash and slag will decline post 2050 due to expected phasing out of coal and BF-BOF steel plants, hence exploring calcined clay deposits in India, construction and demolition (C&D) wastes could also be used as potential blending component in cement manufacture (GCCA 2022). Ministry of Mine and GIS can undertake the exploration and allotment of the clay mines for production of the calcined clay material etc.
Expected Impact	Cumulative emission reduction of **approximately 25 MtCO_2e (approximately 10% lower emissions** compared to BAU) by 2030.
	Annual opex savings of **approximately 12-15%** for the cement industry.
Key risks to be considered	**High costs**: Limited uptake of CSA cement due to high cost driven by import of aluminium/bauxite. As a mitigation strategy, low-cost sources (e.g., through recycling of aluminium waste) may need to be discovered and scaled.
	Limited acceptance and high compliance cost of performance-based standards: Performance based standards are still under discussion in most countries; may suffer from higher compliance costs and lack of awareness of its advantages; successful implementation of these standards would require close collaboration with industry right from testing technologies to creating awareness.

Carbon Capture Utilisation and Storage (CCUS) Pilots for the Cement Sector

CCUS is emerging technology for decarbonising hard-to-abate and CO_2 intensive processes. For supporting CCUS technology and making CCUS project economically viable, Ministry of Power constituted an Inter-Ministerial Committee for drafting the CCUS Mission Document. Under the Mission, the intended target for the cement-sector is 2,000 TPD of capture (~0.67 MTPA) and 2,000 TPD of utilisation (building materials, carbonates, polycarbonates) for pilot projects, with integrated planning for transportation, storage and Enhanced Oil Recovery (EOR). The initial phase of implementation of CCUS in cement sector is expected to occur as part of the National CCUS Mission.

3 Other blended cements namely Portland Composite Cement (PPC) based on both fly ash and limestone, Portland Limestone Cement (PLC), Portland Dolomitic Limestone Cement (PDC), and multicomponent blended cements are at different stages of development in India - Blended Cement - Green, Durable & Sustainable 2022, GCCA

Table 4: CCUS pilots for the Cement Sector

CCUS and India's immediate priorities	CCUS is a key lever for the Decarbonisation of hard-to-abate sectors like cement (approximately 35 to 54% emissions).
	The key **pre-requisites** for CCS project are mapping of storage sites, land acquisition, development of transport infra, etc. which will require at least 5-10 years. Therefore, Carbon Capture and Utilisation (CCU) emerges the best options for Cement Sector as captured CO_2 may be utilised for preparing building material, which is an established and commercially viable technology.
	CCU can be a **valuable interim option** for sectors like cement (approximately 10% of cement sector emissions at point source can be addressed via utilisation in artificial limestone, carbon cured cement by 2050 (Mohd Hanifa et al. 2023).
	Demonstration and pilots are **critical for the eventual scaling** of carbon capture technologies and utilisation pathways.
Selection of Pilots	• **Feasibility assessment** by panel of experts based on **technical maturity, financial maturity, operational maturity and scalability.** • **Financial evaluation** based on technologies with the most cost-effective emission reduction potential, developing economic and business models, evaluating environmental and social impacts, creating CCUS regulations (NITI Aayog 2025).
Capture Technologies and utilisation pathways for pilot projects	**Selection** of projects can be agnostic of technologies and utilisation pathways **focusing on different capture technologies and utilisation pathways** to increase the likelihood of selecting the most effective options for **scaling of the most effective technologies.**
Government support required	**Government corpus** can be funded through a combination of **multilateral funds (e.g., Green Climate Fund), government budget, donor funds and green bonds.**
Expected impact of CCUS pilots	**CCUS pilots** can be used for **identifying the most scalable technologies** along with **the real cost of capture and quantum of support needed for scaling.**
Operating Model	**Government:** Provide financial support, expedite regulatory approvals, enforce verification, energy standards and lifecycle assessments.
	Developer(s): Secure land and infra, adopt low-carbon energy, ensure compliance and reporting, invest in proven technologies, and implement a risk management framework.
Proposed next steps for launching pilots	**National Mission on CCUS to** oversee the launch and implementation of pilots.
	Engage ministries, multilateral institutions and financial bodies to secure funding.
	Develop **selection criteria, financing mechanism, and guidelines** for pilot projects.
Key risks to be considered while implementation	**Economic viability:** Changes in the quantum of VGF, low impact from revenue streams.
	Regulatory Challenges: Permit issues, regulatory support gaps, and long lead times.
	Change in Strategy: Shifts in company priorities towards other projects.
	Others: Technical failures, operational and safety concerns, and socio-economic factors.

Chapter 01

INTRODUCTION

1 Introduction

1.1 Background

To drive inclusive and sustainable growth, the Government of India is expanding infrastructure and manufacturing to meet the evolving aspirations of its people while promoting environmental responsibility and long-term resilience. Recognising the critical role of industries in economic development, the government is also prioritising the decarbonisation of key sectors to reduce emissions, promote green innovation, and ensure a sustainable future. According to the Economic Survey 2023-2024, the industrial sector accounted for approximately 30.9% of India's GVA. In comparison, manufacturing accounts for 17.3%, construction 9.0% and energy and other supply utilities 4.5%. Key government initiatives, including Make-in-India, Housing for All, Smart Cities, Dedicated Freight Corridors and Ultra Mega Power Projects, are expected to increase energy consumption and create significant additional demand for steel and cement over the medium to long term. While rapid development is creating new opportunities, it also brings substantial social and environmental challenges. According to Emissions Gap Report 2024, India's emissions are relatively low at 2.9 tCO_2e/capita compared with 18 tCO_2e/capita for the United States and 11 tCO_2e/capita for China. However, it remains the world's third-largest emitter of GHGs, accounting for 4.14 $GtCO_2e$ in 2023, or eight percent of global emissions (UNEP 2024) driven by energy production, industrial activities, agriculture, and urbanisation. The energy sector contributed the most of the overall emissions with 75.81%, followed by the agriculture sector at 13.44%, IPPU by 8.41% and waste by 2.34% (MoEFCC, GoI 2024). In considering the adoption of low-carbon solutions for the industrial sector, it is essential to balance the need for substantial industrial growth with the country's minimal historical contribution to global emissions.

India's dedication to reducing GHGs and transitioning to a low-carbon economy is reflected in India's "Long-term Low-Carbon Development Strategy" as per Article 4, paragraph 19 of the Paris Agreement, which was submitted to the UNFCCC in November 2022 during the 27th Conference of Parties (COP27) at Sharm-El-Sheikh in Egypt (MoEFCC 2023). This strategy outlines a continued focus on adopting low-carbon technologies in industrial processes, enhancing energy and resource efficiency and promoting the use of natural and bio-based materials. It also highlights the critical role of innovation and sustainability, driving the transition to a circular economy to further reduce carbon footprint. The strategy encourages manufacturing to progressively embrace process and fuel switching, as well as electrification, where it is feasible. Furthermore, the strategy explores CO_2 removal technologies, with a particular focus on CCUS solutions. To facilitate the transition to a low-carbon industrial future, public-private partnership frameworks will be explored to address the significant resource requirements. Industrial decarbonisation is essential for reducing emissions, driving sustainable economic growth and ensuring long-term environmental resilience. Achieving this transition at scale will require substantial climate finance, technology transfer and strong international collaboration. These efforts will enable the widespread adoption of clean technologies, improve energy efficiency and support the implementation of carbon reduction solutions across industries, ensuring a sustainable and low-carbon future for India.

To develop a comprehensive decarbonisation roadmap for the cement industry, a technical working committee (Annexure 1) was established. The committee's objectives include identifying emission sources across the cement production value chain and establishing baseline sectoral emissions, analysing existing government and private sector strategies and assessing international market trends to evaluate the sector's competitiveness. The committee was also tasked to identify key projects, policy and regulatory frameworks, and technological interventions, coupled with an evaluation of commercial viability.

1.2 Scope and Objective

The report focuses on developing a robust framework for identifying and prioritising high-impact solutions to decarbonise the cement sector, which is one of the most energy-intensive industries globally. Recognising the significant role the cement industry plays in carbon emissions, the report sets out to explore practical, scalable, and effective strategies to reduce the sector's carbon footprint.

The report begins by presenting a comprehensive framework for evaluating and prioritising solutions based on their potential impact, feasibility, and alignment with long-term sustainability goals. This framework is designed to guide decision-makers and industry stakeholders in focusing efforts on the most promising and transformative solutions that can drive meaningful progress toward decarbonisation.

The report conducts an in-depth analysis of the prioritised solutions, providing insights into their technical and economic viability, implementation challenges, and potential benefits. Three high impact solutions are examined in greater detail:

1.2.1 **Increased usage of Refuse Derived Fuel (RDF) from Municipal Solid Waste (MSW)**: The utilisation of RDF from MSW in cement manufacturing presents a sustainable solution to two critical challenges: waste management and the reduction of carbon emissions. In cement production, MSW is co-processed in clinker kilns, serving as an alternative fuel and raw material. This practice not only minimises the volume of waste sent to landfills but also reduces the reliance on conventional fossil fuels such as coal and natural gas, thereby lowering the carbon footprint of the industry. Additionally, integrating MSW into the cement manufacturing process aligns with circular economy principles, transforming waste into a valuable resource while enhancing the overall environmental performance and resource efficiency of the sector.

1.2.2 **Increased usage of supplementary cementitious materials /clinker substitutes:** The production of clinker, a key ingredient in cement, is responsible for a large share of the industry's carbon emissions. By increasing the use of clinker substitutes-such as fly ash, slag and other materials-cement producers can lower their carbon intensity while maintaining product quality. The report examines the technical considerations and market potential for scaling this solution.

1.2.3 **CCUS Pilots for the Cement Sector**: CCUS is identified as a critical technology for reducing emissions in cement production. The report explores how CCUS can be integrated into the cement production process to capture and either store or repurpose carbon emissions, thereby contributing to significant reductions in greenhouse gases.

The report goes into detail in these solutions, assesses the current state of the cement industry's decarbonisation efforts, provides recommendations for future courses of action. By highlighting key areas for innovation and policy intervention, the report aims to facilitate the transition towards a more sustainable and low-carbon cement industry.

1.3 Methodology

This study is based on stakeholder consultations, data analysis and field visits. More than 20 consultations were held with key stakeholders. These included international experts on cement decarbonisation, the Bureau of Energy Efficiency (BEE), and industry bodies such as the Global Cement and Concrete Association (GCCA) India and the Cement Manufacturers' Association (CMA). The discussions focused on practical ways to cut emissions in the cement sector and on agreeing upon which options are both effective and feasible.

The work also uses information from more than 30 national and international data sources. These include datasets and reports from the World Economic Forum (WEF), the World Business Council for Sustainable Development (WBCSD), the Council on Energy, Environment and Water (CEEW), RMI, the Shakti Sustainable Energy Foundation and the Confederation of Indian Industry (CII). A visit to the Indore Municipal Corporation and the Indore material recovery facility provided first-hand observations on how municipal solid waste (MSW) can be used in practice to support decarbonisation in the cement sector.

In addition, the study reviews published work from peer-reviewed journals and technical reports. Combining these sources helps to describe the current state of decarbonisation in the sector and to identify options for further action.

Chapter 02

CEMENT INDUSTRY AT A GLANCE

2. Cement industry at a glance

2.1 Background

The cement industry is central to construction and infrastructure. It supplies material for buildings, roads and many other structures that support urbanisation, industry and economic activity. At the same time, cement production is energy-intensive. In India, the sector emitted about 196 $MtCO_2e$ in 2020 (NITI Aayog 2022) making it a major source of greenhouse gases. As sustainability has become a stronger concern for government and business, the sector is expected to reduce emissions while still meeting demand for cement. The challenge is to meet demand for cement while keeping environmental impacts under control.

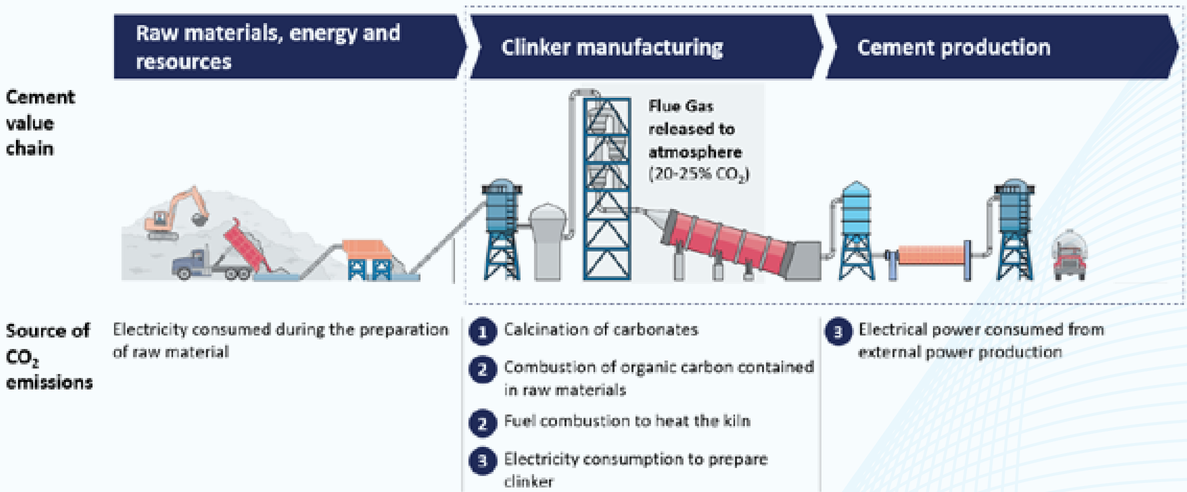
Cement is a fine powder made from limestone, clays, shells, silica sand and other materials. These are heated together to about 1,500°C in a controlled process. Cement has hydraulic binding properties: when it is mixed with water, it forms a paste that hardens and keeps its strength after setting. For this reason, cement is a basic binding material in construction. In mortar, it is mixed with fine aggregates for masonry work. In concrete, it is mixed with aggregates (sand, gravel and other materials) and water to form a composite building material. Concrete is the most widely used construction material in the world. Different types of cement are produced by changing the calcium source and the additives used.

2.2 Cement Manufacturing Process

The cement manufacturing process, as shown in Figure 2.1, begins with the extraction of limestone, the primary raw material for cement production. Limestone is mined from open-cast quarries through drilling and blasting. Once excavated, it is loaded onto dump trucks, which transport the material to limestone crushers for processing. Additional raw materials such as sand, coal, and pet coke are sourced externally and integrated into the process. The raw materials are initially crushed in the primary crushing unit and then transferred to the secondary crushing unit, where they are combined with additives to further reduce their size. The resulting raw mix is transported to a circular storage unit known as the raw mix storage. From there, reclaimers retrieve the mix from the stockpile and convey it to the raw mix bin for grinding. High-purity limestone and coal/pet coke typically have separate crushing and storage systems, while other additives, such as sand, are processed using a shared or common crushing system.

The process of drying, grinding, and homogenising the raw meal begins with blending additives like iron ore or red mud with limestone using a weigh feeder to achieve the desired composition and properties. The raw mill, consisting of a drying chamber and a grinding chamber separated by a diaphragm, is used to process the materials. Hot flue gas from the preheater or kiln system is used for drying, after which the materials enter the grinding chamber for fine grinding. The grinding can be done using a conventional ball mill or an advanced Vertical Roller Mill (VRM). The ground material, along with hot gas, is fed into a separator that distinguishes between fine and coarse products, with the coarse material being returned to the grinding unit. Fine material and gases pass through a cyclone unit for further separation. Fine material is collected in a multi-cyclone unit, while ultra-fine particles carried by flue gas are captured in an ESP. The dust collected in the ESP is mixed with the fine material via screw conveyors. Finally, the raw meal or kiln feed is stored in a blending silo for homogenisation before being fed to the preheater for pyro processing. The process route for different types of cement production is almost similar except for the final blending and grinding process steps.

Figure 2.1: Cement Manufacturing Process



Source: McKinsey & Company

2.2.1 **Clinker Manufacturing:** Clinker is produced through the pyro processing of kiln feed in a preheater-kiln system. This system typically includes a multi-stage cyclone preheater (usually more than five stages), a combustion chamber, riser duct, rotary kiln, and grate cooler. In the preheater section, heat transfer efficiency is influenced by the number of preheater stages. Coal is also burned to meet the additional heat requirements. The preheater plays a crucial role in removing moisture from the feed while increasing its temperature through counter-current heat exchange with the hot flue gas (NITI Aayog 2022).

- The preheated kiln feed undergoes partial calcination in the combustion chamber and riser duct and then completes calcination in the rotary kiln, where it is heated to around 1400-1500°C to form clinker components. Coal, supplied through a burner, serves as the primary heat source for this process, although alternative fuels such as biomass and other solid wastes are also used. The hot clinker is then discharged into the grate cooler, where it is cooled from 1350-1450°C to approximately 1200°C using atmospheric air. After cooling, the clinker is transported to storage hoppers. To produce cement, the cooled clinker is finely ground and mixed with gypsum, limestone, and other potential additives in precise proportions, as specified by standards, to create the final cement product (NITI Aayog 2022).

2.2.2 **Cement production:** Approximately four to five percent gypsum is added to clinker to regulate the setting time of the final cement. The cooled clinker and gypsum mixture is then ground into a grey powder known as OPC or, when combined with other mineral components, used to produce variants like PCC.

While traditional ball mills were commonly used for grinding, modern plants increasingly adopt more efficient technologies such as roller presses, vertical mills, or their combinations.

- **Blending:** Cement can be further mixed with finely ground materials like slag, fly ash, limestone, or other mineral additives to partially replace clinker, significantly reducing CO_2 emissions.
- **Storage:** The finished cement is homogenised and stored in silos before being dispatched either to a packing station for bagged cement or to a silo for bulk transport by road, rail, or water.

The Indian cement industry's product profile has changed significantly over the years to include more blended cement in the mix. This implies that the industry has consciously shifted to high quality and low-carbon production, enhanced by material use that promotes circular economy. For example, fly ash a by-product of burning pulverised coal in a coal-fueled power plant, is used in some cement plants as a raw mix component, while in most cases, it is added to cement to produce Portland Pozzolana Cement (PPC). Approximately 25% of the total fly ash generated is utilised by the cement industry promoting circular economy. However, around 33% remains unutilised due to geographical imbalances and the limitation of incorporating a maximum of 35% fly ash in PPC (CEA, MoP 2020).

2.3 Energy Consumption and Fuel Use in Cement Production

In 2022, the cement sector was the third-largest industrial energy consumer globally, following the chemical and iron and steel industries, with an energy consumption of 12 EJ (3,333 TWh), accounting for 7.18% of global industrial energy use (IEA 2023). The core process of cement production has remained largely unchanged, involving the heating of limestone to temperatures as high as 1450°C.

Cement production requires both electrical and thermal energy, with total energy consumption per tonne of cement ranging from 3.32 GJ to 3.38 GJ (922 kWh to 939 kWh) as of 2024. Thermal energy accounts for over 90% of this, with around 731 kcal/kg of clinker (860 kWh/ton) being used. In comparison, electricity consumption ranges from 65.9 kWh to 83 kWh per tonne of cement (JMK 2024). Energy consumption is projected to decline to about 2.89 GJ per tonne by 2030 and around 2.49 GJ per tonne by 2047 (CMA).

In India, coal and pet coke are the primary sources of energy used in the cement manufacturing process with approximately 97% of the total fuel derived from coal and pet coke, 1% from oil, and 2% from electricity. The average SEC in Indian cement plants stands at 731 kcal/kg clinker (thermal) and 73 kWh/tonne cement (electrical). In contrast, the global cement sector's specific thermal energy consumption is 13% higher than India's average, i.e., 827 kcal/kg clinker and specific electricity consumption is 42% higher i.e., 102 kWh/tonne of cement (JMK 2024). The specific fuel energy demand of clinker burning (as a global weighted yearly average) may decrease from 827 kcal/kg clinker in 2019 to a range of 788-812 kcal/kg Clinker in 2030 (CII 2023).

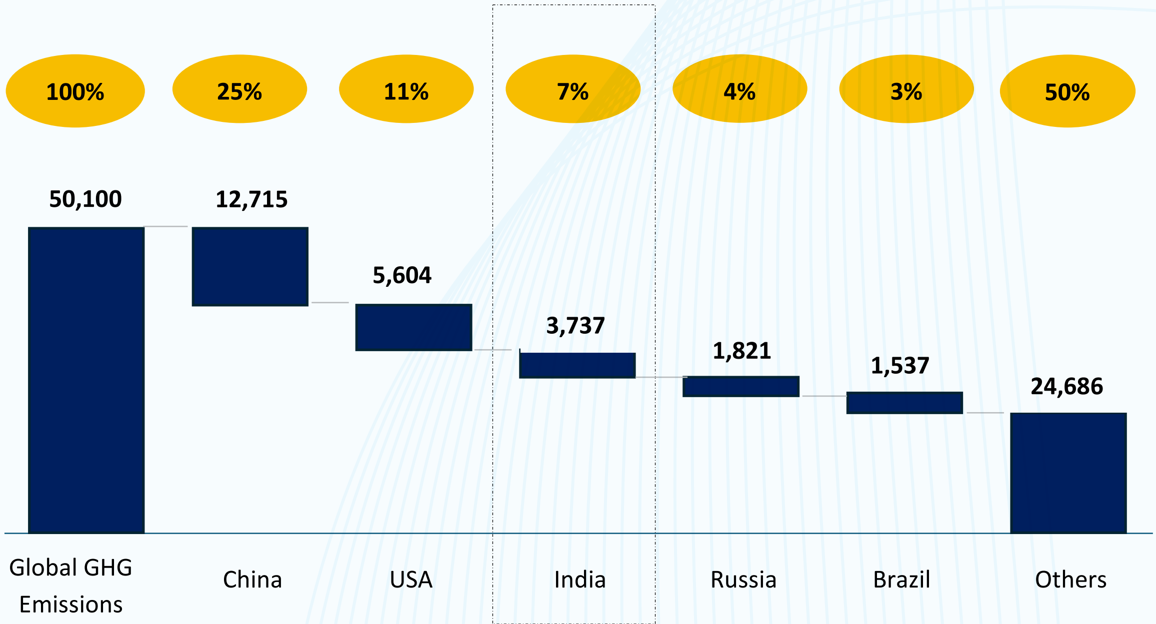
Indian cement plants demonstrate energy efficiency comparable to global counterparts. This can be attributed to the adoption of technologies such as high-efficiency kilns with preheaters and pre-calciners, which help reduce SEC in cement production. A significant portion of the existing cement production capacity in India was commissioned since 2005 and has therefore implemented energy-efficient manufacturing systems (CEEW 2023). Nearly 99% of cement plants in India have transitioned to energy-efficient dry kiln technology, opting for it over the relatively less efficient wet kiln technology. In India, a large share of cement production is in the form of blended cements, which use less clinker than in many other regions. Even so, most of the energy used in cement manufacture still comes from fossil fuels, mainly coal and pet coke, and this adds a lot to the country's CO_2 emissions. On top of that, there are process emissions from the decomposition of limestone in the kiln, and these occur no matter what fuel or energy source is used.

2.4 Green House Gas Emissions

2.4.1 Global Greenhouse Gas Emissions

Global GHG emissions reached a record high of approximately 50,100 $MtCO_2e$ in 2022, as shown in Figure 2.2, marking a 1.3% increase (700 $MtCO_2e$) compared to the previous year. This growth rate exceeds the average annual increase of 0.8% observed in the decade before the COVID-19 pandemic (2010–2019). Atmospheric CO_2 concentrations continue to rise and will persist until annual CO_2 emissions are sufficiently reduced to balance removals (net zero). Fossil CO_2 emissions, which account for approximately 68% of total GHG emissions, are primarily driven by combustion of coal, oil, and gas in the energy sector and by industrial processes such as cement and metal production. The six largest global emitters are China, the United States, India, the European Union, Russia and Brazil (UNEP 2024).

Figure 2.2: Global GHG Emissions in 2022



(Million tons of CO_2e; Source: BUR 2024[4], Climate watch)

4 The BUR report provides data for 2020. We have provided the latest available information, i.e., 2022 data. The referenced sources are largely aligned with the BUR data, with less than ~1% variation. Memo items are also included in this graph.

2.4.2 India's Greenhouse Gas emissions

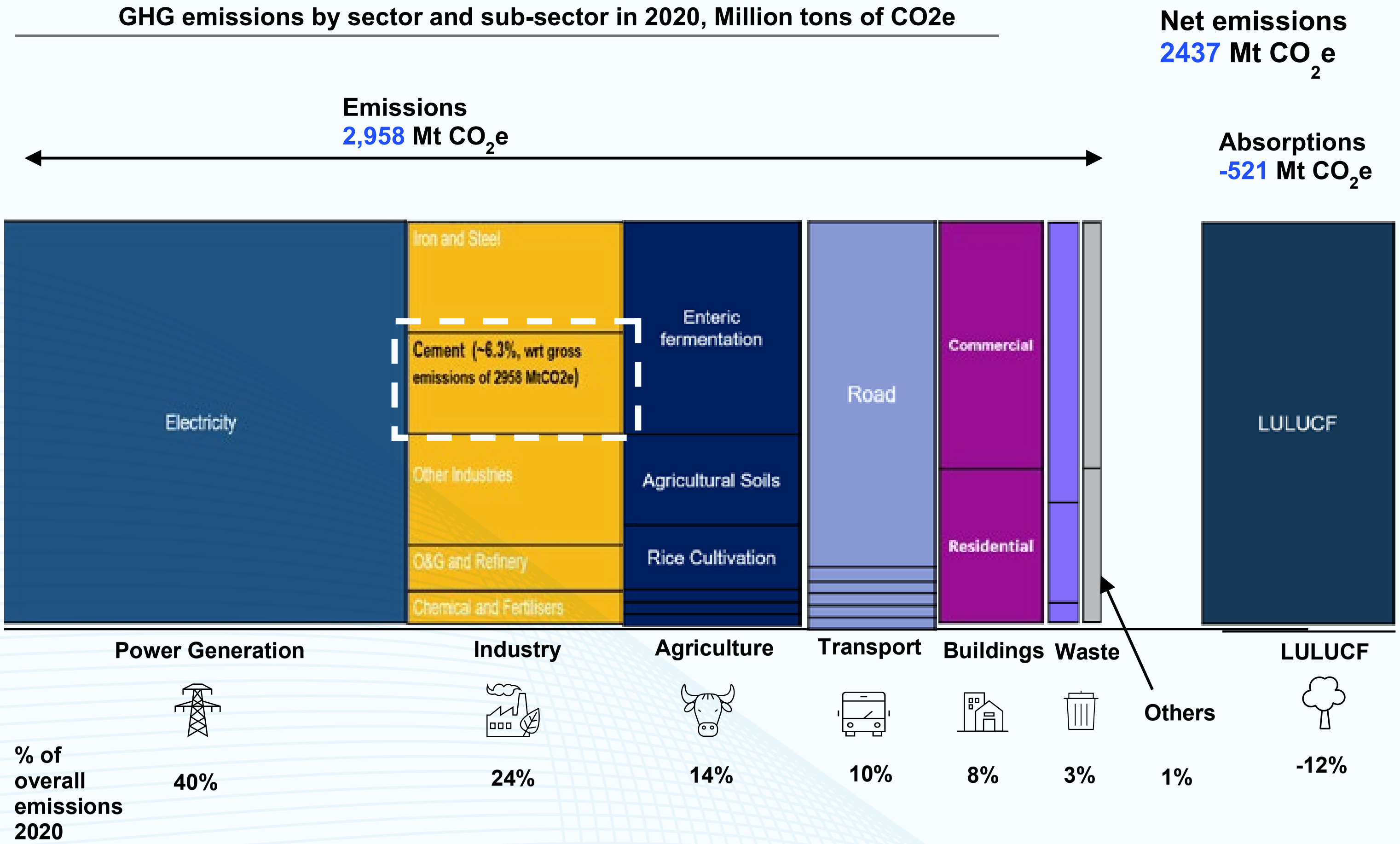
As shown in Figure 2.3, in 2021, India's total GHG emissions amounted to 2,958 $MtCO_2e$, with LULUCF contributing to a net absorption of approximately 521 $MtCO_2e$. This resulted in net emissions of 2,437 $MtCO_2e$. Among other sectors, power generation was the largest contributor, accounting for about 40% of total emissions. The industrial sector followed closely, contributing 24%. The cement sector contributes around 6% of India's total GHG emission.

2.4.3 Global Cement Sector Emissions

Global carbon emissions from cement production currently stand at approximately 2.4 $GtCO_2e$ per year, accounting for about 6% of global energy system emissions. Under a BAU scenario, emissions could be 2.3 $GtCO_2$ annually by 2050. This increase is expected to be driven by growing global cement demand, particularly in regions where energy needs will compete with decarbonisation efforts. Current fuel sources include coal (which varies in quality and carbon intensity by region), petroleum coke, and various forms of waste. Globally, coal accounts for 66% of cement production fuel, with usage ranging from over 86% in China to less than 25% in the EU (Mission Possible, 2018). Cement production in China accounts for the largest share of global carbon dioxide emissions. In 2022, the cement industry in China discharged 763 $MtCO_2e$ into the atmosphere, a quantity approximately three times greater than India's emissions.

Cement manufacture uses a lot of energy, and different steps in the process release CO_2 and other greenhouse gases. The largest share of CO_2 comes from the conversion of limestone to lime in the kiln (calcination). This process is mainly heated by fossil fuels, especially coal and pet coke, and fuel use for calcination accounts for about 57–60% of total emissions. A further 10–13% of emissions comes from electricity use, either drawn from the grid or supplied by mainly thermal captive power plants (CPPs). Another 27–31% is linked to thermal energy used for process heating. Emissions from limestone mining are small in comparison, at around 1–2% of the total. Scope 3 emissions in the cement sector originate from activities across the entire value chain, including capital goods, purchased goods and services, energy-related activities and transportation or distribution. These emissions are influenced by factors such as fuel type, procurement practices, and the extent of transportation involved. However, due to the nature of processes within the cement industry, most of its emissions fall under Scope 1 and Scope 2. The relevance of Scope 3 emissions depends on the specific activities and operations of individual cement companies (WBCSD 2016).

Figure 2.3: India GHG Emissions



1. Non-CO_2 emissions are converted into carbon dioxide equivalents according to their 100-year global warming potential (GWP100)
2. Memo items (not accounted in total emissions) amount to 802 Mt CO□

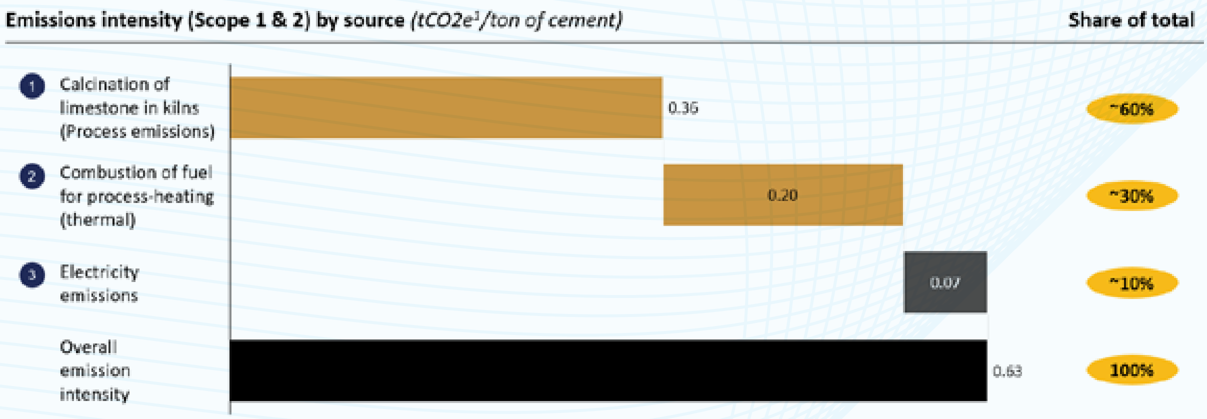
($MtCO_2e$; Source: BUR 2024[5], Climate Watch)

5 The BUR report provides data for 2020. We have provided the latest available information, i.e., 2022 data. The referenced sources are largely aligned with the BUR data, with less than ~1% variation. Memo items are also included in this graph.

2.4.4 India's Cement Sector Emissions

The Indian cement industry has made significant progress in reducing its GHG emissions. As shown in Figure 2.4, the overall emission intensity was 0.63 tCO_2e per tonne of cement and total emissions in 2023 was approximately 246 $MtCO_2e$ corresponding to cement production of 391 Mt.

Figure 2.4: Emission Intensity of Cement Manufacturing



Note: 1. tCO_2e: tons of CO_2 equivalent

Source: Third National Communication and Initial Adaptation Communication to UNFCCC, 2019,: https://pib.gov.in/PressReleasePage.aspx?PRID=2004762, Emissions intensity based on Evaluating Net-zero for the Indian Cement Industry, CEEW (2023)

CMA website - Indian Cement Sector – A Hallmark of Energy Efficient Operations: Clinker to cement ratio = 69.5% in 2021 (https://www.cmaindia.org/indian-cement-sector-hallmark-of-energy-efficient-operations) CIDC website - Decarbonisation in Concrete Industry – Opportunities & Challenges: : Clinker to cement ratio = 65% in 2023 (https://www.cidc.in/support/ICM%202023/Cement.pdf)

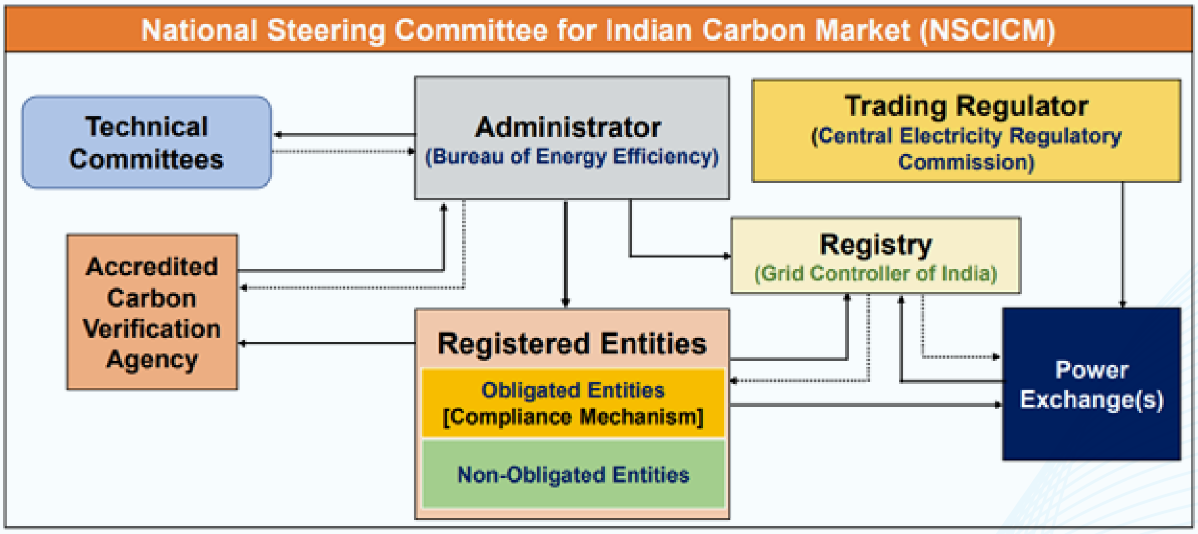
2.5 Carbon Credit Trading System

Carbon markets aim to reduce GHG emissions by enabling the trading of emission units (carbon credits), which are certificates representing emission reductions. By putting a price on carbon emissions, carbon market mechanisms raise awareness of the environmental and social costs of carbon pollution, encouraging investors and consumers to choose lower-carbon paths. There are two main categories of carbon markets: cap-and-trade and voluntary. Cap-and-trade sets a mandatory limit (cap) on GHG emissions and organisations that exceed these limits can purchase excess allowances to fill the gap or pay a fine. Voluntary markets enable the trading of carbon credits outside of the regulatory environment[6].

To establish a robust carbon market in India, key amendments were made to the Energy Conservation Act, 2001, through the Energy Conservation Amendment Act, 2022. This empowered the BEE, to specify a CCTS. As a result, the CCTS was officially notified in June and December 2023. The CCTS is designed to help India meet its climate commitments under the UNFCCC and the Paris Agreement by creating a framework for trading carbon credit certificates, thereby pricing GHG emissions and incentivising decarbonisation across the economy. The BEE has also developed a MRV framework to ensure transparency and credibility, including annual verification of emissions data and accreditation of Carbon Verification Agencies. Figure 2.5 illustrates the National Steering Committee for the Indian Carbon Market.

6 National Indian Carbon Coalition

Figure 2.5: National Steering Committee for Indian Carbon Market



Source: BEE, CII

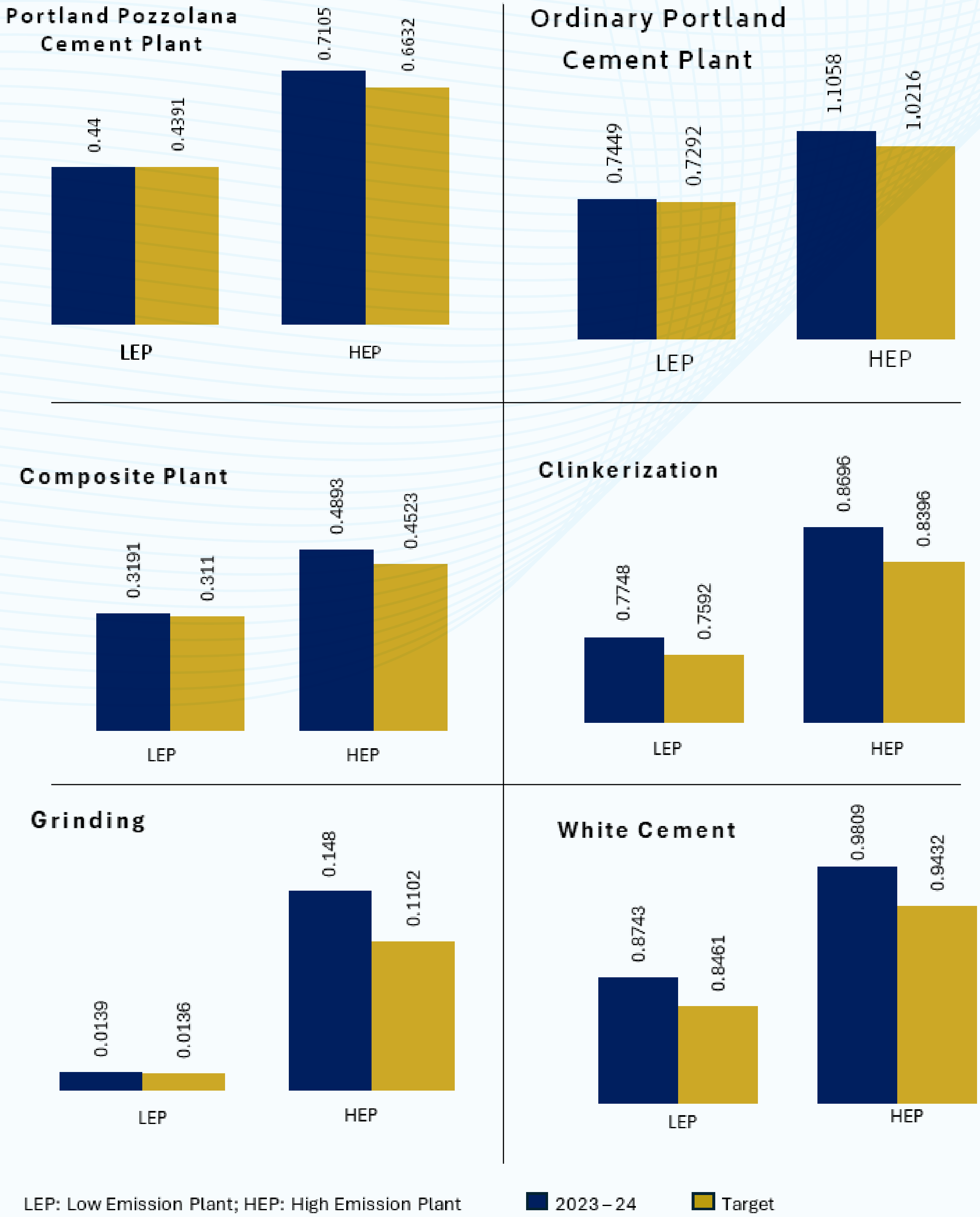
The CCTS operates through two mechanisms as shown in Table 2.1, a compliance mechanism, where obligated entities must meet prescribed GHG emission intensity reduction targets and can earn carbon credits for exceeding these targets; and an offset mechanism, where non-obligated entities can register projects that reduce, remove, or avoid emissions to earn credits. The transition from the Perform, Achieve, and Trade (PAT) scheme to the CCTS is being managed to ensure alignment with national climate goals.

Table 2.1: CCTS Compliance Mechanism

Key aspects	Compliance mechanism	Offset mechanism
Nature	Mandatory	Voluntary
Entities involved	Large-scale emission emitters	Corporations/companies/nonprofits/society (No restriction on size or scale)
Level of implementation	Facility level	Project level
Usage of credit	To meet legally binding emission reduction targets	Crucial criterion, reduction must be beyond baseline scenario
Additionality	Less or no emphasis, primary focus is to meet the targets	Broad and diverse (sector scope based on emission source/reduction)
Scope	Sector Specific, targeting obligated entities (designated consumers)	Broad and diverse (sector scope based on emission source/reduction)
Boundary consideration	Gate-to-gate boundary	Project boundary (but outside boundary of obligated entity under compliance)
Credit issuance	Against the targets (only on overachievement of targets)	Against the baseline and baseline are based on methodology

In April 2025, the MoEFCC, released the Greenhouse Gases Emission Intensity Target Rules (Draft, 2025) as part of the forthcoming compliance carbon market. For the cement sector, 186 entities are covered with a targeted reduction of 3.62% i.e. 264 $MtCO_2e$ emission reduction potential. The baseline year is set as FY 2023–24, while the compliance periods are FY 2025–26 and FY 2026–27, with the GEI reduction targets distributed in a 40:60 ratio with an average reduction goal of 3% over 2 years for these units (MoEFCC, GoI 2025).

The following charts illustrate sample emission intensity targets for plants with the lowest and highest emission intensities in their respective categories, showcasing both LEP and HEP benchmarks.



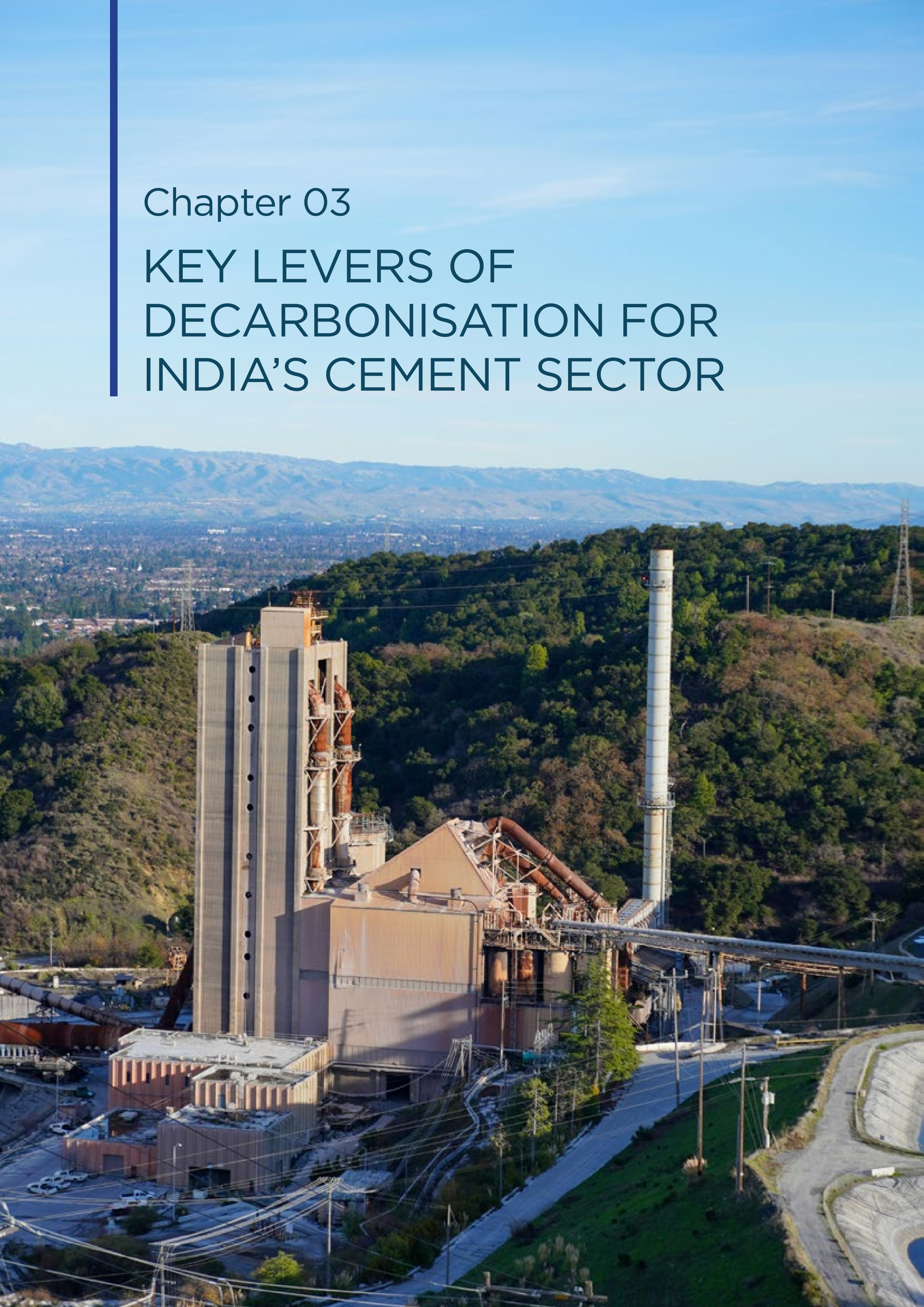
LEP: Low Emission Plant; HEP: High Emission Plant
Source: BEE

The CCTS inherently supports cement industries in manufacturing low-carbon cement by setting clear emission-intensity targets and creating financial incentives for emission reductions. By assigning specific reduction goals, the scheme encourages all facilities-regardless of their starting point-to improve their performance. Plants that achieve or exceed their targets can earn carbon credits, which can be traded for additional revenue or used to offset their own emissions, making investments in cleaner technologies and processes more attractive.

This market-based approach not only motivates continuous improvement but also helps cement manufacturers balance industrial growth with climate commitments. By rewarding early adopters and efficient plants, while also pushing higher-emitting units to catch up, the CCTS drives sector-wide progress toward lower carbon intensity. Over time, this leads to the widespread adoption of best practices, energy efficiency measures, alternate fuels, and innovative production methods, all of which are essential for producing low-carbon cement and supporting India’s broader decarbonisation goals.

Chapter 03

KEY LEVERS OF DECARBONISATION FOR INDIA'S CEMENT SECTOR

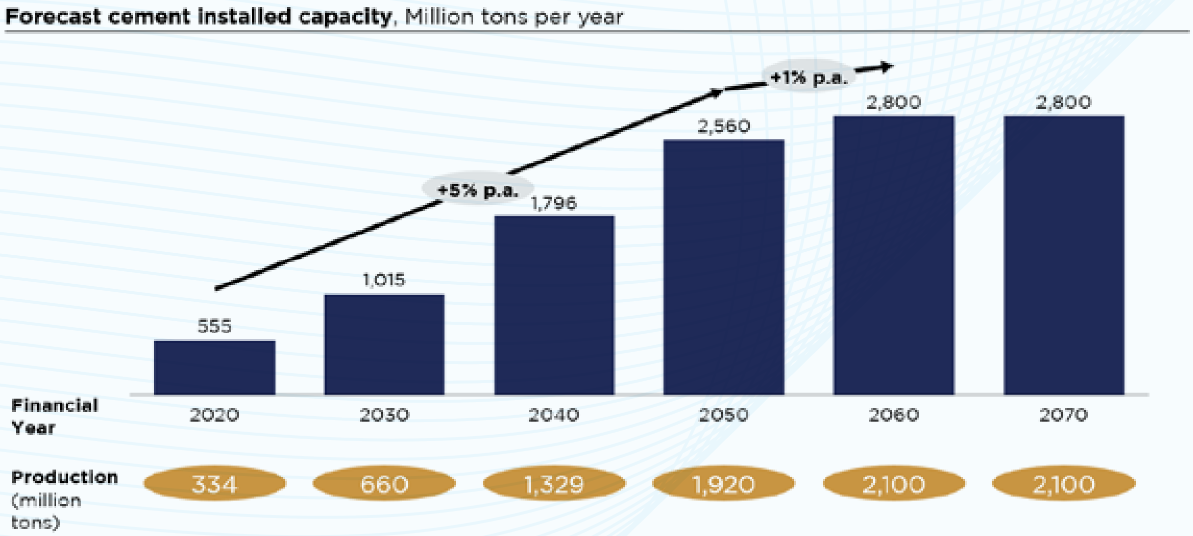


3. Key Levers of Decarbonisation for India's Cement Sector

3.1 Projections of India's Cement Production and Installed Capacity

India's cement production is projected to rise nearly sevenfold, from 334 Mt per year in 2020 to 2,100 Mt by 2070. Figure 3.1 illustrates the forecast for cement installed and production capacity in Mt per year through 2070, presented at decadal intervals[7].

Figure 3.1: Projections of India's Cement Production and Installed Capacity



** All data are approximations*

Source: Projections are drawn from the Cement Manufacturers' Association (CMA). While CMA factors in GDP growth, infrastructure investment, and other real-world demand drivers, its modelling approach differs from NITI Aayog's macro-economic scenarios; the two sets of numbers are therefore not directly comparable

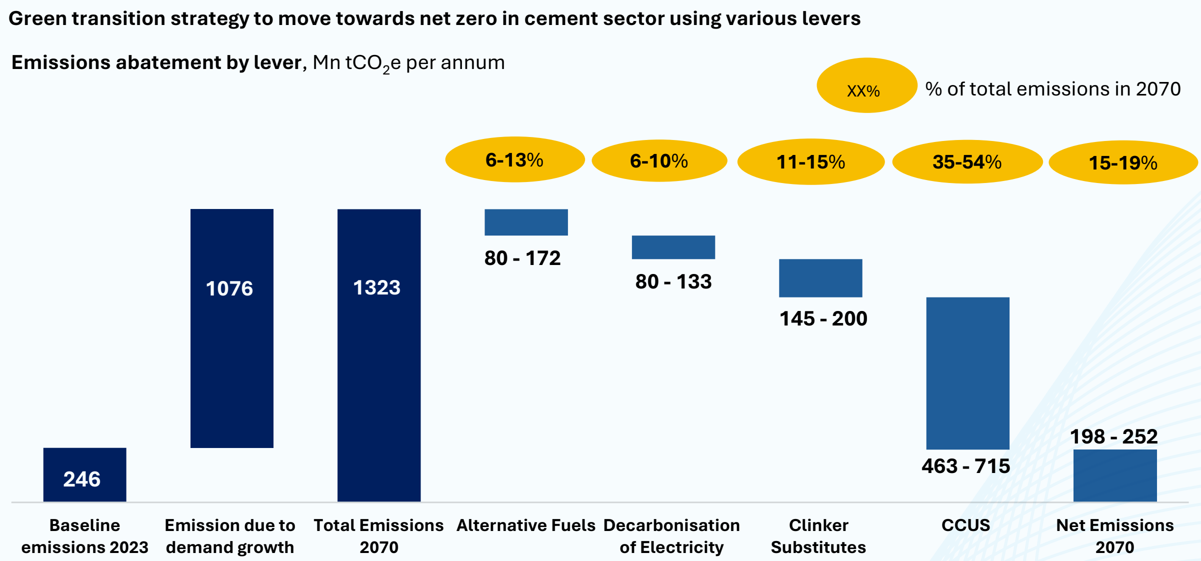
The cement production and installed capacity show a steady upward trend reflecting consistent growth in the sector. In 2024, approximately 427 Mt of cement was produced, with production projected to reach 660 Mt by 2030 and 1750 Mt by 2047, continuing to rise by 30 to 70 Mt per decade. A notable increase is expected until 2050, with production reaching around 1,920 Mt. Following this period, production growth is anticipated to slow and plateau at approximately 2,100 Mt by 2070. This trend suggests that while the cement industry has seen significant growth, it may be nearing the limit of its rapid expansion. Therefore, focusing on sustainability and decarbonisation strategies will be essential to meet future demand while reducing environmental impacts.

Figure 3.2 illustrates a green transition strategy for the cement sector, outlining various levers to achieve net-zero emissions. Emissions are projected to increase from 246 $MtCO_2e$ in 2023 to 1,323 $MtCO_2e$ by 2070 due to demand growth. However, through the implementation of key levers such as alternative fuels (AF),

7 Based on the Installed Cement Capacity data from the IBM Indian Minerals Yearbook 2018, the 2018-19 to 2024-25 data from the Survey of Cement Industry and Directory 2019, along with the IBM Indian Minerals Yearbooks, annual reports, company websites, and media reports accessed on 2 February 2025. Additionally, data from the Monthly Press Release on the Index of Eight Core Industries (available at https://eaindustry.nic.in/) as published by the Office of the Economic Advisor, DPIIT, was also referenced, with access on 2 February 2025. Production figures after June 2021 have been calculated based on the month-on-month growth percentage data published by the Office of the Economic Advisor, DPIIT.

decarbonisation of electricity, clinker substitutes and CCUS, emissions are expected to be reduced to approximately 198–252 $MtCO_2e$ by 2070.

Figure 3.2: Key Levers of Decarbonisation



Source: Based on Data from WBCSD Reports, IBEF, Powerline, CEEW

[Note: The emergence of new technologies such as green hydrogen and kiln electrification presents transformative opportunities for emission reduction in the cement industry by eliminating emissions associated with fuel combustion such as carbon-intensive stages of cement manufacturing. In addition to adopting new technologies and scaling up various decarbonisation measures, the remaining emissions can be addressed through the creation of carbon sinks, afforestation initiatives, and similar efforts, further advancing the cement industry's journey toward net-zero emissions]

Adoption of green alternative fuels can reduce emissions by 6-13%, equivalent to approximately 80-172 $MtCO_2e$, while the decarbonisation of electricity through RE[8] integration and waste heat recovery can contribute an additional reduction of 6-10%. Furthermore, adopting clinker substitutes may lead to an 11-15% reduction, cutting emissions by 145–200 $MtCO_2e$. The most significant impact, however, comes from the implementation of CCUS, which has the potential to reduce emissions by 35-54%. Additionally, the commercialisation of new technologies- including kiln electrification, solar fuels, more efficient clinker production, and accounting for natural recarbonation- could help the cement sector progress toward net-zero emissions.

While key levers such as CCUS, Alternate Fuels, Decarbonisation of electricity, and clinker substitution are expected to drive significant emission reductions, residual emissions by 2070 may persist. These remaining emissions could be addressed through new technology development and developing carbon sink such as afforestation, soil carbon enhancement, and wetland restoration. Lean Design Principles such as pre-cast structures, waste reduction, optimised concrete mix designs, and sustainable building practices will also support to reduce residual

8 To achieve 100% renewable energy (RE) electrical power, it is recommended that a dedicated banking policy tailored specifically for the Cement sector is required. The policy should also enable the storage of surplus RE generated during the peak production period into the grid, which can be accessed when renewable energy generation decreases or ceases. Collaboration between different departments and ministries is necessary to address the existing challenges and make provisions for transition towards 100% Renewable energy.

emissions. Nature-based solutions represent a critical area for further evaluation and integration into long-term decarbonisation strategies.

Table 3.1 outlines key model assumptions for the 2070 scenario, which include the full adoption of green and alternate fuels to meet 100 percent of thermal energy demand, with 30% from green fuels and 70% from alternate sources, supported by efficient supply chains for agricultural waste and RDF, alongside the commercialisation of emerging technologies such as algae-based biofuels. The use of clinker substitutes is expected to increase by 1.5 to 2 times by 2070, driven by advancements in recycling systems and a reliable supply of alternative materials. It is assumed that up to 90% of process emissions will be mitigated through CCUS, supported by advanced carbon storage infrastructure and scalable capture technologies. Approximately 50-60% of electricity demand is projected to be replaced by RE RTC power, with an annual availability of 70-80% through an open-access network. The remaining electricity demand will be met through EE improvements (15-20%) and waste heat recovery systems (25-30%). Additionally, establishing net-zero industrial clusters-where cement plants share renewable power infrastructure-can further optimise energy use and accelerate decarbonisation.

Table 3.1: Key model assumptions for driving decarbonisation by 2070

Levers	2070 Scenario
Alternate fuels	100% of thermal energy demand met by alternate fuels, driven by efficient supply chains for agricultural waste and RDF*, and by the commercialisation of nascent technologies such as algae-based biofuels Scaling of kiln electrification, solar-thermal and GH2 based technologies can further support increase in thermal substitution
Supplementary Cementitious materials/ Clinker substitution	Use of clinker substitutes rises by approximately 1.5 to 2 times by 2070 driven by Efficient systems for collecting and processing construction and demolition waste Ensuring steady supply of other clinker substitutes like calcined clay, pozzolana, and bio-ash R&D investments for developing low-clinker cement
Carbon capture utilisation and storage	Up to approximately 90% of process emissions abated through CCUS Driven by robust carbon storage and transport infrastructure, commercialisation and scaling up of capture (e.g, amine scrubbing, membrane absorption, etc.) and utilisation pathways (e.g, methanol production etc.)
Renewable electricity usage	Approximately 50-60% of the electricity demand would need to be replaced with Renewable Energy Round the Clock (RE RTC) power with annual availability of 70-80% through open-access network. Of the balance electricity demand, 15-20% could be reduced through EE and 25-30% could be supplied by electricity generated through WHR

*Alternate fuels such as MSW contribute to gross emissions but not to net emissions. However, they can help solve the problems of waste management, reduced consumption of fossil fuels and reduction in GHG emissions associated with landfill decomposition, CEEW

3.2 Marginal Abatement Cost Curve (MACC)

Figure 3.3 represents the MACC for the 2070 emissions. MACC analysis shows most levers become economical once enabling measures unlock scale, thereby preserving industry competitiveness. The clinker substitutes lever will have negative abatement costs, indicating savings from adopting these technologies. Other levers including renewable energy, alternative fuels, energy efficiency solutions and CCUS will have positive abatement costs, with CCUS being the highest. It should be noted that this analysis is based on a few assumptions including:

(i) Range of landed cost per tonne of clinker and key clinker substitutes: **clinker (INR 2,800-3,600 approximately), fly ash (INR 2,400-2,800 approximately)[9], slag (INR 2,200-2,600 approximately) and pozzolana (INR 2,400-2,800 approximately).**

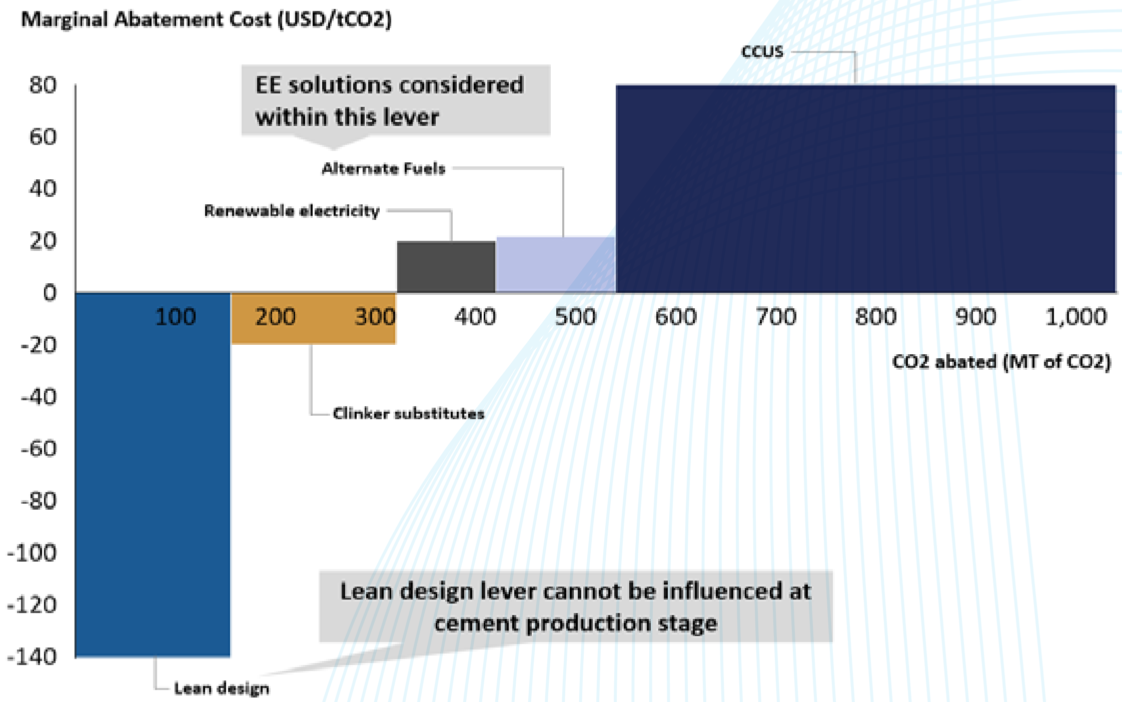
(ii) Cost of **biomass** (including collection, transport, storage and processing) may range between **INR 250-400/GJ** approximately while the cost of coal/pet coke is **INR 160-320/GJ** approximately.

(iii) Cement sector is characterised by **low purity point sources of flue gas stream** driving up cost of carbon capture.

(iv) **Technology for transport and storage infrastructure** for CO_2 is at a nascent stage limiting current CCUS scalability.

(v) Renewable Energy Round the Clock (RTC) **base tariff of INR 3.6/kWh** and **landed cost of INR 5.1/kWh** based on recently floated tenders.

Figure 3.3: MACC for Key Levers of Decarbonisation



Source: GCCA, ECRA, Cembureau, CEEW

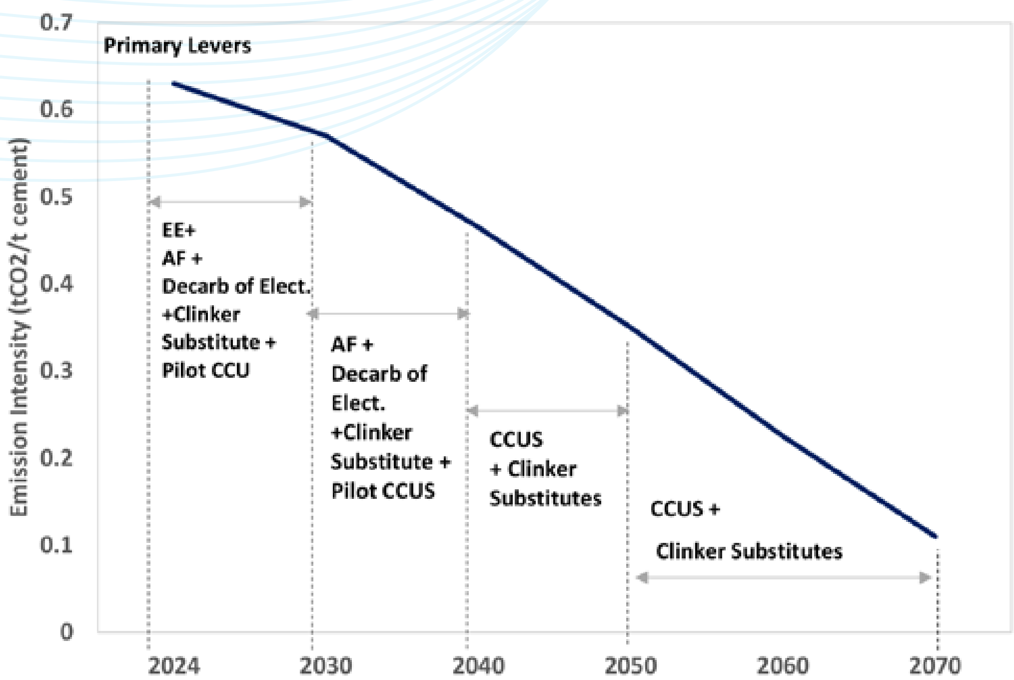
9 At present, freight charges for transporting fly ash through bulkers and trucks range between Rs. 800 per tonne and Rs. 1,200 per tonne, (Narayan & Mangla, 2016), which is significantly higher when compared to transportation costs by railways. Indian Railways has classified fly ash as Class-120 material for full rake load. As per current rates, railway freight charges for transporting fly ash over distances 301-350 km - cement plants of the Rewa–Satna–Katni region are within 250–350 km of power plants - shall be in the range of Rs 393-419 per tonne (Moving Towards A Low-Carbon Transport Future Increasing Rail Share In Freight Transport In India Working Paper – Fly Ash).

3.3 Emission Reduction Projections for Key Decarbonisation Levers

The baseline net emissions in 2023 stand at 246 $MtCO_2e$/year, while emissions driven by demand growth are projected to reach 1,076 $MtCO_2e$/year by 2070. This brings the total projected emissions for 2070 to 1,323 $MtCO_2e$/year (Figure 3.2), which serves as the reference point for assessing the potential impact of various decarbonisation strategies. By 2070, these strategies are expected to reduce net emissions from 1,323 $MtCO_2e$ in 2030 to 198-252 $MtCO_2e$, with a lower emissions intensity of 0.09-0.13 tCO_2e per tonne of cement. The decarbonisation of electricity is projected to reduce emissions by 80-133 $MtCO_2e$ by 2050 and then stabilise. This is based on the assumption that most electricity generation will be sourced from renewables post-2050. Clinker substitutes are projected to cut emissions by 145-200 $MtCO_2e$ by 2070 due to increased usage of blended cement and alternate materials. CCUS is expected to reduce cumulative emissions by 463-715 $MtCO_2e$ by 2070. However, significant reductions are anticipated to start from 2040 onwards, with pilot projects planned for 2030s.

Figure 3.4 illustrates a progressive reduction in the emission intensity of the cement sector. The primary levers contributing to reduced emission is divided into distinct phases each marked by a combination of decarbonisation technologies. Initially EE improvements and adoption of AF drive early reductions. With time and decarbonisation of the electricity sector and increased clinker substitution, emissions will drop further. In the later years, the implementation of CCUS technologies – first at the pilot stage and then at full scale – will enable a significant drop in emissions intensity, guiding the sector towards its long-term decarbonisation targets.

Figure 3.4: Emissions Reduction Impact of Each Lever Through 2070



[Note: The numbers presented in this table are indicative and have been derived from available literature, stakeholder consultations, and a current understanding of the decarbonisation levers identified. These estimates reflect potential emissions reduction pathways under existing assumptions and may evolve with further technological advancements, broader stakeholder adoption, and detailed modeling. For example, higher adoption of clinker substitutes or extended use of alternative fuels beyond 2050 could yield greater emissions reductions than currently estimated]

Chapter 04

DECARBONISATION PATHWAYS: STRATEGIES AND FEASIBLE SOLUTIONS FRAMEWORK

4. Decarbonisation Pathways: Strategies and Feasible Solutions Framework

This section discusses the framework adopted to evaluate and prioritise various decarbonisation solutions. It also highlights actions required for regulatory support, demonstration plants and other necessary assistance. The working group through a combination of literature review, data analysis and extensive stakeholder consultations assessed the existing solutions for decarbonisation of India's cement sector. All decarbonisation solutions have been classified into four groups:

Group A: Solutions industry can implement on their own

Group B: Solutions that require regulatory support for implementation

Group C: Solutions that require policy & financial support from the government

Group D: Deprioritised solutions

Figure 4.1: Framework Adopted to Evaluate Recommendations and Prioritise Solutions

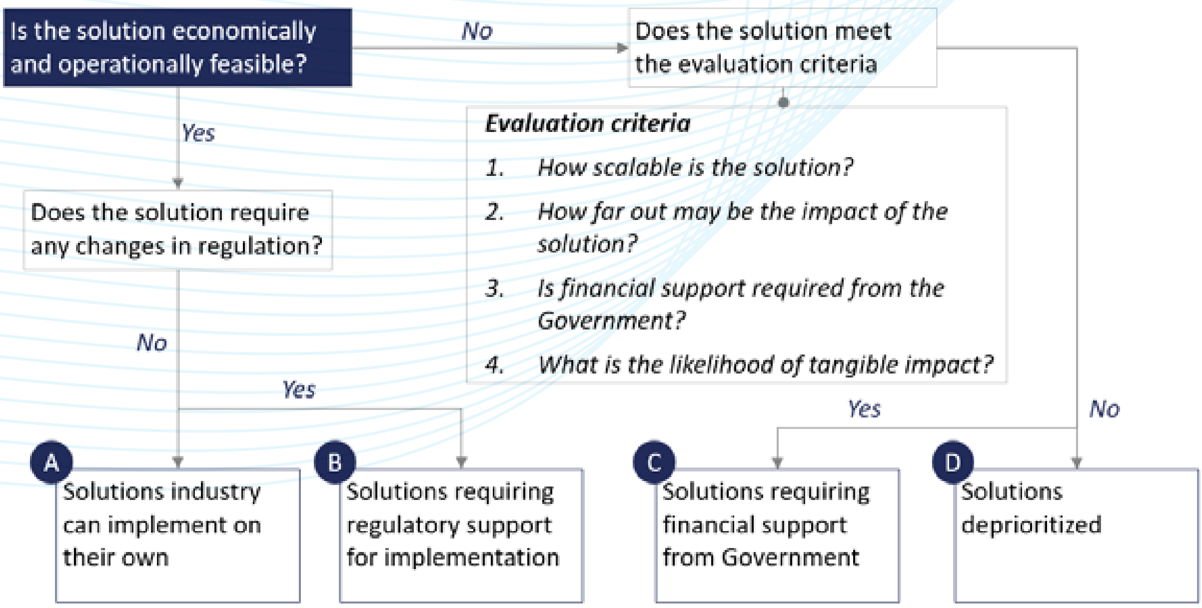
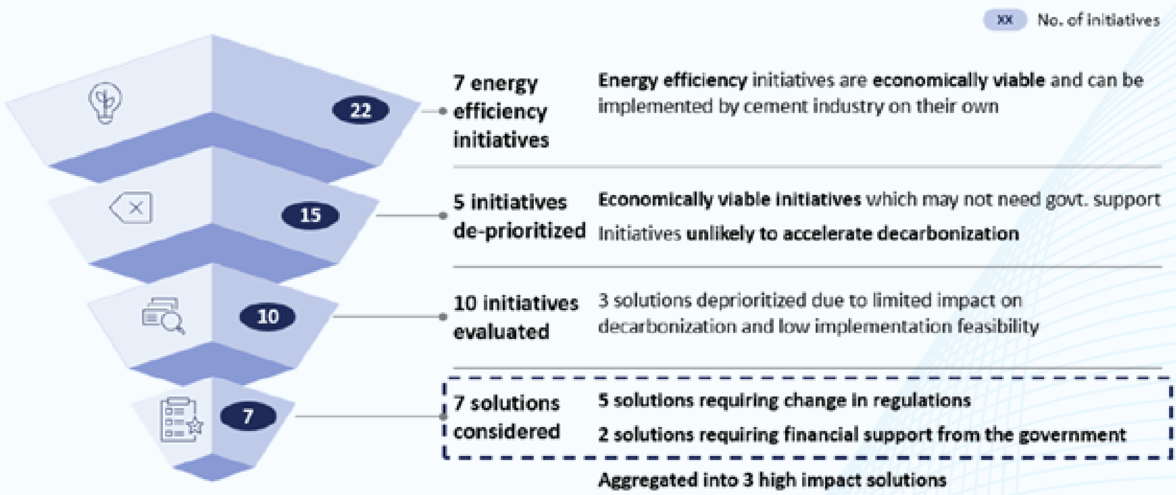


Figure 4.1 shows the framework adopted to evaluate the solutions. The various levers, including green and AF, clinker substitutes, kiln electrification and decarbonisation of electricity (Figure 3.2), were first assessed for their operational and economic feasibility. If a solution was found to be neither economically nor operationally feasible, it was further evaluated based on scalability, potential impact, the likelihood of delivering tangible outcomes, and the need for government financial support. Solutions requiring policy support from the government were prioritised. If none of these conditions were met, the solution was deprioritised.

If the solution is economically and operationally viable, the existing regulations are reviewed to determine if any modifications are needed for its implementation. If no regulatory changes are required, the solution can be adopted directly by the industry. However, if regulatory support is necessary, the solution is further assessed for potential regulatory adjustments and approvals. The prioritised high-impact solutions, based on the framework will be further detailed to include a comprehensive estimate of the required government policy support, governance mechanisms (such as nodal and implementation agencies, task forces, etc.), socio-economic impact estimations assessing benefits like employment, tax revenue, and GVA, criteria for policy validity and milestones for implementation.

Based on an extensive literature review and stakeholder consultations with cement industries and associations such as GCCA and CMA, a total of 22 recommendations for decarbonising the cement sector were evaluated (Annexure 2).

Figure 4.2: Prioritising Solutions: 3 High-Impact Solutions Selected from 22 Recommendations



Of the 22 initiatives, 7 initiatives related to EE solutions (Figure 4.2) that can be implemented by the industry, were prioritised. Throughout its growth and expansion, the Indian cement sector has consistently relied on the BAT and advanced process setups to maintain efficiency and sustainability. EE initiatives are economically viable for the cement sector and the Indian industry is in advanced stages of adopting these best available technologies.

Of the remaining 15 recommendations, 5 initiatives that are already economically viable and may not require government support have been deprioritised based on preliminary assessments. Additionally, initiatives unlikely to significantly accelerate decarbonisation were also been deprioritised.

The remaining 10 recommendations were evaluated based on defined criteria i.e. scalability, potential impact, likelihood of delivering tangible outcomes along with necessity for financial assistance, as well as policy and regulatory backing. Among the 10 recommendations, 3 solutions were deprioritised due to limited impact on decarbonisation and/or were low on implementation feasibility. Out of the 7 solutions evaluated, 5 necessitate regulatory changes, while 2 necessitate financial support from the government, as outlined in Figure 4.2. These 7 solutions have been consolidated into three high-impact solutions:

01

Increased usage of Refuse Derived Fuel from Municipal Solid Waste

02

Increased use of supplementary cementitious materials/clinker substitutes in cement production.

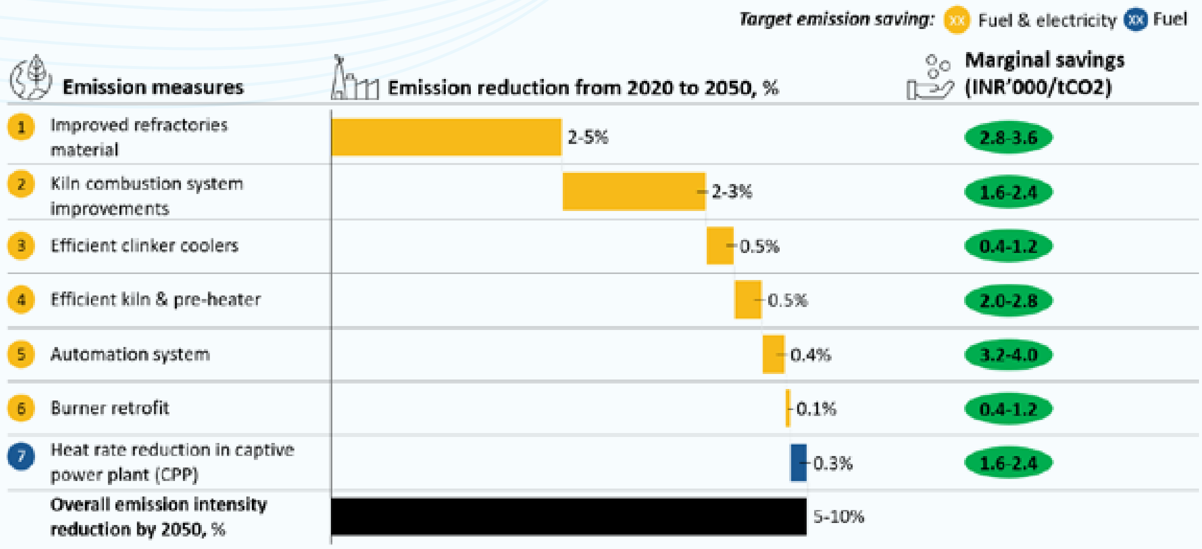
03

Carbon Capture Utilization and Storage pilots for the cement sector

Group A: Solutions that the industry can implement on their own

Group A solutions refer to EE initiatives that cement industries can implement independently. These solutions are economically viable and contribute to sustainable operations. The emission intensity of cement production is expected to decline from 0.63 tCO_2e per tonne of cement in 2020 to 0.33–0.37 tCO_2e per tonne by 2050. Of this reduction, 5-10% will result from implementing 7 energy efficiency initiatives. Six of these solutions involve a combination of fuel and electricity optimisation, while 1 focuses exclusively on reducing the heat rate of captive CPPs. The potential emissions reduction for each technology is illustrated in Figure 4.3. In addition to reducing emissions, these initiatives offer substantial economic benefits, enabling the industry to achieve significant cost savings.

Figure 4.3: Economically Viable EE Solutions



Refractory material improvements play a crucial role in improving EE in industrial processes by minimising heat loss and optimising temperature control in high-temperature environments such as furnaces and kilns. They can contribute to a 2-5% of emissions reduction by 2050 with a marginal cost saving of 2.8-3.6 (INR'000/tCO_2).

Efficient clinker coolers and kiln pre-heaters together have a 1% emission reduction potential, but efficient kilns and pre-heaters have higher marginal savings of 2.0-2.8 (INR'000/ tCO_2) as compared to clinker coolers with marginal savings of 0.4-1.2 (INR'000/tCO_2). The automation system is projected to achieve a 0.4% emissions reduction from 2020 to 2050, with marginal cost savings of INR 3.2-4.0 (INR'000/tCO_2). Burner retrofits have the smallest emission reduction potential of 0.1% and a marginal savings of 0.4-1.2 (INR'000/ tCO_2). Fuel is the biggest expense for a power plant and reducing heat rate in a CPP can lead to significant savings of 1.6-2.4 (INR'000/tCO_2) and lower emissions by 0.3% by 2050. ***It should be noted that Carbon Credit and Trading (CCTS) mechanism designed to reduce Green House Gas emissions is a crucial enabler for accelerating the adoption of energy efficient technologies[10].***

[Note: EE measures contribute approximately 5-10% to emission reductions through initiatives such as kiln combustion system improvements and heat rate optimisation in CPPs. However, there remains significant potential for improvement in many cement plants, as a considerable gap exists between the performance of the best-performing plants and others. Over the next two decades, advancements in cement manufacturing technologies are expected to further enhance EE, offering substantial emissions reduction potential. Research suggests the cement industry could cut three-quarters of its CO2 emissions by 2050 and 7% of overall emissions can be reduced by implementation of existing EE technologies (CII 2023)].

Group B1: Solutions that require regulatory support for implementation

This section discusses economically viable solutions that require additional regulatory support. A total of 5 technological decarbonisation solutions have been identified. Three of these falls under the umbrella of clinker substitution (Figure 4.4), and the remaining 2 solutions are demand enablers and recarbonation (Figure 4.5). These include proposed blending mandates to encourage the adoption of alternative materials such as CSA and hydraulic cement[11].

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10 The Central Government has notified the Carbon Credit Trading Scheme, 2023 vide S.O. 2825(E) dated 28th June 2023 under the powers conferred by clause (w) of Section 14 of the Energy Conservation Act, 2001 (52 of 2001). The Carbon Credit Trading Scheme (CCTS) in India is a mechanism designed to reduce greenhouse gas (GHG) emissions through carbon pricing. It involves two key elements: a compliance mechanism for obligated entities (primarily industrial sectors) and an offset mechanism for voluntary participation. The CCTS aims to incentivise and support entities in their efforts to decarbonise the Indian economy. CCTS laid the foundation for the Indian Carbon Market (ICM) by establishing the institutional framework (PIB. .

11 Other blended cements, namely, Portland Composite Cement (PCC) based on both fly ash and limestone, Portland Limestone Cement (PLC), Portland Dolomitic Limestone Cement (PDC), and multi-component blended cements, are at different stages of development in India - Blended Cement - Green, Durable & Sustainable 2022, GCCA

Figure 4.4: Economically-Viable Solutions, which Require Regulatory Support (Part 1)

Clinker Substitution | Demand enablers | CCUS | Alternate fuels | Energy efficiency | New technologies | Recarbonation

Time to impact: <3 years · 3-7 years · 7-10 years · >10 years **Scoring:** Favorable · Moderate · Not favorable

	Solutions	Scale of impact (% emission reduction/ton of cement)	Time to impact	Government support required	Implementation Feasibility
1	Blending mandates to increase adoption of alternatives to fly ash and slag	Driven by greater utilization of alternate materials in cement production (~5-10% by 2030; ~15-20% by 2050)	Implementation of mandates and industry adaptation may take 3-5 years	Mainly involves regulatory adjustments and enforcement costs Viability for industry to be investigated further	Supply chain for alternate materials may need to be strengthened
2	Mapping of new clinker substitutes[2] in India	Driven by greater usage of clay-based cement types like LC3	Time required for completion of mapping exercise and subsequent development of supply chain	GSI[3] will need to allocate funding for investment in geological surveys and mapping	Exercise to be undertaken by GSI[3]
3	Transition from input-based standards to performance-based standards Definition of standards for CSA[1] cement usage Can be combined into one solution set	Driven by increase in share of blended cement to 80% by 2030 and ~85% by 2050	BIS may take time for feasibility studies to change standards; consumers may need greater awareness for consuming high SCM blended cements	**No State outlay**; requires changing of standards and testing protocols No cost uptick to consumers expected	**BIS** to amend standards; large consumers[4] to follow; Performance based standards **have not yet been adopted in major economies** but under consideration

1. CSA: Calcium Sulpho-Aluminate Cement, 2. E.g., calcined clay deposits, calcium silicate deposits , 3. Geological Survey of India, 4. E.g., Railways, CPWD, NHAI, etc.

Supplementary cementitious materials/ clinker substitutes[12] include a variety of naturally occurring materials and industrial byproducts that can partially replace clinker in Portland cement. Since clinker is the primary contributor to both cost and carbon emissions in cement production, reducing its content (known as the clinker factor) provides dual benefits - lowering production costs and minimising environmental impacts. By reducing the clinker-to-cement ratio with these substitutes, energy consumption and process-related CO_2 emissions can be lowered, promoting a circular economy. This approach is widely recognised as a key strategy for decarbonisation, offering significant reductions in the industry's carbon footprint in the short term with near-zero costs. The clinker substitution technologies mentioned below are economically viable but require regulatory support for wider implementation:

(i) **Blending to increase the adoption of alternatives to fly ash and slag**

In India, the production of OPC has been steadily declining, while the production of blended cement has been on the rise. Currently, blended cements account for 73% of total cement production, compared to 27% for OPC (GCCA 2022). However, successful implementation will depend on strengthening supply chains, revising regulations and managing enforcement costs. Additionally, the financial viability for the cement industry must be thoroughly assessed to ensure the sustainable adoption of these initiatives. Industry adoption may take approximately 3 to 5 years. This progress will be driven by an increased utilisation of alternate materials (GCCA 2022) in cement production, with targets of 5-10% by 2030 and 15-20% by 2050.

(ii) **Mapping of new clinker substitutes in India**

New clinker substitutes, such as calcined clay (produced by heating kaolinite to 650°C –750°C) and calcium silicate deposits, are promising alternatives. These materials are available in large quantities and can reduce clinker content in blended cements, contributing to eco-efficient cement production. However, a feasibility assessment by the GSI is necessary. Moreover, GSI will need to allocate funds for geological surveys and mapping of these reserves across India. The estimated timeframe for completing the mapping and developing the supply chain is 3 to 7 years.

(iii) **Transition from input-based standards to performance-based standards**

Performance-based standards, which focus on strength, durability, and environmental footprint could facilitate a reduction in the clinker-to-cement ratio, promoting the adoption of low-carbon cement and accelerating the industry's decarbonisation, especially given the current reliance on input-based standards. Additionally, there is a need to establish standards for specific types of cement, such as Calcium Sulpho-Aluminate Cement. BIS has published several cement standards in India that must be amended to support the scaling up of low-carbon cement usage, starting with large consumers like the Indian Railways, NHAI, and CPWD. BIS may require 3 to 7 years to conduct feasibility studies for updating standards related to SCMs. Currently, there is no financial allocation or funding from the government; implementing these initiatives will require revising or updating existing standards and testing procedures. However, consumers are not expected to experience any increase in costs as a result of these changes. This reduction is primarily driven by an increase in the share of blended cement, which is expected to reach 80% by 2030 and approximately 85% by 2050.

12 The terms 'clinker substitutes' and 'supplementary cementitious materials (SCMs) are often used interchangeably. However, SCM is more widely recognised.

Group B2: Economically viable solutions requiring regulatory support

Figure 4.5: Economically Viable Solutions Requiring Regulatory Support (Part 2)

Clinker Substitution | Demand enablers | CCUS | Alternate fuels | Energy efficiency | New technologies | Recarbonation

Time to impact: <3 years, 3-7 years, 7-10 years, >10 years **Scoring:** Favorable, Moderate, Not favorable

Solutions	Scale of impact (% emission reduction/ton of cement)	Time to impact	Government support required	Implementation Feasibility
1 Amendment of green building rating to increase usage of low carbon cement	Driven by increase in cement with low clinker and have low embodied carbon	MoHUA may need to undertake evaluation Adoption in construction industry can happen in 1-2 years	**No State outlay**; requires adjusting green rating framework No additional cost expected for end-consumers	**MoHUA** to issue guidelines for green building in consultation with agencies like IGBC, GRIHA, etc.
2 Assessment study for India's recarbonation potential	Natural recarbonation of concrete absorbs more than 20% of process emissions from cement manufacturing.	The recarbonation of concrete cast decades ago is occurring today and will continue into the future.	Limited funding required	Requires **assessment study orchestrated by MoEFCC** to report in annual GHG inventory of India

Figure 4.5 shows technologies that need regulatory support, will be proposed to concerned ministries - MoHUA and MoEFCC, to implement this roadmap.

(i) **Demand enabler: Amendment of green building ratings to increase usage of low carbon cement**

To encourage the use of low-carbon materials, it is important to promote green building rating systems in India. MoHUA can issue guidelines, in consultation with agencies such as the IGBC, GRIHA to encourage greater use of low-carbon cement and circularity-related practices within these rating systems. These initiatives would entail updating the recommended measures within the ratings, without necessitating state funding or incurring extra costs for consumers. MoHUA may need to conduct an evaluation, and the construction industry could adopt these guidelines at the earliest.

(ii) **Recarbonation: Assessment study for India's recarbonation potential**

Cement recarbonation refers to the process where part of the CO_2 emitted during the cement production is reabsorbed by concrete in use through carbonation. Carbonation is a slow process that occurs in concrete where lime (calcium hydroxide) in the cement reacts with carbon dioxide from the air and to form calcium carbonate. At the end of their useful life, buildings and infrastructure (reinforced concrete structures) are demolished. If the concrete is then crushed, its exposed surface area increases, which in turn enhances the recarbonation rate[13] (IVL Research Foundation and Cementa AB 2018). The amount of recarbonation is even greater if stockpiles of crushed concrete are left exposed to the air prior to its reuse. To benefit from this CO_2 trapping potential, crushed concrete should be exposed to atmospheric CO_2 for several months before being reused (CEMBUREAU). An assessment study for India's recarbonation potential requires an evaluation led by the MoEFCC and incorporated into the annual GHG inventory. This assessment will need limited funding and can follow other country assessments that are built on the internationally-recognised methodologies such as Tier 1, CO_2 uptake model - Simplified Methodology, Tier 2, CO_2 uptake model - Advanced Methodology and Tier 3, CO_2 uptake model - Advanced User Developed Models[14]. As a lower bound estimate, the natural recarbonation of concrete over the 50-100 year lifecycle accounts for approximately 20% of the process emissions for the manufacturing of cement (IVL Research Foundation and Cementa AB 2018).

Group C: Initiatives that Require policy & financial support from Government

(i) **Scaling CCUS for the cement industry**

CCUS can be used to abate both process emissions and thermal emissions, making it a particularly impactful decarbonisation option for the cement industry if scaled

Substantial fiscal support and a robust regulatory framework are essential to facilitate progress. CCUS is currently in its nascent stage, and requires considerable time and investment to establish a robust ecosystem in India, which may take over 10 years to develop. The scale of impact will depend on the high capture efficiency of advanced CCUS technologies, which are expected to mature over the coming decades.

13 European Circular Economy Stakeholder Platform

14 Tier 1 represents a general but simplified calculation method for the uptake of CO_2. Tier 2 and 3 represent more accurate but complex calculation methods, which are preferred if sufficiently good input data on the use of cement in concrete applications are available. Tier 2 is a proposed advanced methodology including several aspects that will affect the CO_2 uptake. Tier 3 opens up for the use of even more advanced and accurate methods and models developed in scientific projects in different countries.

Figure 4.6: Solutions, which Require Policy & Financial Support from the Government

Clinker Substitution | Demand enablers | CCUS | Alternate fuels | Energy efficiency | New technologies | Recarbonation

Time to impact: <3 years, 3-7 years, 7-10 years, >10 years **Scoring:** Favorable, Moderate, Not favorable

Solutions	Scale of impact (% emission reduction/ton of cement)	Time to impact	Government support required	Implementation Feasibility
1 Scaling CCUS for cement industry	Favorable: Driven by high capture efficiency of advanced CCUS technologies which is expected to mature in next couple of decades	>10 years: CCUS is currently in nascent stages; significant time and investment needed to establish CCUS ecosystem in India	Moderate: Capex for the project would be ~INR 1,200-1,400 cr	Moderate: **Inter-ministerial effort**[i] Significant fiscal support and regulatory framework needed
2 Development of supply chain of green and alternate fuels	Moderate: Share of green and alternate fuels to rise to ~20% by 2030 and ~50% by 2050	3-7 years: Implementation of comprehensive collection, pre-processing, and logistics infrastructure may take 3-5 years	Not favorable: Requires investment in infrastructure development, pre-processing facilities, and logistical systems. Increase in cost which can be subsidized or passed on to customers or can impact margins	Not favorable: Limited availability and variability in quality of agri-waste based fuels would need to be addressed for effective implementation

[[i]Steel, DPIIT, Fertiliser, Petroleum, Coal, Mines, etc.]

(ii) **Development of supply chains for green and Alternate Fuels**

The cement industry incorporates AF derived from waste through a combination of material recycling and energy recovery, aligning with principles of a circular economy. However, to ensure effective implementation, challenges such as limited availability and variability in the quality of agricultural waste-based fuels, must be addressed. This initiative requires investment in infrastructure development, pre-processing facilities, and logistical systems. An increase in costs may occur, which could be subsidised, passed on to customers, or impact profit margins. Establishing a comprehensive infrastructure for collection, pre-processing, and logistics, may take 3-5 years. The anticipated proportion of green and AF is expected to reach around 20% by 2030 and 50% by 2050.

Group D: Deprioritised solutions

In this section, deprioritised solutions are discussed. The solutions are further classified into two categories: those deprioritised due to limited impact and/or low implementation feasibility and those that may require further investigation to assess their viability in the future (Figure 4.7).

(i) **Allocating 100% of fly ash and pond ash generated in the country for cement manufacturing:**

Currently, around 25% of the fly ash generated is utilised by the cement sector (CEA, MoP 2020), and the demand for ash in this sector may surpass supply by 2030-2035. Allocating 100% of fly ash could reduce the clinker factor and might not require financial support. It is also a low-hanging fruit that can be leveraged to meet near-term decarbonisation goals; however, the availability of fly ash is expected to reduce post 2050 due to the phasedown of coal plants. Also, allocating significant share of fly ash is challenging due to potential negative impacts such as the upward pressure on fly ash prices for consumers such as brick factories. To support increased usage of fly ash in cement industry, it could be provided at zero ex-plant cost. This would enable the cement industry to allocate resources towards investing in decarbonisation technologies that can be deployed at scale to mitigate its climate impact.

(ii) **Implementing the Polluter Pays Principle (PoPaP) with preferential allocation to the cement sector for waste**

Implementing the PoPaP in India is challenging due to the absence of landfill taxes and limited financial capacity of government bodies, such as ULBs. Waste like MSW and hazardous waste may have a limited potential for decarbonisation unless emissions from landfill decomposition are addressed. In India, it may take approximately 2-5 years to fully operationalise the implementation of gate fees, establish necessary infrastructure, and build reliable supply chains. In countries like the U.S., cement plants typically receive an average gate fee of USD 2-5 (Rs 160-400) per tonne, which varies depending on the type of waste received.

Waste that cannot be recycled or reused should be preferentially allocated to the cement sector, because the waste treatment enables both energy and mineral recovery. Furthermore, energy recovery in a cement kiln (because the heat generated acts directly in the industrial process) is significantly more efficient than in a waste incinerator in which heat energy must be transformed to enable energy recovery. Treatment in a kiln (co-processing) is above energy recovery alone in the waste hierarchy.

Figure 4.7: Solutions Deprioritised Due to Limited Impact and/or Low Implementation Feasibility.

Clinker Substitution | Demand enablers | CCUS | Alternate fuels | Energy efficiency | New technologies | Recarbonation

Time to impact: <3 years, 3-7 years, 7-10 years, >10 years **Scoring:** Favorable, Moderate, Not favorable

Solutions	Scale of impact (% emission reduction/ton of cement)	Time to impact	Government support required	Implementation Feasibility
100% fly ash and pond ash generated in the country to be allocated to cement manufacturing (Clinker Substitution)	Moderate: ~25% of fly ash currently generated is used by cement sector[1] Demand for fly ash by cement sector may exceed fly ash supply by 2030-2035	7-10 years: Can be implemented immediately but its significance will increase as availability of fly ash reduces	Favorable: No financial support required from State; support needed for policy implementation and monitoring May lead to upward pressure on fly ash prices for other consumers	Not favorable: Difficult to implement due to potential adverse implications on thermal power plants and other major consumers of fly ash (e.g., brick industry)
Polluter pays principle Preferential allocation to cement sector for usage of wastes (Alternate fuels)	Not favorable: Co-processing of unreusable/unrecyclable waste in cement kilns avoids emissions from other waste treatment (including landfill methane). Accounting rules recognise these emission savings.	3-7 years: ~2-5 years to fully operationalize implementation of gate fees, setting up necessary infra and supply chains	Moderate: ~Average gate fee of ~USD 2-5 (~INR 160-400) per tonne (highly variable depending on the type of waste) paid to cement plants in countries like US	Not favorable: **Polluter pays principle is difficult to implement in India** due to absence of landfill tax and limited ability of govt. bodies like ULBs to finance outlay For waste that cannot be recycled/reused, waste should be preferentially allocated to the cement sector because waste treatment enables both energy recovery and mineral recovery

Chapter 05

SOLUTION PATHWAYS: A DETAILED EXAMINATION

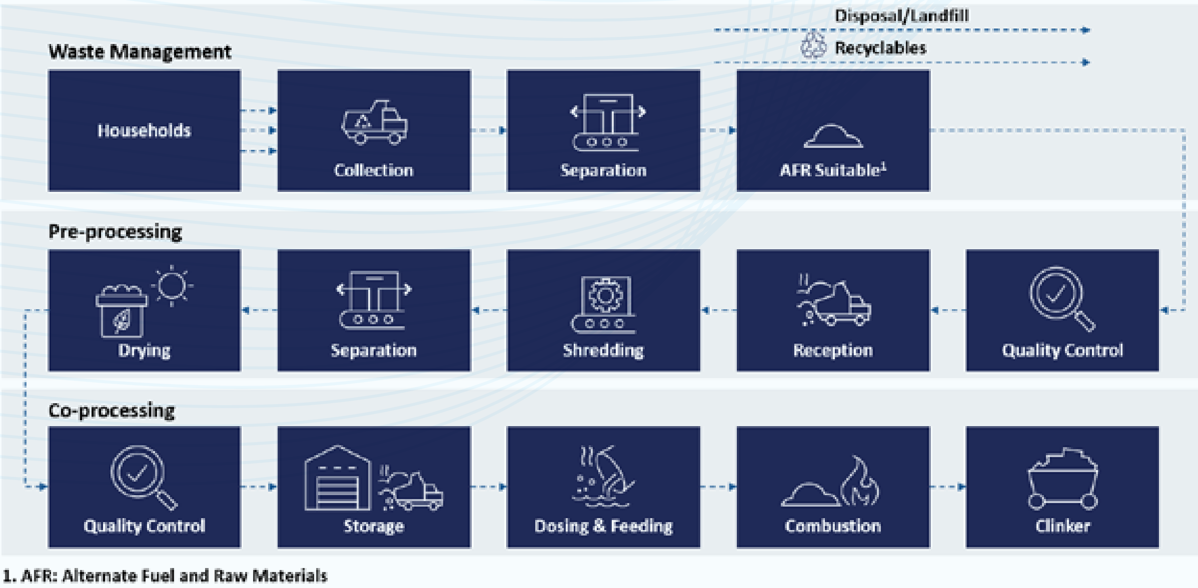
5. Solution Pathways: A Detailed Examination

As Carbon Credit Trading Scheme of the MoEFCC has given emission reduction targets to cement plants under compliance mechanism, therefore, Working Group did not give any emission reduction target for the Cement Sector but it has prioritised three high impact long term advance technology & material-based solutions. To make the recommended solutions commercially viable, policy and regulatory interventions from Central and State Governments would be required. The cement sector may implement this solution based on their requirement for decarbonisation in long-run. The solutions are (1) Increased usage of RDF from municipal solid waste (2) Increased usage of Supplementary Cementitious Materials / Clinker Substitutes and (3) Scaling up CCUS in the cement industry.

5.1 Increased Usage of Refuse Derived Fuel from Municipal Solid Waste

5.1.1 Journey of MSW to cement plants

Figure 5.1: Journey of RDF from MSW to Cement Plants



Source: Guidelines on Pre-processing and Co-processing of Waste in Cement Production, Lafarge Holcim and GIZ

(i) **Waste Management**

The Solid Waste Management Rules, 2016 specify the segregation of waste at source into the following categories: biodegradable, non-biodegradable (including recyclable and combustible components); sanitary waste, and domestic hazardous waste. These rules also require the collection of solid waste directly from households, shops, commercial establishments, offices, institutions, and other non-residential premises. In the case of multi-storey buildings, housing societies, or large residential, commercial, or institutional complexes, waste must be collected from the entry gate or a designated location on the ground floor. The Rules further specify the transportation of solid waste - whether treated, partly treated, or untreated - ensuring that it is moved in an environmentally sound manner. This involves the use of specially designed, covered transport systems to prevent foul odors, littering, and unsightly conditions during the movement of waste from one location to another. Additionally, the Rules outline requirements for sorting different waste components to enable further categorisation of waste to produce suitable alternate fuels.

Alternative Fuels and Raw Materials (AFR) refers to selected waste and by-products that can be co-processed in cement production. Among these, Alternative Fuels (AF) have recoverable energy content (calorific value) that can replace a portion of the conventional fossil fuels used in cement manufacturing. For example, RDF is produced from the combustible fraction of solid waste - including materials like plastic, wood, pulp, and organic waste-excluding chlorinated materials. The waste is processed through drying, shredding, dehydrating, and compacting to create RDF in the form of pellets or fluff that can be co-processed in cement production. ARs contain valuable minerals such as calcium, silica, alumina, iron and sulfur, which can substitute natural raw materials in clinker production or as mineral components in cement production. Co-processing AFs and ARs in the cement industry can reduce both energy consumption and the environmental impacts associated with fossil fuels.

AFs used in the cement industry can be either liquid or solid, depending on their composition and organic content, with appropriate chemical properties for combustion. The calciner and clinker-forming kiln are the primary sites for thermal energy use and CO_2 emissions. Substituting conventional fossil fuels with low-carbon alternatives can significantly reduce CO_2 emissions. Additionally, the use of AFs has been shown to extend the lifespan of refractory materials while lowering carbon emissions. Since most AFs are derived from waste that would otherwise require disposal, they are more cost-effective than fossil fuels. However, pre-processing, and logistical challenges associated with AFs utilisation can pose economic barriers. Co-processing waste in cement kilns results in a greater net reduction in global CO_2 emissions due to the biogenic carbon content, which varies across different AFs. This approach provides a more favorable CO_2 balance than incinerating waste in dedicated facilities. While the adoption of AFs has grown significantly in developed countries and is expected to continue, the TSR in the cement industry of developing nations remains considerably lower, typically around 4% to 5%(CMA).

(ii) **Pre-processing**

Most waste streams are too diverse in their chemical composition and physical properties to be directly co-processed in cement plants. Therefore, they require initial treatment, known as pre-processing, to transform them into a uniform AFR that meets the environmental and operational standards of cement facilities. Pre-processing refers to the initial treatment and preparation of waste materials before they are used in industrial processes such as cement production. According to the 'Guidelines on Pre- and Co-processing of Waste in Cement Production', pre-processing involves steps such as sorting, shredding, drying, and removing any contaminants or hazardous components from the waste. The goal is to ensure that the waste is suitable for use as an AF or raw material in cement manufacturing. This treatment not only enhances the energy content of the fuel, but improves combustion quality enabling it to effectively substitute fossil fuels and raw materials- thus contributing to more sustainable and resource-efficient cement manufacturing. Pre-processing typically involves separation/sorting, mixing/blending, size reduction (shredding or crushing) and drying. The different methods for producing waste-derived fuels are detailed in European Union's Best Available Techniques Reference Document (BREF) for Waste Treatment Industries (BREF, 2017). Solid waste is generally pre-processed through mechanical systems, biological treatment or a combination of both mechanical-biological (MBT) systems to produce solid alternative fuels, such as SRF or RDF. When the waste contains minimal biodegradable material, the pre-processing process mainly involves mechanical treatment, focusing on size reduction and the removal of non-combustible inert materials like stones, glass and metals. In contrast, waste streams with significant biodegradable content often require a combined MBT-based approach (GIZ, LafargeHolcim 2020).

(iii) **Co-processing**

The Solid Waste Management Rules, 2016 define "co-processing" as the use of non-biodegradable and non-recyclable solid waste with a calorific value exceeding 1500 Kcal, either as a raw material, a source of energy, or both, to replace or supplement natural mineral resources and fossil fuels in industrial processes. In cement production, co-processing involves the controlled use of AFRs at designated feed-in points within the cement plant. This allows AFRs to serve both as fuel and raw material, enabling the substitution of primary fuels - such as coal, petroleum coke and natural gas - and raw materials. Co-processing facilitates the recovery of energy from waste and the recycling of its mineral content. Only qualified waste materials, meeting specific criteria are allowed for co-processing, highlighting the significance of quality control in the use of AFRs.

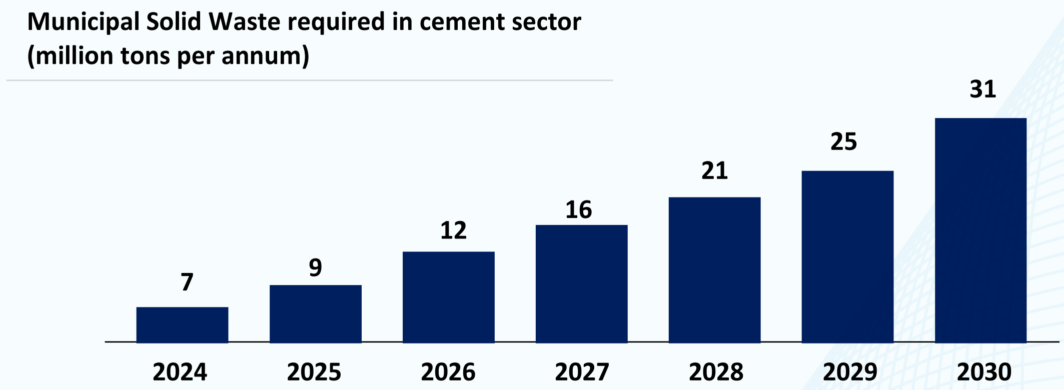
Effective co-processing in cement manufacturing requires addressing several critical factors. Pre-processing is a fundamental step that transforms waste into a homogeneous material suitable for co-processing. Following this, a testing laboratory is essential to assess calorific value, ash content, moisture levels, chloride concentration, the presence of heavy metals, and mineral composition. These parameters directly affect the environmental impact, product quality and the operational stability of the cement kiln. Additionally, a secure storage and conveying system is required to transfer the processed waste from the storage to the kiln in a controlled manner. This typically includes covered storage facilities and conveyors to ensure efficient and safe handling. A dedicated feeding mechanism must also be installed in the cement plant to introduce AFs into the calciner or kiln.

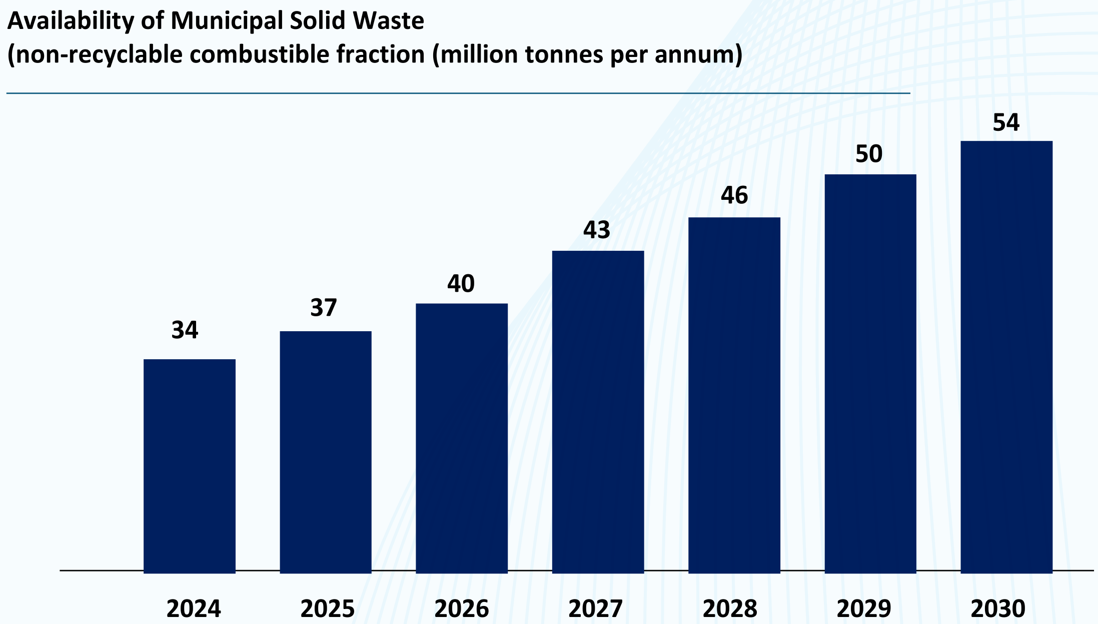
Co-processing materials can be introduced into the cement production process through various feed points such as main burner at the rotary kiln outlet, rotary kiln inlet, pre-calciner, mid-kiln (for long dry and wet kilns). The selection of an appropriate feed point depends on the physical, chemical and toxicological properties of the waste material.

5.1.2 Availability of Municipal Solid Waste

India is expected to have sufficient MSW to ensure it contributes to approximately 20% of total thermal energy required by the cement industry by 2030. Figure 5.2 illustrates the MSW required by the cement sector and its projected availability until 2030. The supply is expected to exceed the demand, presenting a potential solution for decarbonising the cement industry and promoting circularity. However, scaling would require an additional capital investment of approximately INR 15,000 crore. Additionally, this initiative has the potential to create employment for around 65,000 people across various levels of the MSW supply chain.

Figure 5.2: The projected Availability of Municipal Solid Waste up to 2030





Source: Guidelines on Usage of Refuse Derived Fuels in Various Industries, MOHUA; Circular Economy in Municipal Solid and Liquid Waste, MOHUA

5.1.3 Refuse Derived Fuel

According to the Solid Waste Management Rules 2016, RDF refers to fuel derived from the combustible fraction of solid waste. This fraction includes materials such as plastic, wood, pulp, and organic matter, and excludes chlorinated substances. It is produced through processes such as drying, shredding, dehydrating, and compacting solid waste into pellets or fluff. RDF typically comprises the residual, dry, combustible portion of MSW, including paper, textiles, rags, leather, rubber, non-recyclable plastics, jute, multi-layered and composite packaging, thermocol, and coconut shells.

Processing the combustible fraction of MSW yields RDF, which can play a significant role in replacing fossil fuels in cement kilns. Currently, the TSR of fossil fuels with AFs- including industrial waste, biomass and municipal waste- remains at approximately 3%, which is far below the double-digit rates seen in developed countries. The use of SCF and/or RDF derived from MSW in cement kilns accounts for only 0.6% of the overall thermal substitution. Organisations like the CMA and the Cement Sustainability Initiative (CSI) are actively supporting the use of AFR.

The use of RDF is regulated under the Solid Waste Management Rules 2016. For producing RDF, rigorous segregation must be implemented, and collection and transportation of the dry fraction of the MSW must be carried out separately. The dry fraction is first processed to remove the recyclable materials. The left-over material, which is the segregated combustible fraction, is then processed through a dedicated facility that can screen, shred, separate using air density, blend, etc. to produce the desired quality of RDF.

(i) Refuse Derived Fuel and the Cement Industry

Over the last decade, the substitution rate has increased from less than 1% in 2010 to more than 3% in 2016. The industry aims to achieve a TSR of 25% by 2025[15]. Currently, most cement manufacturers use a variety of fuel types such as coal, domestic, and imported petroleum coke, etc. as high calorific value inputs in kilns. The net CO_2 emission factor of pet coke is the highest among all fuels used in cement plants-105% that of coal, 134% that of plastic and 1060% that of RDF (MoHUA 2018). Cement kilns serve as a means of co-processing waste; hence EPR guidelines, which set specific targets for collection, recycling, end-of-life management, and use of recycled content, are essential. EPR is a policy framework that holds producers accountable for the entire lifecycle of their products, including their end-of-life management. By assigning responsibilities to respective stakeholders, EPR helps divert waste from landfills and encourages its use as an alternative fuel in industries like cement manufacturing. One such example of this is the collection of plastic waste under EPR and transporting it to the cement plant for co-processing (CPCB 2017).

15 Considering the projected cement production volume by 2070, along with an increasing TSR and decreasing clinker factor, it is recommended that the industry be allowed to import AFs, alternative raw materials, and clinker-substituting materials from other countries. This would help achieve the net-zero target with reduced investment in CCUS projects, thereby lowering the financial burden on the Indian cement industry. Additionally, the government should allocate degraded forest areas for the cultivation of biofuels and the creation of carbon sinks through afforestation, in collaboration with both state and central governments.

5.1.4 Benefits of using RDF in cement industries

Table 5.1: Benefits of Using RDF in Cement Industries

Indicators	Benefits
RDF specifications	Cement plants typically require RDF to be shredded to particle sizes smaller than 50 mm - a requirement that does not pose a technological challenge. In an oxygen rich atmosphere as is present in a cement kiln, particles smaller than 50 mm disintegrate completely with 4-5 seconds.
Feeding of RDF	Installing a dedicated AFs feeding mechanism enables RDF to be introduced into cement kilns without any operational challenges. Cement factories typically construct a separate entry point for AFs, which may include pharmaceutical waste, FMCG waste, packaging waste, lubricants, etc. The same feeding mechanism is suitable for RDF.
Impact on product	RDF combusts completely at high temperatures of approximately 1400°C and a residence time of 4-5 seconds in an oxygen rich atmosphere without affecting the productivity. With a calorific value of around 3000 Kcal, RDF generates sufficient thermal, reducing dependence on fossil fuels such as coal.
Environmental impact	Using RDF in place of fossil fuels prevent waste from being landfilled, thereby reducing GHGs. Avoiding improper landfilling also minimises the risk of leachate polluting groundwater, which has become a major source of pollution. Emission control equipment further reduces the release of dioxins and furans into the atmosphere.
Residual disposal	Acidic gases produced during RDF combustion are neutralised by the alkaline raw materials in the cement kiln and are incorporated into the cement clinker. The interaction between the raw materials and the flue gases in the clinker ensures that the non-combustible residue is held back in the process and incorporated in the clinker in an almost irreversible manner with no additional waste generated.

5.1.5 Compliance by the cement industry

Some waste processing facilities producing RDF have struggled to find buyers due to the high production costs. MoHUA came up with guidelines in 2018 (Table 5.2) to modify clause 18 of SWM Rules 2016, which deals with usage of RDF. The modification was proposed in view of the current TSR of the cement industry being <10% against a target of 25%. In 2020, the Central Electricity Regulatory Commission (CERC) set the cost of RDF at INR 2,084/Mt to help RDF plants recover expenses related to waste screening and processing. MoHUA issued an advisory on the use of RDF in the cement industry, suggesting that the process is financially viable with a payback period of just 3-4 years (MoHUA 2021). However, this pricing has not been widely accepted by stakeholders.

Table 5.2: Guidelines for Usage of RDF, 2018, MoHUA

Original Clause 18 of the SWM Rules, 2016	In 2018 MoHUA modified Clause 18 of the SWM Rules, 2016
"All industrial units using fuel and located within 100 km from a solid waste-based RDF plant shall make arrangements within six months from the date of notification of these rules to replace at least 5% of their fuel requirement by RDF so produced."	The cement plants located within 400 km from a solid waste-based RDF plant shall make necessary arrangements to utilise RDF in the following phase wise manner at a price fixed by state government: Replace at least 6% of fuel intake, within 1 year from the date of amendment of these rules (equivalent calorific value/TSR) by MSW-based SCF and/or RDF, subject to the availability of RDF. Replace at least 10% of fuel intake within 2 years from the date of amendment of these rules (equivalent calorific value/TSR) by MSW based SCF and/or RDF, subject to the availability of RDF. Replace at least 15% of its fuel intake within 3 years from the date of amendment of these rules (equivalent calorific value/TSR) by MSW-based SCF and/or RDF, subject to the availability of RDF.

5.1.6 Challenges in the uptake of MSW in the cement sector

The adoption of RDF from MSW in the cement sector faces multiple challenges that impact both operational efficiency and sustainability as shown in Table 5.3: Challenges in the uptake of RDF from MSW in the cement sector.

The quality of RDF is compromised by its low-calorific value due to high moisture and ash content. Contaminants like stone, glass, and low-quality MSW further reduce its effectiveness and complicate operations. RDF supply is inconsistent due to seasonal fluctuations, regulatory restrictions, and short-term contracts, leading to disruptions and gaps in availability. Establishing long-term agreements between cement plants and waste management bodies can help further ensure consistent RDF supply and improve planning for infrastructure investment. Cement plants also face challenges with limited RDF storage capacity, requiring significant infrastructure investments and specialised equipment. Burning RDF in smaller kilns is particularly difficult, while additional issues include energy inefficiencies from moisture, odor, and ongoing maintenance costs. These factors collectively impact the overall efficiency and sustainability of RDF use in cement plants.

Table 5.3: Challenges in the Uptake of RDF from MSW in the Cement Sector

Material quality issues	Supply chain and consistency issues	Infrastructural challenges	Operational challenges
Low calorific value:	**Limited RDF storage capacity:**	**Technical requirements:**	**Ash and moisture impact:**
The RDF received has a Gross Calorific Value (GCV) of 1500-1600 Kcal/kg with 35-40% moisture and 50% ash. The resulting Net Calorific Value (NCV) is 2,500 Kcal/kg. (expected NCV for usage in cement kilns >3000 KCal/kg net)	Cement plants can store RDF for only 10-12 days during kiln stoppages or surges, limiting consumption.	Specialised machinery – mechanical feeders, separate stockpiles – are required for RDF use.	High ash and moisture raise specific heat consumption and require high-grade limestone, which is scarce and often imported.
Contaminants in RDF:	**Inconsistent RDF supply:**	**High infrastructure costs:**	**Energy efficiency issues:**
RDF often contains sediment, stones and glass due to poor sorting, damaging kiln operations and reducing shredder life.	Regulatory restrictions and seasonal issues disrupt RDF availability, and this holds up operations for months.	An estimated INR 15 crore is needed for a 100 TPD RDF co-processing platform per cement unit.	High moisture in RDF increases the need for supplementary coal or petcoke, undermining energy efficiency.
Limited fresh MSW processing:	**Short term contracts:**	**Burning difficulty:**	**Odor issues:**
Few facilities process fresh MSW, resulting in poor quality RDF.	MSW operator agreements are often limited to 18 months, creating supply gaps of 3-4 months.	Small calciners or short retention times make it difficult to burn RDF efficiently.	Persistent odors from RDF cause discomfort for workers and communities.
Additional heat input, lower clinker production, and maintenance of RDF yards and staff contribute to high operating costs. Support is needed for viable RDF substitution.			

5.1.7 Urban Local Bodies and Municipal Solid Waste Management

Urban Local Bodies (ULBs) across India are primarily responsible for ensuring efficient and sustainable waste management. In line with the Solid Waste Management Rules, 2016, ULBs prepare Municipal Solid Waste Management (MSWM) plans that align with their state's policy or strategy. These state frameworks guide ULBs in the planning, design, implementation, and monitoring of waste systems, with an emphasis on environmental and financial sustainability.

The Swachh Bharat Mission (Urban) (SBM-U) 2.0, launched on October 1, 2021, by the MoHUA, aims to create a "Garbage Free" Urban India by 2026. Building on the achievements of the first phase, SBM-U 2.0 focusses on intensifying efforts in waste management, sanitation and hygiene. Key objectives include 100 percent door-to-door collection and segregation of waste, scientific processing and disposal of all waste, and remediation of legacy dumpsites. The mission also aims to reduce single-use plastics, manage plastic waste and managing construction and demolition (C&D) waste.

Experiences from cities like Indore, Pune, Goa, and Ahmedabad show different governance models for the MSW value chain. In Pune, a public–community partnership operates through Solid Waste Collection and Handling (SWaCH) Cooperative Society[16] , a fully member-owned cooperative of waste pickers with over 3,500 members. In this model, pairs of SWaCH workers collect segregated waste from about 150–400 households each and hand over wet waste and recyclables to city-run collection vehicles with transport specific contract terms. Their income comes from user fees paid directly by households and commercial establishments, along with the sale of recyclables to scrap dealers. Ahmedabad Municipal Corporation collects segregated (dry and wet) waste from households and commercial areas in a collection vehicle with two separate chambers. Three Material Recovery Facility (MRFs) are provided at RDF premises. In each zone, there are transfer stations where small vehicles transfer the waste to hook loaders which takes the waste to dumpsites/ RDF facilities. Existing treatment and disposal facilities are for 2500 TPD, of which 1000 TPD is for Composting, 1000 TPD for C & D Waste, 100 TPD for Plastic waste, 400 TPD is MRF. There are three composting plants for wet waste developed on PPP mode with AMC providing the land to set up the facility and receive revenue from the sale of compost[17] .

Goa follows a Design–Build–Finance–Operate–Transfer (DBFOT) model within a Public–Private Partnership (PPP). The government provides land; a portion of collection costs is recovered from households; Panaji practices 16 way source segregation; and non recyclable waste, including Refuse Derived Fuel (RDF) through Goa Waste Management Corporation's (GWMC) facilities[18] . Indore generates about 1,200 tons of municipal solid waste (MSW) per day. The city practices source segregation, which helps produce high quality Refuse Derived Fuel (RDF) for processing. The **Goa and Indore Municipal Corporation models** offer detailed key insights that demonstrate their success in utilising RDF from MSW leading to significant uptake in the cement sector. This integration is facilitated by strong political support, active community engagement, an effective communication strategy, structured user charges, regular monitoring and robust technical oversight. The key learnings from both models are detailed in **Annexure 3.**

16 https://swachcoop.com/
17 Gujarat Resilient Cities Partnership: Ahmedabad City Resilience Project (G-ACRP) 2022
18 https://gwmc.goa.gov.in/swmf-saligao/

Figure 5.3: Comparative Cost of RDF vs Pet Coke

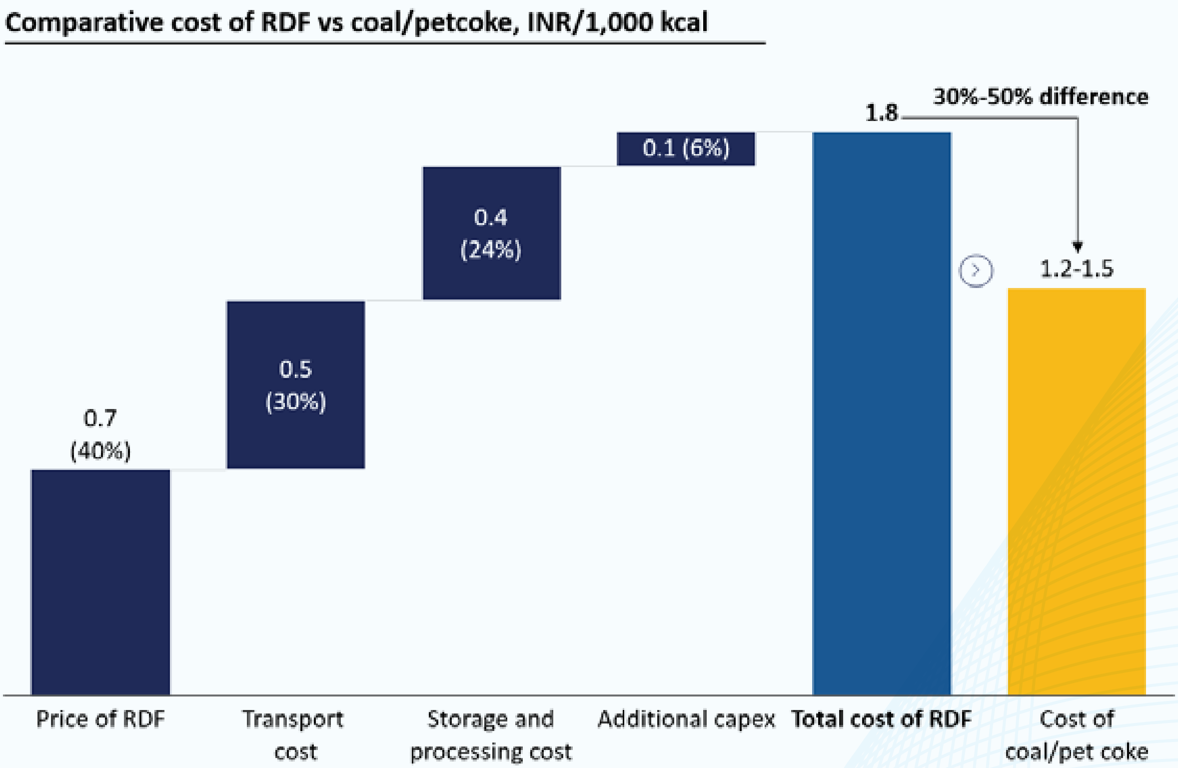


Figure 5.3 illustrates the cost comparison between RDF and coal/pet coke, standardised to cost per 1,000 Kcal. The following assumptions are made: the average net calorific value of RDF is around 2500 Kcal/kg, with RDF costs ranging from INR 1,500 to INR 2,000 per ton. Transportation costs are INR 5 per ton per km for distances up to 200 km, and INR 4.5 per ton per km for distances over 400 km. Given the current economics, the total cost of RDF is significantly higher than that of coal or pet coke (which is around INR 1,200 to 1,500 per ton), primarily because transportation is a major cost driver.

5.1.8 **Economic Impact of 20% thermal substitute using RDF for producing one ton cement**

For example, at a 20% thermal substitution rate (TSR) using RDF in Ordinary Portland Cement (OPC) production (with 95% clinker per ton of cement), the kiln requires 730 kcal/kg of clinker. The baseline case with 100% coal (for thermal energy) at 1.5 INR/1,000 kcal costs about 5,600 INR/ton and emits 1,000 kgCO_2/ton. With 20% RDF blending (RDF CV 2,500 kcal/kg; coal CV 4,000 kcal/kg), roughly 55.48 kg of RDF replaces 34.675 kg of coal per ton. Energy costs are about 249.7 INR/ton for RDF and 208.1 INR/ton for coal, resulting in an incremental cost of 41.6 INR/ton and a new cement cost of 5,641.6 INR/ton (+0.74%). Emissions drop by 52.53 kgCO_2 per ton (~5%). The CCTS targets for OPC cement are about 7% by 2027, and this pathway can approximately deliver 5% towards achieving the CCTS target. The additional cost of RDF blending for thermal substitution maybe mitigated through a Public

Private Partnership model by Municipal Bodies. The PPP model for providing land at concessional rate, collection, segregation and transportation charges and other support is already being implemented by municipal corporation like Indore, Goa, Pune and Ahmedabad

5.1.9 **Proposed intervention by Centre & State Government and Local Urban Bodies for making RDF commercially viable for cement sector**

To promote the increased usage of RDF from MSW by cement plants, MoHUA could consider developing a framework for MSW processing through a PPP framework. Table 5.4 presents an overview of the operational framework which adopts a collaborative approach to encourage RDF usage in the cement sector through a PPP model. Municipal corporations will play a central role by providing land for RDF plants, setting tipping fee per ton of waste collected and segregated, ensuring the quality and offtake of RDF by cement plants.

Table 5.4: Institutional Mechanisms for Increased Usage of RDF from MSW

Recommendation	Action	Implementation by
Model Framework for establishing RDF Plant	PPP framework for municipal bodies[19] • Municipal Corporation to provide **Land on minimum lease rate,** tipping fees for waste collection and segregation to waste processing plant • **Long-term offtake agreements** with Urban Local Bodies, vendors of RDFs and cement plants • Right to refusal of the low quality and inconsistent supply of RDF (Grade I and Grade II) to Cement plants • **Quality Compliance** by third party inspection	MoHUA
Policy/ Rules for Fuel Substitution	Modification of SWM Rules 2016 • The cement plants located within **400 km** from a solid waste-based RDF plant shall make necessary arrangements to achieve **20% thermal substitution rate by 2030**. Currently, the clause mentions to replace at least 15% of its fuel intake within 3 years from the date of amendment of the rules for all industries • RDF processing (50% of total capacity) for waste processing plants located within **400 kms** of cement plant • Municipal corporations to charge **waste handling cess** from commercial and industrial units to fund RDF processing	MoHUA

19 Using the PPP Model can reduce price of RDF (1.8 INR/1000Kcal) by 22% making it at par with coal (1.5 INR/1000Kcal)

Carbon Credits to waste handling plant	• The National Steering Committee for the Indian Carbon Market (NSC ICM), under the **Offset mechanism** has approved ten sectors: energy, industry, **waste handling and disposal**, agriculture, forestry, transport, construction, fugitive emissions, solvent use, and CCUS • It is suggested that NSC-ICM may formulate a suitable guideline for availing carbon credit and benefit of the carbon market for selected 10 sectors including waste handling plant, i.e., RDF plants, etc.	MoEFCC

(i) **Model Framework for Establishing RDF plant**

A municipality can enable a waste processing plant by offering land on a low-cost lease and paying tipping fees for collected and segregated waste. Together, these measures create the financial incentives needed for private participation in a waste management sector that might otherwise be commercially unviable. Establish long term offtake agreements between ULBs, RDF vendors, and cement plants. These contracts are foundational for bankability and scale: they secure volumes, define quality standards, set prices with indexation, and clarify performance obligations—unlocking investment across the MSW to RDF to cement value chain. Also, including a clear right to refuse low quality RDF that does not meet agreed specifications (grade, moisture, calorific value, contamination, banned materials), protects operational integrity and product quality, enforces adherence to standards, and creates incentives for reliable, compliant RDF supply across the chain. To enhance the quality and technical viability of using RDF in cement plants, it is essential to ensure a consistent and reliable supply of high-quality RDF, particularly Grade I and Grade II, to meet the operational demands of the industry. Technical feasibility testing should be conducted to assess the compatibility of RDF with cement plant processes, with a focus on maintaining chloride and sulfur balance in relation to limestone quality, ensuring compliance with BIS norms. Also, evolving technologies such as RDF gasification and Torrefaction can be considered to increase the quality of the fuel. Additionally, stringent quality control measures must be implemented, including third-party audits at the RDF processing facility prior to dispatch, to maintain the required standards and optimise performance in cement kilns. Quality standards for enhanced utilisation of MSW is provided in Table 5.5.

(ii) **Policy/ Rules for Fuel Substitution**

It is estimated that Municipal Solid Waste (MSW) accounts for a significant 57.07% of alternative fuel (AF) use in the cement industry as of 2025. Other contributors include biomass (33.97%), tyre waste (7.33%), hazardous waste (3.46%), and spent pot lining (0.81%). Currently, about 4% of the Indian cement industry's total energy input comes from alternative fuels (CMA). It is recommended that the cement plants located within 400 km from a solid waste-based RDF plant shall make necessary arrangements to achieve 20% thermal substitution rate by 2030.

It is recommended that waste processing plants within 400 km of a cement plant allocate at least 50% of their capacity to RDF processing securing a predictable supply for nearby kilns. It also recommended that municipal corporations levy a waste handling cess on commercial and industrial units to fund RDF preparation. Evidence from MSW-to-RDF supply chains shows that proximity, assured volumes, and dedicated funding are critical to produce kiln grade, consistent RDF and to raise Thermal Substitution Rates.

(iii) **Carbon Credits to waste handling plant**

Carbon Credits to waste handling plant: The National Steering Committee for the Indian Carbon Market (NSC ICM), under the Offset mechanism has approved ten sectors: energy, industry, waste handling and disposal, agriculture, forestry, transport, construction, fugitive emissions, solvent use, and CCUS. Under CCTS, non obligated entities may register projects that follow government established sectoral methodologies to quantify GHG reductions or removals. Projects that demonstrate verified reductions or removals are issued Carbon Credit Certificates (CCCs), which can be traded for compliance or voluntary purposes. The MoEFCC can issue guidelines for allocating carbon credits to waste processing plants involved in waste management.

Table 5.5 : Quality Parameters for Increased Consumption of RDF from MSW[ii]

S. No	Parameters	SCF	RDF – Grade III	RDF – Grade II	RDF – Grade I
1	Intended use	Input material for the waste to energy plant or RDF pre-processing facility	For co-processing directly or after processing with other waste materials in cement kiln	For direct co-processing cement kilns	For direct co-processing cement kilns
2	Size	Anything above 400mm has to be mutually agreed between urban local body/SCF supplier and cement plants	<50mm or <20mm depending upon use in ILC or SLC respectively		
3	Ash – maximum permissible	<20%	<15%	<10%	<10%
4	Moisture – maximum permissible	<35%	<20%	<15%	<10%
5	Chlorine – maximum permissible	<1%	<1%	<0.7%	<0.5%
6	Sulphur – maximum permissible	<1.5%	<1.5%	-	-
7	Net calorific value (NCV) - in kcal/kg	>1,500 kcal/kg net	>3,000 kcal/kg net	>3,750 kcal/kg net	>4,500 kcal/kg net
8	Any other parameter	SCF – any offensive odour to be controlled	RDF – any offensive odour to be controlled	RDF – any offensive odour to be controlled	RDF – any offensive odour to be controlled

ii Guidelines on Usage of Refuse Derived Fuel in Various Industries – MoHUA

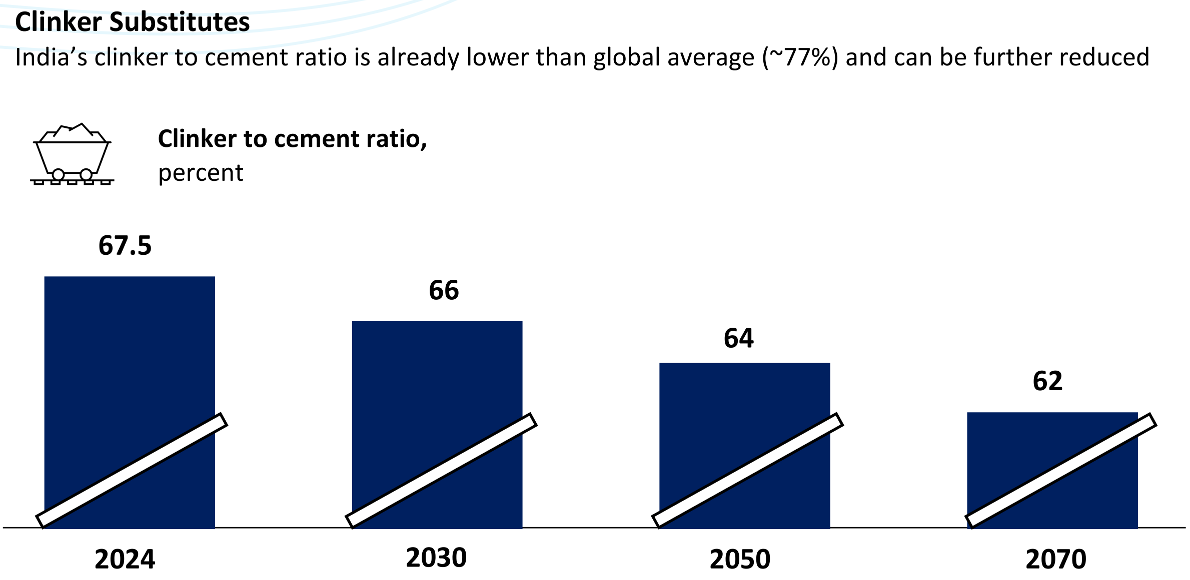
5.2 Increased Usage of Supplementary Cementitious Materials/Clinker Substitutes

Clinker is the principal component of cement that is responsible for the majority of process-related emissions in the cement industry. BIS has outlined specifications for 16 types of cement and clinker, including Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC), Composite Cement, Limestone Calcined Clay Cement, and various other special-purpose cements. PPC enjoys the majority share (65%) of the total cement production in India followed by OPC (27%) and PSC (7%) (DPIIT 2024). The Indian cement industry's product profile has changed significantly over the years to include more blended cement in the mix and the clinker to cement ratio is already lower than the global average of 77% (GCCA 2022), and it can be reduced further through increased use of clinker substitutes.

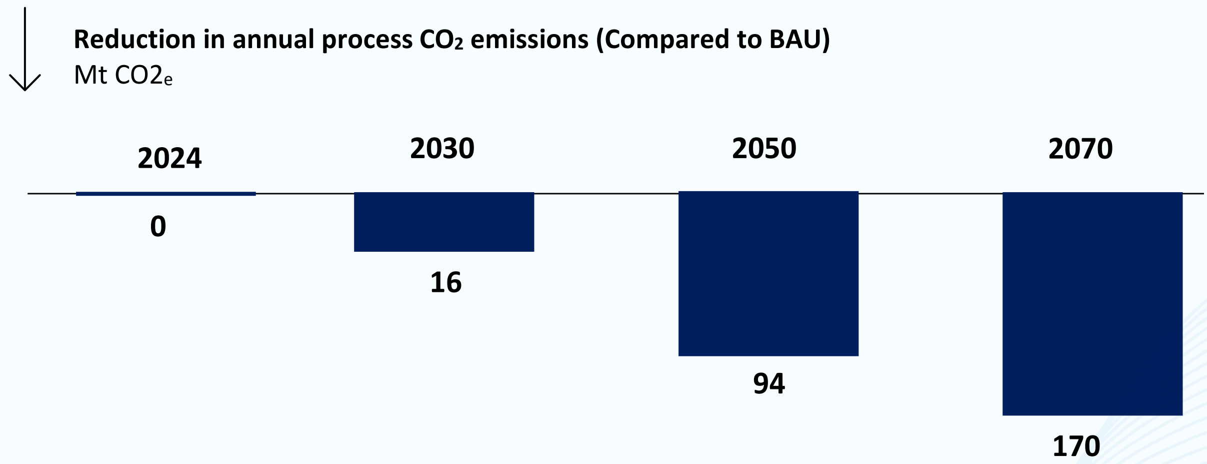
Figure 5.4 illustrates the reduction potential in the clinker-to-cement ratio over the years, along with corresponding reductions in process emissions. The analysis indicates that clinker-to-cement ratio is estimated to decrease from 67.5% in 2024 to 62% by 2050. This reduction is projected to result in a cumulative decrease of approximately 170 MtCO_2e in process emissions by 2050.

The key drivers of this trend include the increased use of clinker substitutes such as slag and fly ash. However, the long-term availability of slag and fly ash is expected to due to the phasing out of blast furnace technology. Alternate, low-carbon cement is another key driver for declining cement-to-clinker ratio. Share of OPC that consists of 90-95% clinker is expected to reduce over time and will be compensated by an equivalent increase in blended cement such as LC3.

Figure 5.4: Reduction in Clinker-to-Cement Ratio and Associated Process Emissions[20]



20 Based on available data; estimates are indicative, subject to change



Source: GCCA, Team Analysis

5.2.1 Availability of clinker substitutes

The availability of slag and fly ash will be significantly curtailed post 2050 due to phasing down of coal and blast furnace plants. As a result, it will be necessary to explore alternative materials to continue reducing the clinker-to-cement ratio. Several promising substitutes beyond fly ash and slag including calcined clay, limestone, bio ash, have been identified and need further exploration and development.

Their indicative potential has been summarised below:

(i) Availability of slag and fly ash is expected to decrease post 2050.

(ii) **Calcined clay:** India has an estimated 1.5 Bt of utilisable reserves, with additional unexplored potential reserves that could significantly contribute to cement blending.

(iii) **Limestone:** Approximately 200 Bt of limestone reserves can be used as substitute for clinker, beyond its current use in clinker production.

(iv) **Bio ash:** Rice husk, rice straw ash and bagasse ash can provide 15-20 million TPY, provided strong supply chain essentials are developed.

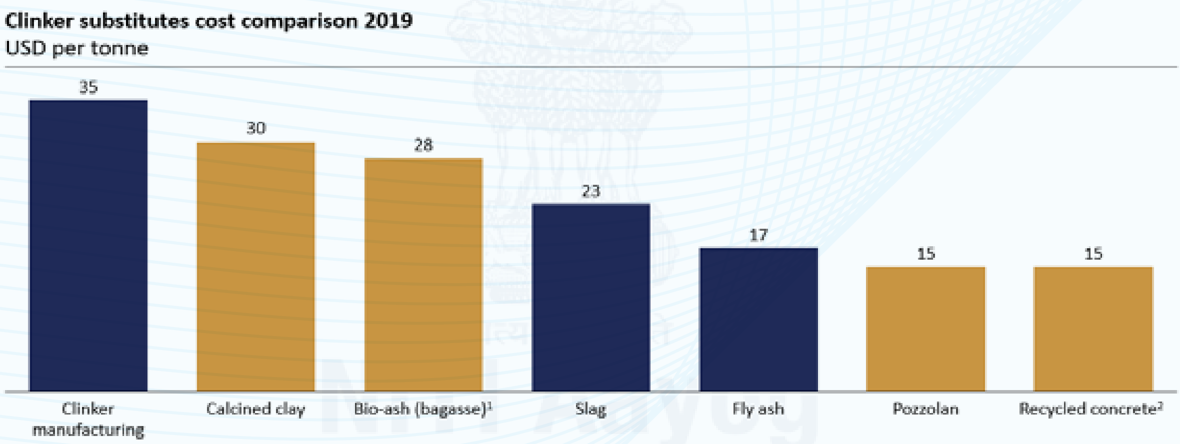
(v) **Construction & Demolition waste:** BIS now permits the use of concrete made from recycled material and processed C&D waste. However, concrete users must integrate this into circular value chains.

As of 2022 in India, BIS had approved only three blended cements - PPC, PSC and Composite Cement. The other types of blended cements namely PCC made with fly ash and limestone (PCC), PLC, PDC, LC3 and multi-component blended cements are at different stages of development in India (GCCA 2022). Additionally, alternative low-carbon cements such as Geopolymer Cement and Super Sulphated Cement are emerging as promising options and may warrant further research and standardisation support.

5.2.2 The role of clinker substitutes in green cement

The increased use of clinker substitutes in cement production could significantly enhance the green cement market. By replacing clinker with SCMs, carbon emissions from cement production can be substantially reduced. This shift supports global sustainability goals. As the demand for environment friendly materials grows, clinker substitutes will serve as a catalyst for technological innovation and investment in the sector. This evolving opportunity will add substantial value to the sector. The cost comparison of the various clinker substitutes varies in the range of USD 15-30 per ton and is presented in the Figure 5.5.

Figure 5.5: Supplementary Cementitious Materials Cost Comparison, 2019[21]

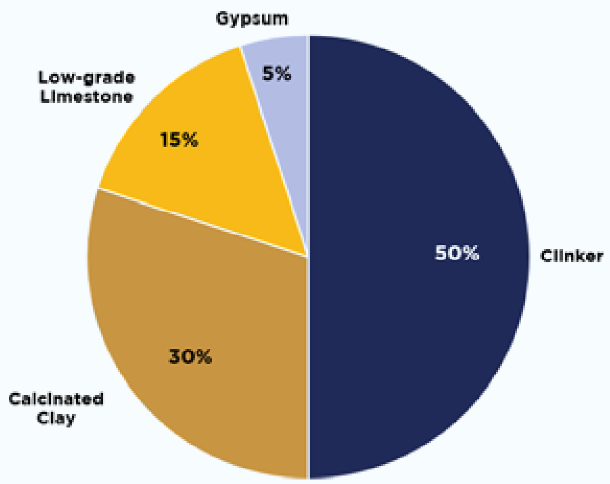


5.2.3 Alternative low-carbon cement

Limestone Calcined Clay Cement (LC3) is a blend of clinker, low-grade limestone, calcined clay and gypsum. Figure 5.6 illustrates the composition of LC3 cement. It has **50% clinker ratio**, resulting in approximately 35-45% less CO_2 emissions compared to OPC. In the production of LC3, clay is calcined at **lower kiln temperatures** (800°C) as compared to the 1500°C required for OPC. This lower temperature minimises CO_2 emissions associated with the calcination of limestone. Furthermore, clinker produced for LC3 is softer as compared to OPC clinkers, thus requires less energy in grinding Annexure 4.

21 Based on bagasse prices from CERC, bio-ash is likely to cost less; Based on recycled concrete prices in US (lower cost in range assumed). These estimates are indicative based on available data and are subject to change

Figure 5.6: Composition of LC3



The raw materials required to produce LC3 are more readily available in India. As of 2015, clay and limestone reserves were 2,941 Mt and 16,336 Mt respectively. Notably, the production of LC3 **does not require additional sophisticated equipment.** The equipment- old rotary kilns used in wet processing, suitable for clay calcination, is already available in cement plants. **LC3 exhibits a similar performance and strength compared to OPC after 28 days setting of concrete (comparable to CEM I).** This efficacy can be attributed to the highly reactive nature of calcined clay and its synergistic interaction with limestone. However, the initial setting strength of LC3 concrete (1 and 3 days) is lower compared to OPC-based concrete.

Currently, LC3 technology is being scaled up for commercial production, particularly in Africa and South America, with some developments in Asia. Key drivers for this expansion include reduced clinker imports, lower production-related energy costs, and the availability of kaolinite clay. In India, LC3 is also actively under development, and a BIS standard (IS 18189:2023) was released in 2023 to support its adoption. Plants in Europe are also being established and were expected to commence production by the end of 2023. Overall, the cumulative global capacity for LC3 is projected to reach approximately 2.2 Mt per year.

To promote LC3, several key actions need to be taken. While calcined clay is available in abundance in Rajasthan, Kerala, West Bengal, a comprehensive mapping exercise is needed to assess the feasibility of transporting clay to cement plants. Building confidence among consumers is crucial by developing knowledge products on the benefits of LC3. It is important to create a compelling business case for developers, contractors and consumers by assessing techno-economic benefits of LC3 over traditional cement.

5.2.4 Calcium sulfoaluminate

CSA cement, also known as Calcium sulfoaluminate, is another low-carbon alternative cement being used in countries like China and Australia. CSA cement or Belitic clinker, is a type of cement characterised by its high alumina content and is known for its fast setting and low-shrinkage properties. The main constituents of CSA are 20-45% ye'elimite, 45-75% belite and gypsum.

Key properties of CSA cement:

(i) Fast Setting: CSA cement has a rapid setting time, which can be advantageous in construction projects requiring quick turnaround.

(ii) Low shrinkage: It exhibits low shrinkage, reducing the risk of cracking.

(iii) High early strength: It achieves high early strength, making it suitable for applications where early load-bearing capacity is essential.

5.2.5 Environmental Benefits:

CSA cement is considered a green cement due to its potential to reduce carbon emissions by 20-50% compared to traditional OPC. However, its production involves the use of bauxite to achieve the desired ye'elimite content, which can be expensive. This results in higher costs compared to OPC.

Cost considerations:

(i) **Cost in Europe:** CSA cement typically costs 2-3 times more than OPC.

(ii) **Cost in China:** In China, the cost is about 1.5-2 times higher than OPC.

Due to its higher cost, the use of CSA cement is typically limited to specific applications where its benefits can justify the expense. These applications include:

(i) **Specialised construction projects:** Projects requiring rapid setting and high early strength, such as repairs and precast concrete elements.

(ii) **Sustainability-Focused Projects:** Projects aiming to reduce carbon emissions and achieve lower emissions.

5.2.6 Market Dynamics:

The market for CSA cement is relatively niche, with production primarily concentrated in a few countries. Major producers include companies in China and Bluey CSA Cement in Australia. Currently, CSA cement penetration in the global market is currently around 2-3%

(i) **Input-based versus performance-based standards for cement**

Input/recipe-based standards often focus on the composition, restricting it to a set of predefined chemical and/or physical requirements. In contrast, performance-based standards focus on the final performance of the concrete mix rather than prescribing specific ratios or materials to meet certain thresholds (e.g., strength), without specifying how these standards must be achieved. This approach encourages the production of low-carbon products aiming to reduce overall environmental impact (ECOS 2024). The detailed comparison of the input-based standards and performance-based standards is provided in Table 5.6.

Table 5.6: Comparison of Input-based and Performance-based Standards for Cement

	Input-based standards	Performance-based standards
Definition	Specify the composition and physical properties of the raw materials and additives used in cement production. Focus on the technical product standards, including the hydraulic and cementitious properties of SCMs.	Focus on the desired performance outcomes of the final cement product in real-world applications, such as strength and durability, rather than prescribing specific input materials or processes.
Pros	Ensures consistency and quality of raw materials. Provides clear guidelines for manufacturers, facilitating regulatory compliance. Easier to enforce and lower compliance costs for producers.	Allows for flexibility and innovation in achieving desired performance outcomes. Ensures higher quality and safety of the final product. Encourages adaptation to specific project requirements.
Cons	May limit innovation and flexibility in product development. Does not guarantee the desired performance of the final product. Limits potential for maximising clinker substitution and hence, decarbonisation.	US: Requires more complex testing and evaluation processes but advancements in testing technology and methodologies make them more reliable and efficient for ASTM C1157 EU: Higher compliance costs for producers and potential for non-compliance. This was addressed with industry collaboration and demonstration projects for EN 206 Australia: Requires re-evaluation of existing standards and changeover. All stakeholders were involved, and clear guidelines were developed for the Australian standard, AS 3600.
Examples	ASTM C150: This standard specification for Portland Cement specifies the allowable limits for components such as calcium oxide, silicon dioxide and aluminum oxide, among others. IS 269: This Indian standard specifies chemical composition, physical properties and performance characteristics for OPC. It also includes guidelines for the use of raw materials and additives.	ASTM[22] C1157: This is the American Standard performance[23] specification for hydraulic cement and has been incorporated into the International Building Code. It allows use of various raw materials and additives if the final product meets specified performance criteria, such as strength, durability and setting time. (ASTM standards are evolving and new specifications are being developed to allow the use of more sustainable materials) EN 206: This European Standard similarly specifies the performance requirements for concrete allowing use of different types of cement and additives.

22 Advancing Standards Transforming Markets Standards for cement and concrete

23 The Prescription to Performance (P2P) initiative by the National Ready Mixed Concrete Association (NRMCA) was created to develop and encourage implementation of performance specifications.

(ii) **Proposed interventions to expand the usage of clinker substitutes**

To enhance the adoption of clinker substitutes and promote decarbonisation in the cement sector, the following interventions have been proposed: 1. Transition from input-based standards to performance-based standards 2. Defining standards for CSA cement usage 3. Mapping of new clinker substitutes in India (e.g, calcined clay, calcium silicate deposits, etc.) 4. A mining and transportation policy for new clinker substitutes like calcined clay.

The transition from input-based standards to performance-based standards aims to enhance the efficiency and sustainability of the cement sector. The BIS can lead the process of defining usage standards for CSA cement as illustrated in Figure 5.7 For mapping new clinker substitutes, efforts will focus on identifying alternative materials and conducting geological surveys to pinpoint potential deposits. The GSI can undertake resource mapping to detail the location, size, and quality of these deposits. An evaluation of the current supply chain infrastructure will help identify gaps in the transportation and processing of these new materials, with support from Ministry of Mines and DPIIT.

Figure 5.7: Proposed Interventions for Clinker Substitution

Intervention	Responsible Entity
Transition from input-based standards to performance-based standards for cement	BIS
Defining standards for CSA Cement (Calcium Sulpho Aluminate) Usage	BIS
Mapping of new clinker substitutes in India e.g. calcined clay, calcium silicate deposits, etc.	Geological Survey of India
Mining and transportation policy for new clinker substitutes like Calcined clay	Ministry of Mines and DPIIT

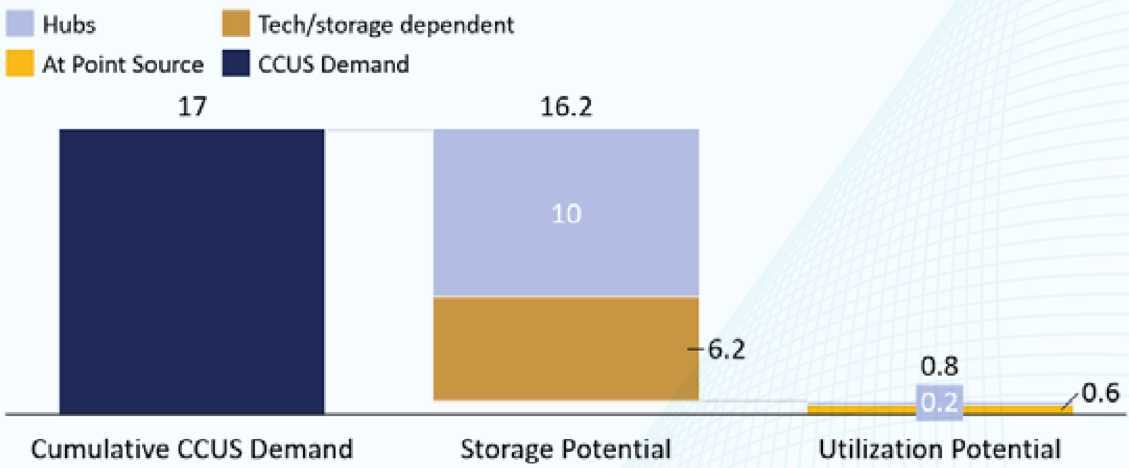
5.3 Carbon Capture Utilisation and Storage (CCUS) Pilots for the Cement Sector

Conventional cement production presents limited deep decarbonisation pathways due its combination of process-reared emissions and high heat demand- making CCUS one the few viable solutions. By addressing both process and thermal emissions, CCUS stands out as a particularly impactful option for reducing emissions in the cement industry-provided it can be scaled effectively.

5.3.1 CCUS potential in India

Most roadmaps agree that CCUS will need to play a significant role in decarbonising the cement sector. For example, the Global Cement and Concrete Roadmap (GCCA 2021) shows that CCUS will need to be responsible for 36% emissions reduction in a global net-zero scenario by 2050. This means that out of the estimated 524 MtCO_2e per year by 2070, CCUS will need to abate 157-210 MtCO_2e annually (McKinsey Sustainability 2022).

Figure 5.8: CCUS Abatement Potential in India; Cumulative Emissions by 2070, GtCO_2e



Overall, out of the estimated 17 GtCO_2 per year demand for CCUS by 2070, 16.2 GtCO_2 i.e. 95% will be met through CCS in underground storage and 0.8 GtCO_2 i.e. 5% is likely to be through CCU (Figure 5.8). This 95% CCS potential, however, has extensive pre-requisites related to investments and infrastructure development, which will need 5-10 years of preparation to begin being viable. These key pre-requisites include:

(i) Conducting geological survey and **mapping to locate suitable storage sites**.

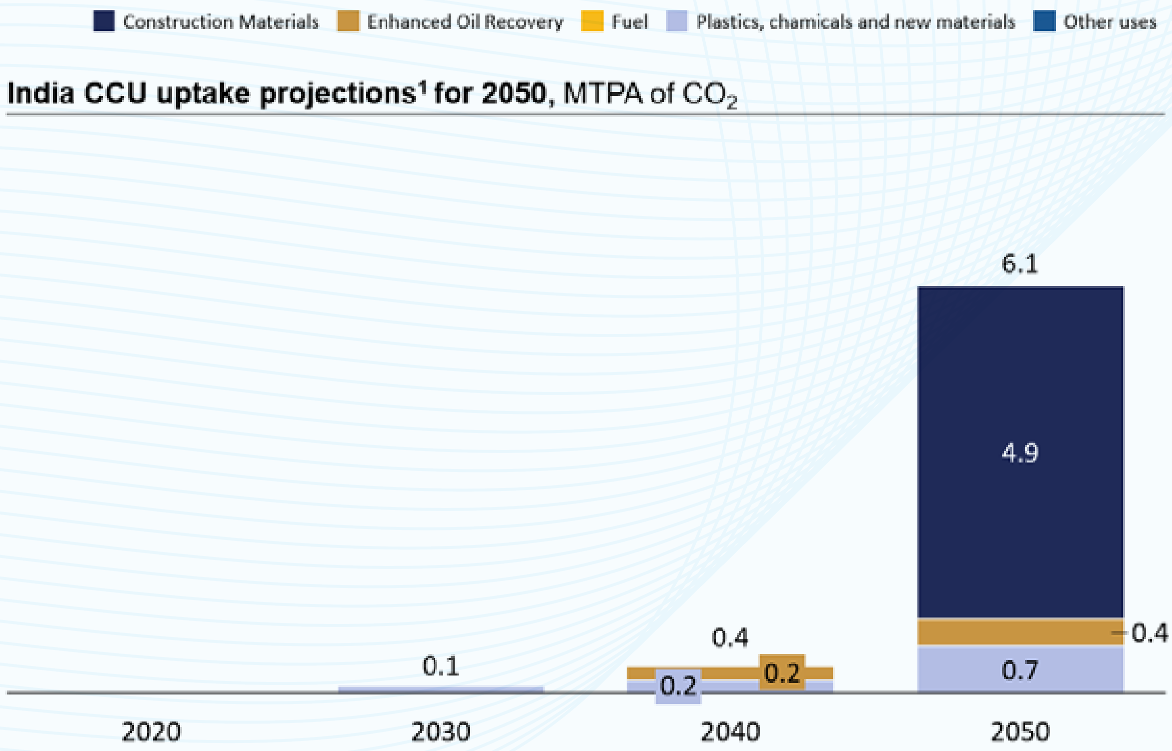
(ii) **Identifying and securing land** through government land leases and public-private partnerships.

(iii) Conducting route planning and environmental assessments, securing rights-of-way and constructing pipelines for the **development of infrastructure**.

These pre-requisite steps will also need extensive public consultation, complex multi-stakeholder engagement to create a policy framework, along with feedback channels to address local community concerns.

5.3.2 **CCUS potential and key barriers**

Figure 5.9: Projections for CCUS Uptake by Usage Type in India by 2050



Source: Decarbonising India, McKinsey, October 2022

Note: (MTPA of CO2 based on preliminary analysis)

Based on preliminary analysis by McKinsey, as shown in Figure 5.9, around 80% of CCUS demand is expected to come from its application in construction materials. However, several key challenges need to be addressed to unlock the potential of CCUS in the cement sector. These include:

(i) Demonstrating the technical feasibility of various CCUS technologies, which remains a significant challenge. Many technologies lack large-scale demonstration projects, creating **technical uncertainty**.

(ii) Accurately estimating the real costs of carbon capture at a local level is difficult and deters investments due to **uncertainties on returns**.

(iii) Uncertainties regarding the commercial potential and demand for CO_2 derived products, which poses **market viability uncertainty**.

(iv) The absence of local pilot projects results in **inefficiencies and delays** optimisation of capture and utilisation processes for cost-effectiveness and efficiency at scale.

(v) **Insufficient infrastructure** for the transportation, storage and utilisation of captured CO_2 such as pipelines, transportation routes, injections wells and facilities to temporary CO_2 storage facilities.

(vi) A **lack of regulatory support** and the absence of a robust regulatory framework and incentives limits the adoption and scaling of CCUS technologies.

5.3.3 Intervention approach to unlock CCUS potential in India

NITI Aayog constituted four inter-ministerial committees in the area of safety and technical standard development, carbon capture, utilisation, transportation and storage and presented it during the 25th Prime Minister's Science, Technology & Innovation Advisory Council (PM-STIAC) meeting. Based on the decision during the meeting, Ministry of Power constituted an Inter-Ministerial Committee for drafting the CCUS Mission Document.

Objectives of the CCUS Mission:

(i) To facilitate RDI (Research, Development & Innovation) of CCUS technologies and undertake necessary steps for cost reduction of these technologies to nurture human resource and infrastructure for capacity building.

(ii) Leverage bilateral and multilateral linkages for accelerating the CCUS technologies to higher TRLs and market readiness levels.

(iii) To formulate strategic framework for CCUS aligned with national environmental and energy commitments.

(iv) To identify the potential of carbon capture in India and mapping the source and sink areas for development of potential hubs.

(v) To facilitate pilot level/large scale deployment of CCUS demonstration projects in major CO_2 emission sectors.

(vi) To formulate/develop policy measures related to economic feasibility of CCUS projects such as Direct Capital Grant, Operational subsidies, Carbon credit mechanism, Tax incentive/penalty etc.

(vii) To take steps for increasing the manufacturing capacity for deployment of CCUS projects.

(viii) To enable India to assume leadership in carbon capture, utilisation, transportation and storage technologies.

5.3.4 Focus on the cement sector: targets and investments

Under the Mission, the intended target for the cement-sector is 2,000 TPD of capture (~0.67 MTPA) and 2,000 TPD of utilisation (building materials, carbonates, polycarbonates) for pilot projects, with integrated planning for transportation, storage and Enhanced Oil Recovery (EOR). The initial planned CCU projects under the proposed National Mission on CCUS are expected to capture and utilise 2,000 TPD, with an estimated investment of INR 1,100 crore.

The initial phase of implementation of CCUS in cement sector is expected to occur as part of the National CCUS Mission.

CONCLUSION

Conclusion

Decarbonising the cement industry will require a multifaceted approach. This report prioritises three high-impact solutions given their significant emission reduction potential and favorable cost-benefit analysis - **Alternative Fuels, Clinker Substitutes, Carbon Capture Utilisation and Storage.** Each of these decarbonisation measures presents distinct challenges. However, analysis indicates that implementing a combination of measures could help achieve a cumulative emissions reduction of approximately 100-150 $MtCO_2e$ by 2030.

Increasing the usage of **Refuse Derived Fuel** from Municipal Solid Waste is projected to cumulatively cut emissions by around 30 to 70 $MtCO_2e$ by 2030. Developing a robust MSW management ecosystem could also attract investments of approximately INR 15,000 crore and generate an estimated 62,000 jobs across the value chain[24]. This demonstrates how resource circularity not only enables significant emissions reductions by providing alternate fuels, low-carbon fuel sources and but also supports sustainable development by generating substantial employment opportunities throughout the waste-to-fuel value chain.

Incorporating **clinker substitutes**, which is already underway in the cement sector, must expand to incorporate alternative materials such as calcined clay and limestone. With the expected decline of slag and fly ash post-2050, it will become essential to use recycled materials, processed construction and demolition waste, establish robust supply chains and integrate circular value chains across production systems.

CCUS is expected to play a critical role in decarbonising hard-to-abate sectors, especially the cement industry, where process emissions alone account for nearly 50% of total emissions. In this context, CCUS has the potential to reduce 35-54% of emissions in the cement sector in a phased manner. CCS implementation, which represents nearly 95% of the total potential, requires identifying and mapping suitable storage sites, land acquisition, and developing transport infrastructure. As an immediate step, the cement sector can look at implementing CCU-based projects. The initial planned CCU projects under the proposed National Mission on CCUS are expected to capture and utilise 2,000 TPD, with an estimated investment of INR 1,100 crore.

The successful decarbonisation of the cement sector will depend on: enhanced stakeholder collaboration, advancement in research and development, adoption of innovative technologies, and robust policy and regulatory support. Together these enablers will enable the cement sector to achieve decarbonisation goals, while contributing to greener economy and sustainable future.

24 Job creation rate of ~ 4.13 jobs per crore of investment
(These estimates are indicative based on available data and are subject to change)

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ANNEXURE

Annexure 1

Technical Working Committee on Cement Sector

413878/2024/ENERGY

File No. 13(49)/2024-I&M(I)
Government of India
NITI Aayog
(Industry Vertical)

Dated: 10th May, 2024

Office Memorandum

Subject: Constitution of Technical Working Committees for formulating Decarbonisation Roadmap of Industry Sectors (i.e. Steel, Cement & Aluminium) and the selected MSME Sector.

India has made commitments to transit towards a more environmentally friendly economy. At COP26, India announced its ambition to become a net-zero emitter by 2070. Decarbonisation of industry sector will be a critical aspect to realize international commitments on climate change. Industry sector is wide and diverse and therefore it is felt that sectoral roadmaps especially for Hard to Abate Sectors shall be a way forward towards green transition.

2) In view of the above, with an objective to take a comprehensive approach and formulate sectoral decarbonization roadmap for the selected Hard to Abate Sectors i.e. Steel, Aluminium & Cement and the MSME sector, the following sectoral technical working committees are constituted:

A. Technical Working Committee on Steel Sector

Sr. no.	Composition	
1	Shri Ishtiyaque Ahmed, Sr. Advisor, NITI Aayog	Chairman
2	Shri Rajnath Ram, Adviser, NITI Aayog	Member
3	Representative from the Ministry of Steel	Member
4	Representative from BEE	Member
5	Representatives at the level of Chief Sustainability Officer or equivalent from:	
	• Tata Steel Limited,	Member
	• Jindal Steel Works,	Member
	• Arcelor Mittal Nippon Steel India,	Member
	• Jindal Steel & Power,	Member
	• Jindal Stainless Limited,	Member
	• Steel Authority of India Limited	Member
	• Kalyani Steels Limited	Member
6	McKinsey & Company	Knowledge Partner
7	Shri. Rupesh Singh, Sr. Specialist, NITI Aayog	Member-Secretary

B. Technical Working Committee on Cement Sector

Sr. no.	Composition	
1	Shri Ishtiyaque Ahmed, Sr. Advisor, NITI Aayog	Chairman

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Generated from eOffice by Ravi Kumar, CG-I(Energy)-RK, CONSULTANT GRADE I, NITI aayog on 02/04/2025 11:32 am

2	Shri Rajnath Ram, Adviser, NITI Aayog	Member
3	Representative from DPIIT	Member
4	Representative from BEE	Member
5	Representatives at the level of Chief Sustainability Officer or equivalent from:	
	• Ultratech Cement	Member
	• ACC	Member
	• Ambuja	Member
	• Shree Cement	Member
	• Dalmia Cement	Member
6	Representative of Global Cement and Concrete Association	Member
7	Representative of Cement Manufacturers Association of India	Member
8	McKinsey & Company	Knowledge Partner
9	Shri Manoj Kumar Upadhyay, Deputy Adviser, NITI Aayog	Member-Secretary

C. Technical Working Committee on Aluminium

Sr. no.	Composition	
1	Shri Ishtiyaque Ahmed, Sr. Advisor, NITI Aayog	Chairman
2	Shri Rajnath Ram, Adviser, NITI Aayog	Member
3	Representative from Ministry of Mines	Member
4	Representative from BEE	Member
5	Representative from Jawaharlal Nehru Aluminium Research Development & Design Centre	Member
6	Representatives at the level of Chief Sustainability Officer or equivalent:	
	• Hindalco	Member
	• Vedanta	Member
	• NALCO	Member
	• Jindal Aluminium	Member
7	McKinsey & Company	Knowledge Partner
8	Shri. Jawahar Lal, Chief Engineer, NITI Aayog	Member-Secretary

D. Technical Working Committee on MSME

Sr. no.	Composition	
1	Shri Ishtiyaque Ahmed, Sr. Advisor, NITI Aayog	Chairman
2	Shri Rajnath Ram, Adviser, NITI Aayog	Member
3	Shri Ateesh Kumar Singh, Joint Secretary, Ministry of MSME	Member
4	Ms Neha Nautiyal, Deputy Secretary, NITI Aayog	Member
5	Representative from BEE	Member

6	Representative from Federation of Small-Scale Industries (FSSI)	Member
7	Representative from Karnataka Small Scale Industries Association (KASSIA)	Member
8	Representative from Federation of Small & Medium Industries (FOSMI)	Member
9	Representative from SIDCUL Manufacturers Association of Uttarakhand (SMAU)	Member
10	Representative from Federation of Indian Micro and Small & Medium Enterprises FISME	Member
11	Representation from Laghu Udyog Bharti	Member
12	McKinsey & Company	Knowledge Partner
13	Shri. Aman Hans, Resident Fellow, NITI Aayog	Member-Secretary

3) TERMS OF REFERENCE:

I. Identifying the sources of emission along the production value chains and establishing baseline sectoral emissions.
II. Analysing the current strategies of the government and private sector.
III. Analysing the international market trends and preparing the sector outlook on competitiveness.
IV. Identifying and prioritising, the various decarbonisation levers for each sector including circular economy and resource efficiency.
V. Developing sector specific abatement curves to illustrate decarbonisation levers, their potential abatement and associated costs.
VI. Identifying key projects and enablers required to achieve aspired decarbonisation pathways including:
    a. Policy and Regulatory frameworks
    b. Technology interventions, with high-level assessment on commercial viability
    c. Sources of capital and funding
VII. Formulating sector specific action plan and associated financial funding mechanism.
VIII. Any other measures/activities required for achieving the objectives of the Committee.

4) Industry Vertical, NITI Aayog will be responsible for overall co-ordination.

This issues with the approval of competent authority.

10/5/2024

(Rupesh Singh)
Senior Specialist
Telephone: 23096801

To,

All the Member (Via e-mail and request to nominate representative)

3/4

Annexure 2

List of 22 Recommendations

S.no.	No. of Solutions	Category	Recommendations
1	**7**	**Economically viable solutions industries can implement independently based on energy efficiency**	Improved Refractory Materials
2			Kiln combustion systems improvements
3			Efficient clinker coolers
4			Efficient kiln and pre-heater
5			Automation system
6			Burner retrofit
7			Heat rate reduction in captive power plant
8	**5**	**Economically viable solutions, which require regulatory support**	Transition from input-based standards to performance-based standards Definition of standards for CSA cement usage
9			Mapping of new clinker substitutes in India
10			Blending mandates to increase adoption of alternatives to fly ash and slag
11			Amendment of green building rating to increase usage of low carbon cement
12			Assessment study for India's recarbonation potential
13	**2**	**Initiatives that require policy support from the Government**	Scaling CCUS for cement industry
14			Development of supply chain of green and alternate fuels
15	**8**	**De-prioritised solutions** (Economically viable initiatives, which may not need govt. support, initiatives unlikely to accelerate decarbonisation)	100% fly ash and pond ash generated in the country to be allocated to cement manufacturing
16			Preferential allocation to cement sector for usage of wastes
17			Polluter Pays Principle
18			Freight subsidy for fly ash transport
19			Procurement of low-carbon cement
20			Substituting materials, which have a high decarbonisation potential
21			Consideration of Waste Heat Recovery (WHR) as renewable energy for the purpose of RPO
22			Propagation of cast structures for the efficient use of cement

Annexure 3

Increased usage of RDF from MSW

Comparative analysis of RDF usage across key sectors

Criteria for ease of implementation	Cement Plants	Thermal Power	Iron and Steel	**Brick Kilns** (Not recommended in SWM Rules, 2016 compared for analysis purpose only)
RDF size Specifications	RDF size is acceptable(<50mm)	Additional shredding required(<2 mm)	RDF cannot be used as fuel for steelmaking as the process is autogenous. The usage of RDF as fuel in other processes like sinter making or in reheating furnaces was also explored by Steel Authority of India (SAIL) and it was opined that since the present mode of energy supply to sinter and reheating furnaces is gaseous, solid RDF would not be appropriate for those applications also	RDF size is acceptable
Impact on Final Output	Negligible impact on final product	RDF contaminants like Silica and Chlorides corrode the heating surface, there by affecting the boiler	Burning RDF affects forward reaction rate which leads to lower production of pure iron from the ore	No impact on final product
Feeding Mechanism	Alternate feeding mechanism in place for feeding AFR	Alternate feeding mechanism needs to be installed	Alternate feeding mechanism needs to be installed	Alternate feeding mechanism not needed
Environmental Impact	None if proper safe guards are in place; additionally it leads to net reduction in GHG emissions	Toxic emissions like dioxins and furans	Toxic emissions like dioxins and furans	Toxic emissions like dioxins and furans
Residue Disposal	None, as it becomes part of the clinker	Higher generation of fly ash and clinker formation on grate	Higher generation of slag, which is a difficult to manage waste	Ash and non-combustible part of RDF need to be disposed

Source: Guidelines on Usage of RDF in Various Industries, MoHUA

Learnings from the Indore and Goa Municipal Corporation

Effectively managing MSW is a complex task that requires continuous monitoring and efficient service delivery. The Indore Municipal Corporation has emerged as a national benchmark of excellence in MSW management, demonstrating remarkable innovation and efficiency under the Swachh Bharat Mission (SBM). Indore has consistently ranked among the cleanest cities in India since 2017, according to the Swachh Survekshan Surveys. (iCED, TERI 2022).

Municipal Solid Waste Management, Source: Indore Municipal Corporation

Indore's success stems from its holistic, citizen-centric approach to implementing the SBM. The city emphasises on sustained engagement, innovative solutions, and highly efficient waste management systems. This sustained commitment to cleanliness and sanitation has positioned Indore as a model city, continuously setting new standards for creating cleaner, healthier urban environments across the country.

Indore has achieved nearly 100 percent door-to-door collection of segregated waste from households, commercial establishments and institutions. Waste is segregated at the source into categories such as wet waste, dry waste (plastic and other recyclables), sanitary waste, Domestic Hazardous Waste (DHW) and e-waste. This significantly enhances the efficiency of waste processing. The city has a dedicated waste stream collection system and operates multiple waste processing facilities, including composting plants, bio-methanation units and material recovery facilities (MRFs). This ensures that only non-recyclable residual waste is sent to landfills, and scientific disposal methods are employed to minimise environmental impact. The city has also made substantial progress in remediating legacy dumpsites, converting them into green zones and reclaiming valuable urban land.

Indore leverages Information and Communication Technology (ICT) tools, utilising digital platforms for real-time monitoring of waste collection and processing, to enhance waste management and sanitation, while ensuring transparency and efficiency. The Swachhata App and the Indore 311, a grievance redressal platform, launched in 2016, empower residents to report sanitation issues, which are promptly addressed by municipal authorities. Additionally, Indore has invested in capacity building for municipal staff and stakeholders involved in waste management. Regular training programs and workshops equip them with the necessary skills and knowledge to manage sanitation and waste effectively, contributing to the city's continued success in maintaining a clean and sustainable urban environment.

Moreover, Indore has successfully integrated MSW into the cement sector by transforming the value chain, beginning with effective source segregation. Initially, the Indore Municipal

Corporation faced challenges such as waste accumulation, frequent overflows and inefficient collection systems. The image below highlights how these issues were addressed through improved segregation, resource recovery, financial sustainability and technological interventions.

Impact and Results: By the end of 2017, Indore had achieved near-complete source segregation across households, with a three-bin system implemented in multi-storey buildings and commercial establishments.

Waste-to-Energy: RDF generated from segregated waste has been utilised as AFs in cement plants, reducing landfill dependency and promoting sustainable waste utilisation.

INITIAL CHALLENGES (2015)

Contract with A2Z: Initially, the Indore Municipal Corporation (IMC) outsourced waste collection and transportation to a private company, A2Z.

Secondary storage bins: Waste was primarily dumped in secondary storage bins, which led to waste accumulation, overflows, and inefficient collection.

DOOR-TO-DOOR COLLECTION

Area-specific pla**nning:** Critical insights for area-specific waste collection strategies was essential. High-density areas such as tourist zones required frequent cleaning-up to 4 times a day.

NGO engagement: NGOs were brought in to profile the city by analyzing family sizes, waste generation patterns, and specific needs of different zones (commercial, residential, and tourist areas).

INCREASED WORKFORCE AND INFRASTRUCTURE

Scaling the workforce: The waste management workforce grew from 4,000 to 10,000 employees, with 90% of them being contractual staff. IMC leveraged Smart City Mission funds, which allocated around INR 10 crore per month for manpower.

Infrastructure improvements: Indore set up 10 garbage transfer stations (GTS) and a fleet of vehicles mapped through an ICT-based monitoring system to optimize collection routes and frequency.

SEGREGATION AND RESOURCE RECOVERY

Segregation at source: Households were taught to segregate waste into wet, dry, and other categories. Fines of INR 2.5-3 lakhs per day were imposed for non-compliance, leading to a remarkable improvement in waste segregation and resultant quality.

Material Recovery Facility: A material recovery facility was established, where dry waste was sorted into 13-14 components for recycling. The RDF generated from segregated waste was supplied to cement plants, even up to 600 km away.

FINANCIAL SUSTAINABILITY

User charges: Indore implemented a system of user charges in 2017, where households paid between INR 60-150 per month depending on the area. Religious fairs, political rallies, and large gatherings were also charged for the waste they generated.

Fines for non-compliance: A strict system of spot fines was introduced, encouraging households and businesses to comply with segregation and timely waste disposal.

TECHNOLOGICAL INTERVENTIONS

Indore 311 App: The city developed a service-delivery model via the Indore 311 App, allowing citizens to raise complaints and monitor the waste management process.

Vehicle monitoring and fleet management: Waste collection vehicles were equipped with GPS, allowing real-time tracking of routes and collection efficiency. The fleet made 4-5 trips per day, covering over 1,000 pockets across the city

The Goa Waste Management Corporation

In December 2016, the Government of Goa established the Goa Waste Management Corporation (GWMC) under the Goa Waste Management Corporation Act, 2016 (Goa Act 19 of 2016) to address all the waste-related issues in the state, including remediation of legacy dump sites. The GWMC is therefore a unique Special Purpose Vehicle (SPV), which is proactively working on solid waste management in the state.

250 TPD Integrated solid waste management facility, Saligao. Source: GWMC

GWMC operates a **250 TPD Integrated Solid Waste Management Facility** in Saligao, a first-of-its-kind project in the country, which is fully compliant with the *Solid Waste Management Rules, 2016*. The facility was developed on a former quarry site, which had been used as a waste dumping ground for over 25 years, leaving the area severely degraded. With the construction of the facility, the site was rehabilitated and restored to its natural state, making it a unique example of brownfield development in India.

The project is overseen by the Department of Science, Technology and Waste Management (DST&WM), which serves as the nodal department, while the Goa State Infrastructure Development Corporation (GSIDC) acts as the managing associate. The facility was developed a Design, Finance, Build, Operate and Transfer (DFBOT) model with a 10-year operation and maintenance period. The facility processes waste from village panchayats and urban local bodies in the northern coastal belt of Goa.

The facility underwent an expansion in response to increasing per capita waste generation and seasonal spikes especially during the tourist season. The upgradation, carried out by the GWMC, commenced on 29 August 2020 and was completed in December 2021 at a cost of INR 103.87 crore. Post-expansion, the facility's capacity increased from 150 TPD to 250-300 TPD, incorporating advanced waste treatment technologies. The GWMC pays the developer INR2,209.6 per ton of waste, plus 18% GST. As of May 2022, the facility has treated approximately 3 lakh tons of solid waste and generates around 25,000 units of electricity per day. Additionally, three more projects with a cumulative capacity of 450 TPD are under development.

Nodal department Department of Science, Technology and Waste Management	**PPP Model** DBFOT	**O&M Period** 10 years	**Private partner** Hindustan Waste Management	**Commencement of operations** 30 May 2016
Source of waste Northern coastal belt village panchayats and ULBs	**Solid waste treated** ~3 lakh tons till May 2022	**Electricity generated** ~ 25,000 + units per day	**Project cost** ~INR 250 crore	**Land** 12 hectares
Payment terms INR 2,209.6 +18% GST per ton of waste paid by GWMC to developer	**Contract duration with cement plants** 5-10 years	**Support provided** 50% transportation cost borne by GWMC		

Integrated Solid Waste Management, Goa Municipal Corporation

Key insights from the Goa and Indore models demonstrate their success in utilising RDF from MSW in the cement sector. This integration is facilitated by strong political support, active community engagement, an effective communication strategy, structured user charges, regular monitoring and robust technical oversight.

Annexure 4

Increased Usage of Clinker Substitutes - What is LC3?

Limestone Calcined Clay Cement or LC3 is an alternative binder to Ordinary Portland Cement (OPC), the most widely used type of cement today.

Ordinary Portland Cement (OPC)	Limestone Calcined Clay Cement or LC3
OPC is composed of 95% cement clinker and 5% of other additives such as gypsum	LC3 is prepared by **combining** • **50-60% of OPC clinker** • **Calcined kaolinite clay** (30%), **limestone** (15%) and **gypsum** (5%)

Key advantages of LC3:

(i) **Lower carbon footprint:** LC3 has an approximately 43% lower footprint compared to OPC due to lower kiln temperature (800 °C) for the calcined clay compared to 1500 °C for OPC and no CO_2 emissions from limestone calcination.

(ii) **Comparable performance:** LC3 is similar strength to OPC, requiring 28 days to set (comparable to CEM I).

(iii) **Synergistic efforts:** LC3 takes advantage of highly reactive calcined clay and its synergy with limestone.

(iv) **Highly scalable:** Both limestone and calcined clay are abundantly available worldwide supporting large-scale adoption.

Considerations while adopting LC3:

(i) **Lower early strength:** LC3 concrete (1 and 3 days) compared to OPC-based concrete.

(ii) **Commercial scale-up:** LC3 is still evolving in terms of commercial viability and cost competitiveness.

(iii) **Higher water demand:** Due to presence of metakaolin, LC3 requires more water for production.

Role of LC3 in decarbonising cement and concrete:

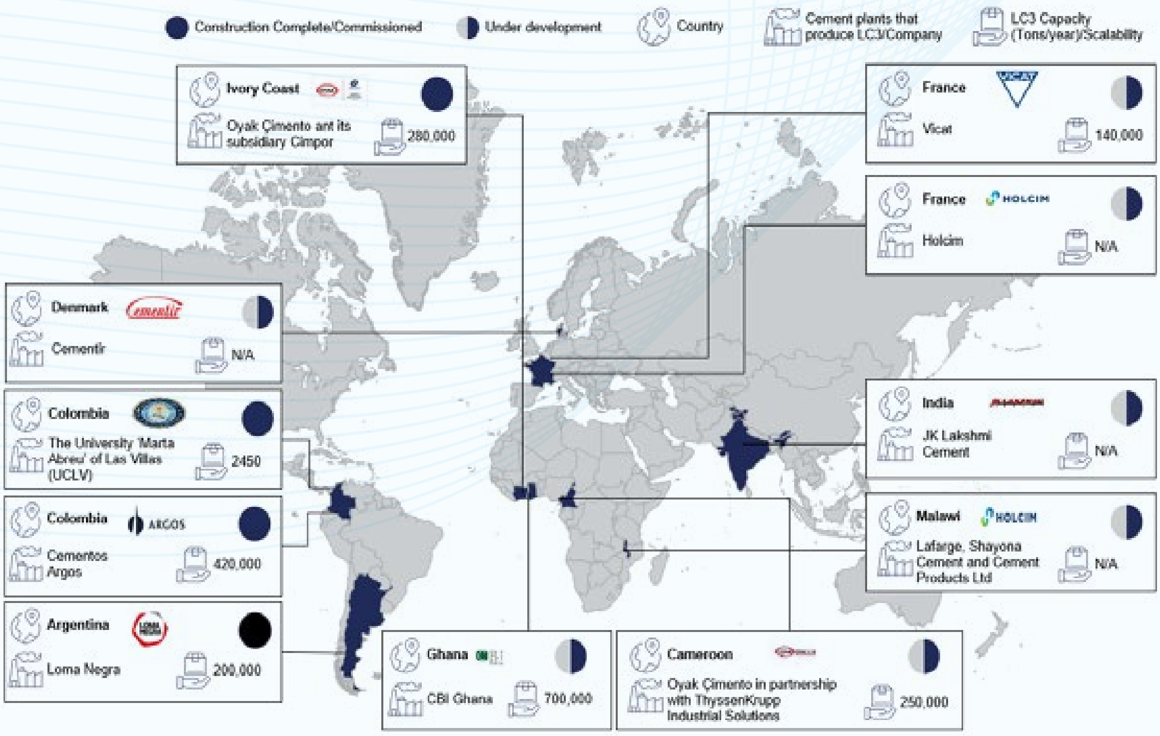
(i) **Clinker substitution:** LC3 production involves replacing 40-50% of OPC clinker with LC2 to produce LC3.

(ii) **Lower embedded carbon:** LC3 cement has approximately 35-45% less embedded carbon compared to OPC

(iii) **Main decarbonisation driver:** Clinker substitution through LC2 accounts for 55% of net carbon reduction compared to OPC cement.

	OPC (kgCO2/ ton)	LC3 (kgCO2/ ton)
Raw materials	480-500	240-270[1]
Fuel	260-380	150-189[2]
Other process elements	~80	~80
Total	**820-960**	**480-539**

Carbon reduction in LC3 compared to OPC



Source: Global Cement New, Cemnet News

Global Availability of LC3; Currently the largest plant is situated in Continental Blue investment (CBI) Ghana with a capacity of 7,00,000 tons per year

Key Takeaways

(i) **LC3 Technology** is primarily being **scaled up in Africa, South America with some additions in Asia.** Key drivers include reducing clinker imports, production-related energy costs and the availability of kaolinite clay

(ii) **Cumulative LC3 capacity globally of around 2.2 Mt/year** (Assuming 200,000 tons/year capacity for the unknown plant capacity

Annexure 5

1. CCUS: Oxyfuel, LEILAC, Amine are High Priority Carbon Capture Technologies (Part 1)

Prioritized in the medium-term · R&D · Demo/small Pilot · Industrial pilot · Industrial use

Approaches	Advantages	Disadvantages	Example pilots / companies	Technology Implementation	Implementation horizon	Capture efficiency (%)	Cost of capture[1]
Oxyfuel approach uses pure oxygen for combustion while recirculating flue gas to maintain temperature and increase CO_2 concentration	Potentially lower OpEx than post-combustion capture	High CapEx investment, equipment modification required	NORCEM, Heidelberg-Cement	Demo/small Pilot	Post-2025 Lab tests, demo plant pending	~85%	40-50 EUR/ton CO_2
LEILAC is a direct separation technology that separates CO_2 emissions generated from limestone processing in calciner	Low CapEx and OpEx, minimal retrofitting needed	Additional carbon capture technology necessary to process separated CO2	Heidelberg-Cement	Demo/small Pilot	Post-2020 Demo plant Post 2020	~60%	30-40 EUR/ton CO_2
Electrolysis creates cement without kiln and produces separated CO, as output	Low OpEx, O, fuel possible (and produced)	High CapEx, full process/equipment change	MIT	R&D	Research proof of concept	95%	<65-110 EUR/tCO2

Source: ECRA, CRS 2013, ZeroCO2.no, LEILAC.eu, NETL, NORCEM CO2 capture project (publ. Energy Procedia – 2014), Heilogen.com

2. CCUS: Oxyfuel, LEILAC, Amine are High Priority Carbon Capture Technologies (Part 2)

Prioritized in the medium-term · Capture efficiency, % · R&D · Demo/small Pilot · Industrial pilot · Industrial use

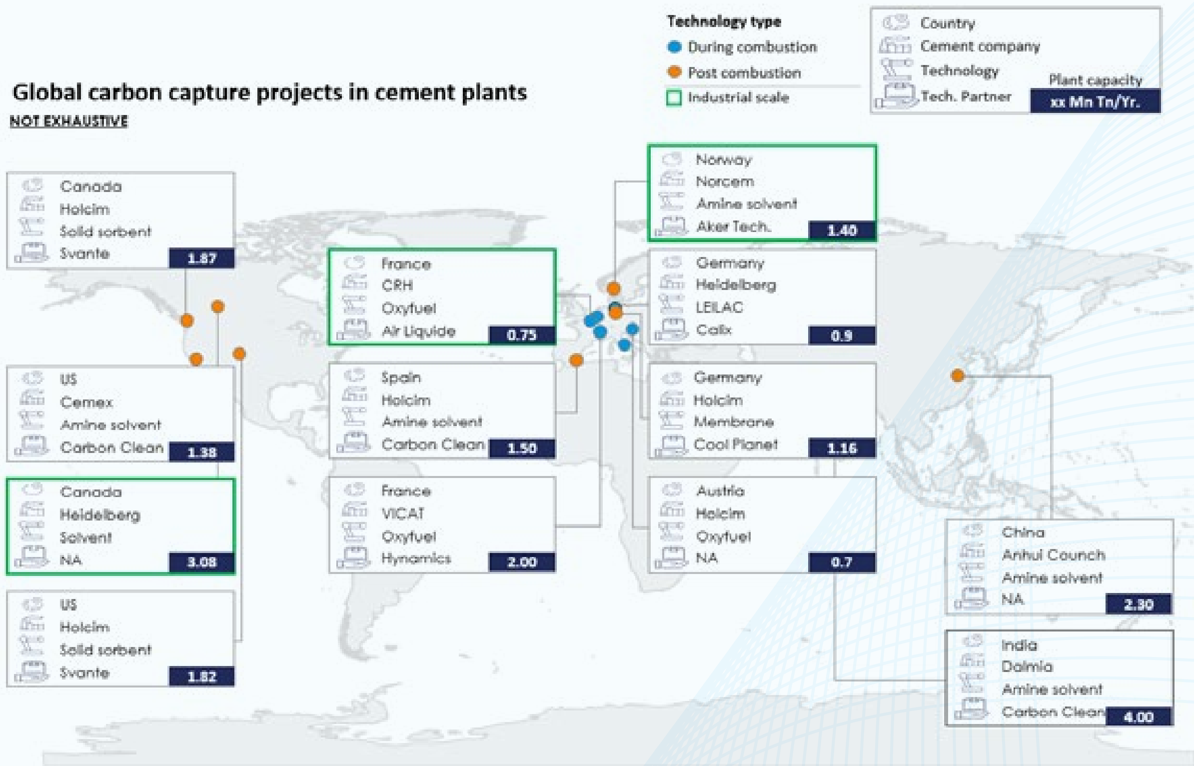
Approaches	Advantages	Disadvantages	Example pilots / companies	Technology Implementation	Implementation horizon	Capture efficiency (%)	Cost of capture[1]
Liquid solvents (e.g.,**amino scrubbing**) dissolve CO, from flue gas	Commercialized in other sectors	High energy (OpEx) costs	NORCEM	Industrial pilot	Post-2024 Pilot, plan for industrial scale-up Post 2024	~85%	65-110 EUR/ton CO_2
Membranes filter CO; from flue gas	Solvent regeneration not required	High energy (OpEx) costs, not yet scaled	NORCEM	R&D	Post-2025 Industrial tests	~90%	
Carbon looping takes carbon from flue gas and uses it to re-carbonize recycled concrete	Directly use anthropogenic CO_2 in own production	High energy (OpEx) costs	BUZZI Cement (CLEANKER project), NORCEM	Demo/small Pilot	Small pilot	~90%	<30EUR/ton CO_2
Solid **sorbents** adsorb CO from flue gas	More energy efficient than solvents	High energy (OpEx) costs, not yet commercialized	Cemex (Houston), NORCEM	Demo/small Pilot	Small pilot	~90%	

Source: ECRA, CRS 2013, ZeroCO_2no, LEILAC.eu, NETL, NORCEM CO_2 capture Project (publ. Energy Procedia – 2014), Heilogen.com

3. CCUS: Technological Pathways are Still being Developed, with Significant Cost Variation

CEMCAP analysis of cement CO_2 capture technologies; Costs assumed for a plant with 1 million tons clinker capacity per year. Multiple carbon capture technologies being developed in cement that may have lower costs than the primary industry pathways today – meaning costs may continue to fall

4. CCUS: Global Examples for Carbon Capture Implemented in Cement Plants



Source: Global Cement and Concrete Association

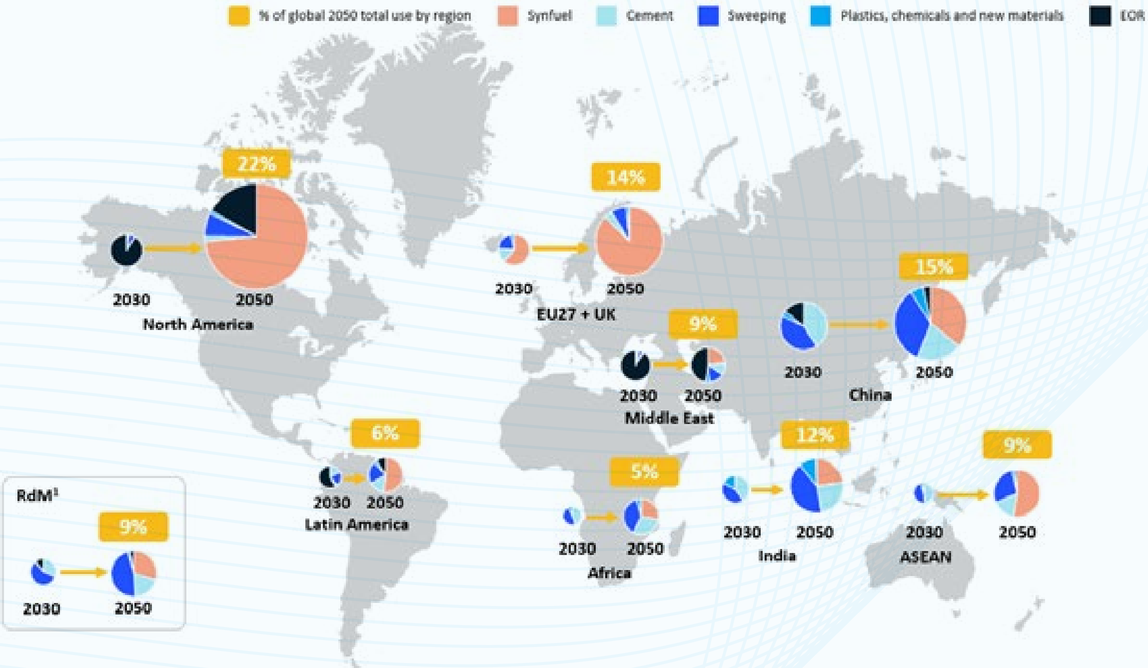
Key insights

(i) Globally, **approximately 26 cement plants currently implement carbon capture.**

(ii) >80% of these projects are in the **US, Canada and Europe**

(iii) Industrial scale carbon capture and storage facility Norcem plant, Brevik in Norway has been launched in June 2025 **which aims to capture 400kCO_2 per annum.**

5. CCUS: Portfolio of CO_2 Potential Utilisation Varies by Region

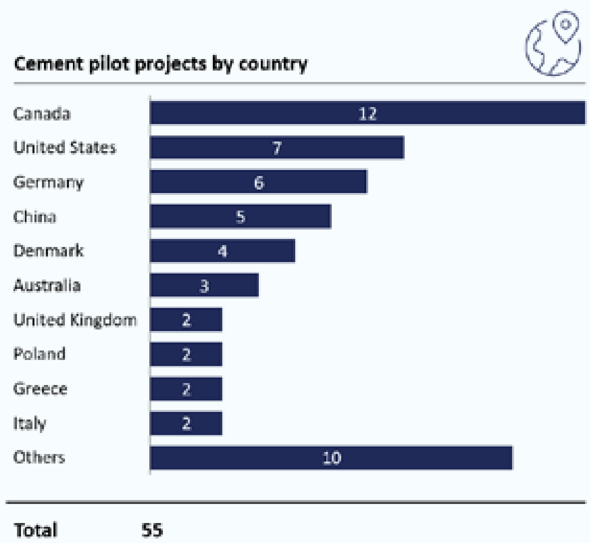


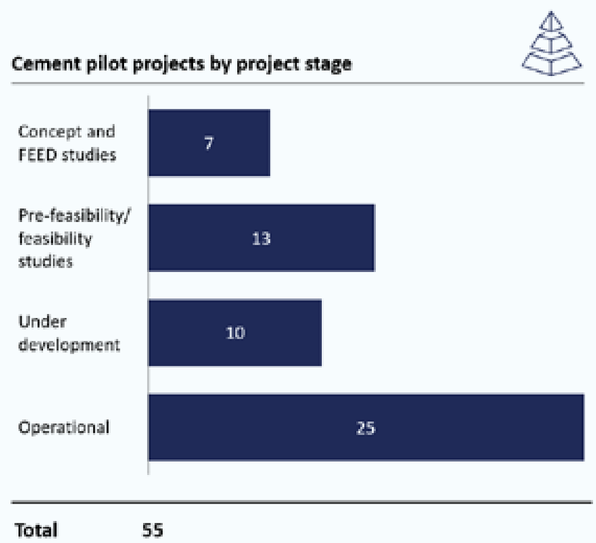
Source: McKinsey Energy Insights- CCUS demand model, 2022; 1. CIS, rest of Asia and rest of Europe

(i) North America and the EU27+UK have the highest demand for CO_2 feedstock for synthetic fuel. In addition, North America and the EU also benefit from mature technologies and economies of scale, making global market leaders.

(ii) The use of CO_2 in construction materials is mainly driven by Asian countries, as the regional demand for cement and aggregates is the underlying engine.

CCUS: Global CCU pilots in the cement sector



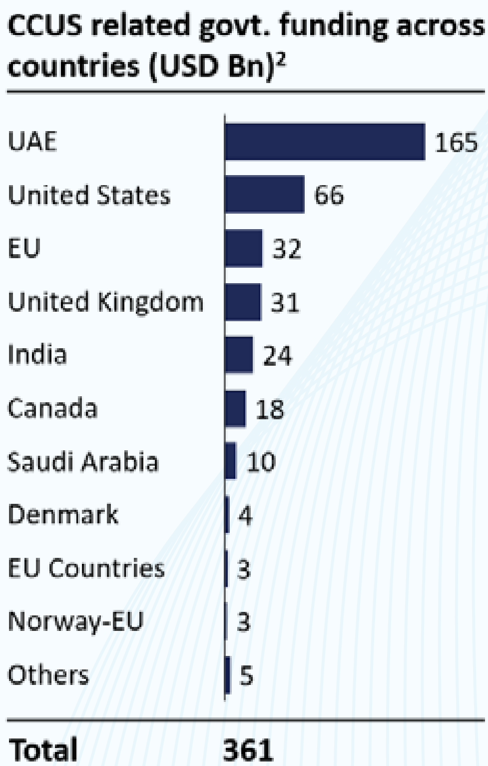


Source: Rystad CCUS Database (July 2024)

CCUS: Snapshot of Cement CCU pilot projects across the world

Country	Company	Start Year	CO_2 utilization pathway	Capacity (Mtpa)
Belgium	Ineos Group	2023	Storage	0.5
Denmark	Cementir (Aalborg Portland Group)	2020	Methanol fuel	0.2
United States	Skyonic	2015	Sodium bicarbonate	0.07
China	Anhui Conch Cement Company	2018	Unknown	0.05
Germany	Holcim	2022	Unknown	0.0056
Switzerland	SINTEF	2021	Calcium carbonate	0.0017
Denmark	Cementir (Aalborg Portland Group)	2021	Various	0.0009
Poland	SINTEF	2021	Unknown	0.0007

Source: Rystad CCUs Database, Press Search



CCUS: Snapshot of other CCU pilot projects across the world

Country	Company	Start Year	CO_2 utilization pathway	Sector	Capacity (Mtpa)
Netherlands	University College of London	2020	Unknown	Iron and Steel	10
Canada	Mitsubishi Heavy Industries (MHI)	2015	Unknown	Coal power generation	2
France	Engie	2019	Formic acid	Coal power generation	0.5
France	Engie	2019	Dimethyl ether(DME)	Coal power generation	0.5
France	Engie	2019	Formic acid	Iron and Steel	0.5
France	Engie	2019	Dimethyl ether (DME)	Iron and Steel	0.5
Croatia	MOL	2015	Enhanced oil recovery	Gas processing	0.43
Sweden	Oresundskraft	2022	Unknown	Waste Incineration	0.2

Source: Rystad CCUs Database, Press Search

CCUS: Snapshot of cement CCU commercial projects across the world

Country	Company	Start Year	CO_2 utilization pathway	Capacity (Mtpa)	LCOC (USD/t)	LCOT (USD/t)
United States	University of Illinois	2029	Unknown	2.75	94	0
United States	Holcim	2032	Enhanced oil recovery	2.0	84	6.5
United States	CRH	2029	Unknown	1.4	90	0
Germany	Holcim	2027	Methanol -fuel	1.2	162	0
Germany	Holcim	2026	Unknown	1.0	165	0
Greece	Holcim	2029	Unknown	1.0	166	0
France	Holcim	2030	e-Kerosene	1.0	168	11.5
France	Vicat	2025	Methanol -fuel	1.0	190	0

Source: Rystad CCUs Database, Press Search

CCUS: Snapshot of other CCU commercial projects across the world

Country	Company	Start Year	CO_2 utilization pathway	Capacity (Mtpa)	Sector	LCOC (USD/t)	LCOT (USD/t)
United States	ExxonMobil	1986	Enhanced oil recovery	7.0	Gas processing	31	9
United States	Enchant Energy	2026	Enhanced oil recovery	6.0	Coal power generation	56	5
United States	Century Gas Processing LLC	2010	Enhanced oil recovery	5.0	Gas processing	31	8
United States	Bakken Energy (Dakota Gasification Company)	2000	Enhanced oil recovery	3.0	Hydrogen production	133	7
Qatar	Qatar Energy	2019	Enhanced oil recovery	2.1	Gas processing	29	5
UAE	Abu Dhabi NOC	2027	Enhanced oil recovery	1.5	Gas processing	26	1
UAE	Abu Dhabi NOC	2026	Enhanced oil recovery	1.5	Gas processing	27	1
China	Huaneng Group	2024	Enhanced oil recovery	1.5	Coal power generation	83	10

Source: Rystad CCUs Database, Press Search

CCUS: Snapshot of government support provided to cement CCU projects across the world

Country	Company	Start Year	CO_2 utilization pathway	Capacity (Mtpa)	Amount of Govt. Support (USD Mn)
Belgium	Ineos Group	2023	Storage	0.5	28
Denmark	Cementir (Aalborg Portland Group)	2020	Methanol fuel	0.2	1.1
United States	Skyonic	2015	Sodium bicarbonate	0.07	28.5
Denmark	Cementir (Aalborg Portland Group)	2021	Various	0.0009	14
United States	Eagle Materials	2024	Unknown	0.01	5

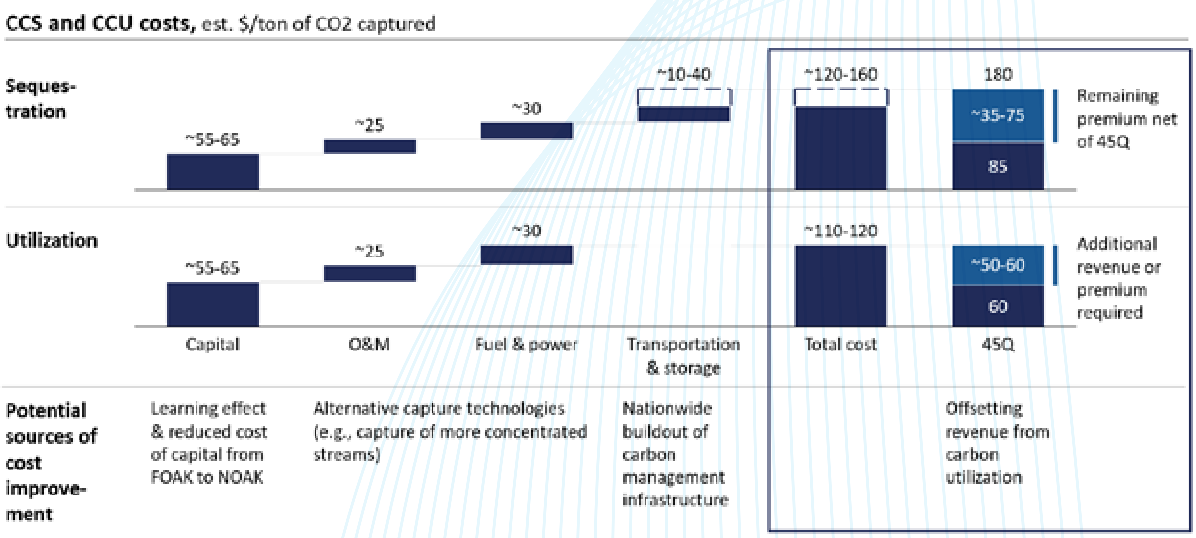
Source: Rystad CCUs Database, Press Search

CCUS: Snapshot of government support provided to other CCU projects across the world

Country	Company	Start Year	CO_2 utilization pathway	Capacity (Mtpa)	Amount of Govt. Support (USD Mn)
Netherlands	University College of London	2020	Unknown	10	28
France	Engie	2019	Formic acid	0.5	1.1
Croatia	MOL	2015	Enhanced oil recovery	0.43	28.5
United States	Linde	2023	Unknown	0.073	14
United States	Basin Electric Power Cooperative	2018	Non-specific	0.073	5

Source: Rystad CCUS Database, Press Search

CCUS: Break-up of premium required for CCS and CCU in USA



Source: Pathways to commercial liftoff: Low-carbon cement, US Department of Energy (September 2023)

Notes

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