Techno-economic Analysis and Strategic Decarbonization of the Indian Cement Industry

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Abstract

India, being a developing nation, will witness tremendous growth in the industrial sector, particularly cement production and consumption for constructing its buildings, roads, and other infrastructure. As India's GDP strengthens due to its industrial growth, living standards will rise too, increasing consumption patterns and CO_2 emissions. Climate change is border agnostic. Its effects are everywhere and transcend across nations. The success of the world's ability to limit the global rise in temperatures to under 2°C or 1.5°C to meet climate goals depends heavily on India's ability to decarbonize its fast-growing industry sector, primarily cement and iron & steel.

For India to decarbonize its cement sector, several challenges exist calling for strategic decision making in the Indian Cement Industry to mitigate climate impacts and carbon taxes in the future. First, most CO_2 emissions arise not from energy consumption but process emissions resulting from the chemical reaction of decomposition of limestone into lime during clinker making. It makes cement a hard-to-abate sector as long as the process involves calcination of limestone unless extreme measures are undertaken, such as Carbon Capture and Storage (CCS) or CCUS technologies. Second, these emerging technologies are still not feasible due to high implementation costs, financial barriers, and technology readiness level (TRL). Unlike in China, where the majority of plants are state owned and have access to capital, the cement industry in India has to raise capital on its own or be subject to being bought out by international firms that have access to larger, low-cost capital. Moreover, India has an abundance of low-grade limestone but limited high-grade limestone which is used in OPC clinker suitable for construction. India has already started importing limestone for OPC clinker making due to limited reserves of high-grade limestone that present a dependence on imports and pose raw material risks. This research investigates possible ways to decarbonize on the supply side, demand side, and operational side, and explores the pathways to reach the target emission intensity of 0.35 tonne of CO_2 per tonne of cement to meet the climate goals while considering these constraints.

The findings suggest that improving grid emission intensity or using alternative fuels alone will not be sufficient to achieve the target intensity as the majority of emissions result from process emissions during chemical reaction of calcination of limestone. Additionally, the IEA prescribed roadmap to achieve the target emission intensity of 0.35 t of CO_2 per t of cement is not possible without a major capital expenditure (CAPEX) and new technologies like CCS. Continuing to utilize high-emission intensive and high-grade limestone-based clinker coupled with setting up

costly CCS infrastructure for limestone-based cement alone may not be a feasible strategy due to dwindling resources that may cause these systems to become obsolete in the future.

Considering these factors, alternative binders with varying emission intensities and raw material reserves such as geopolymers and other green cement types were optimized to solve for the ideal mix that achieves the emission intensity target of 0.35 t CO_2/ t cement. The closest optimization result to the target was 0.37 t CO_2/ t cement when using the following industry production mix: OPC 21%, PPC 20%, PSC 10%, and Geopolymers 39%. For this scenario to be practical, there has to be more research on the geopolymers which require additional research and development to bring from lab to market. This means there is no one solution, but considering to bring such cements into market is perhaps a better and cost-effective alternative when coupled with grid intensity and alternative fuels and raw materials in a circular economy. While decarbonizing CO_2 emissions by improving grid intensity and alternative fuels alone are insufficient for long-term decarbonization goals, they, when coupled with the green cement mix have the potential to limit temperature rise to 2°C.

While CCUS can abate the industrial sector to meet climate goals and relevant when the carbon tax is imposed, limitations exist in technology, financial barriers, and raw material risks (such as limited availability of high-grade limestone reserves). An excessive carbon tax would might kill the growing industry. Therefore, the industry needs to explore new cement types such as geopolymers, and further extend system boundary to decarbonize the energy system and to include the transportation system for benefiting from the logistics optimization.

Finally, the research recommends policy makers to consider diverting R&D funds towards non-limestone-bearing raw materials and binders, especially for developing geopolymer and novel cement that requires chemical bonding instead of lime to reduce CO_2 emissions from cement sector. Existing research has already demonstrated that a circular economy has high potential to lower emissions at the lowest cost. Facilitating an efficient circular economy system will require expansion of system boundary, and will need diverting funds into R&D for developing integrated systems and capabilities but is the most effective route for the Indian cement industry that has limited access to capital and limestone-bearing raw material risks.

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Finally, I want to dedicate this work to my father, Rama Gopal Sakhamuru, my grandfather, and my aunt, who passed away last year. My father was my favorite person and source of inspiration, and I have always looked up to him for wisdom. He will always be in my thoughts and work.

DEDICATED TO MY FATHER
RAMAGOPAL SAKHAMURU

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List of Acronyms

AF – Alternative fuels
AFR – Alternative Fuels and Raw Materials
AR – Alternate Raw Materials
AMRUT – Atal Mission for Rejuvenation and Urban Transformation
BEE – Bureau of Energy Efficiency
BFSC – Blast Furnace Slag Cement
BIS – Bureau of Indian Standards
CAGR – Compounded Annual Growth Rate
CCS – Carbon Capture and Storage
CCUS – Carbon Capture Utilization and Storage
CO_2 – Carbon Dioxide
C_2S – Alite
C_3A – Belite
C_3S – Tricalcium Aluminate
CSA – Calcium Sulfoaluminate
CSI – Cement Sustainability Initiative
CSP – Concentrated Solar Power
CII – Confederation of Indian industries
CPP – Captive Power Plant
CMA – Cement Manufacturers' Association
EE – Energy Efficiency
FDI – Foreign Direct Investment
FY – Fiscal Year
GC – Geopolymer Concrete
GDP – Gross Domestic Product
GOI – Government of India
GGBFS – Ground-Granulated Blast Furnace Slag
GHG – Greenhouse Gases
GJ – Gigajoule
GPC – Geopolymer cement
GMCNF – Generalized Multi-Commodity Network Flow Analysis
IEA – International Energy Agency
IBEF – India Brand Equity Foundation
INCCA – Indian Network for Climate Change Assessment
INR – Indian Rupee
IPCC – Intergovernmental Panel on Climate Change
kWh – Kilowatt-Hour
MBtu – Million British Thermal Units
MSW – Municipal Solid Wastes
MT – Million Tonnes
MTPA – Million Tonne Per Annum
MSMEs – Micro, Small & Medium Enterprises
NMEEE – National Mission for Enhanced Energy Efficiency
OPC – Ordinary Portland Cement

PAT – Perform, Achieve, and Trade
PPC – Portland Pozzolana Cement
PSC – Portland Slag Cement
RS – Rupees (India)
SEC – Specific Energy Consumption
SOx – Oxides of Sulphur
TPP – Thermal Power Plant
UNFCC – United Nations Framework Convention on Climate Change
UNIDO – United Nations Industrial Development Organization
USD – United States Dollar
VRM – Vertical Roller Mill
WBCSD – World Business Council for Sustainable Development
WHR – Waste Heat Recovery
WHRB – Waste Heat Recovery Boiler
WHRS – Waste Heat Recovery System
YoY – Year over Year

1 Introduction

The cement industry, a highly emission-intensive industry, is fundamental to the economy of India. Being a fast-developing nation, India depends on this industry's growth to meet its growing demands for infrastructure and housing. Concrete, whose essential ingredient is cement along with sand, gravel and water, is the second most-consumed product on earth, only next to the water. The cement sector contributes around 5-8% to anthropogenic CO_2 emissions globally (Figure 1).

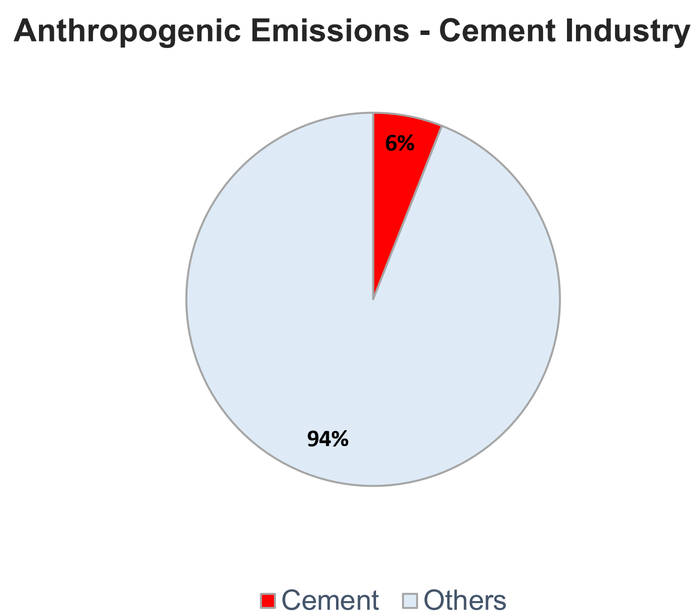


Figure 1: Global anthropogenic emissions from cement Industry [1][2][3]

Motivation

Human-induced global warming reached 1ºC in 2017 from before industrialization levels and is increasing at the rate of 0.1 – 0.3 ºC per decade (high-confidence estimates).[4] Many nations are pledging net-zero by 2050 or earlier to limit the rise in global temperatures from pre-industrial levels by 1.5 ºC. Failure to address climate change will allow global temperatures to rise above 3-4 ºC by 2100, which will result in frequent droughts, flooding, and storms, affect small and large businesses alike and cost the global economy billions of dollars annually. For this thesis, I specifically chose India as my focus because climate mitigation and sustainability are a shared concern globally. The world's ability to successfully achieve sustainability goals depends mainly on India's ability to decarbonize its industry. India has the second-largest market share of the cement industry globally and is only growing in its demand and production. Clinker is the crucial ingredient in cement obtained by calcination of limestone ($CaCO_3$), which releases a large amount of CO_2 (2/3rd of direct process emissions). It requires the burning of highly-carbon fossil fuels to reach high temperatures in the kiln to facilitate the calcination reaction (releasing 1/3rd of direct process emissions). Due to this, it makes the ability to stop the global temperature rise at 1.5 ºC or even 2 ºC a challenge. I chose to study the Indian cement industry specifically due to its influence on world sustainability.

Research Questions

- What decarbonization technologies at the industry level will allow the Indian cement industry emissions intensity to reach the target of 0.35 tonne of CO_2 per tonne of cement by 2050?
- Suppose an emissions intensity of 0.35 tonne of CO_2 per tonne of cement is achievable by 2050. Will it be sufficient over a range of economic factors not to exceed the carbon budget allotted for the Indian cement industry needed to limit the global rise in temperature under 2 ºC rise?
- Suppose the Indian cement industry's target process emissions intensity of 0.35 tonne of CO_2 per tonne of cement is hard to achieve by the sector as a whole for a range of economic factors. Then, is there still a scope for logistics to be improved to reach the required 2 ºC or 1.5 ºC climate goal? Note that this is a broader system scope beyond the cement plant itself to include factors such as transportation modes, distances, supply demand factors, load capacity, transport emissions factors, and network architectures.

Primary Objective

The primary objective is to identify the technologies and pathways that will allow the cement industry to meet climate goals. Since unsustainable amounts of process CO_2 emissions released into the atmosphere cause global warming, the first objective will look at the pathways that help decarbonize the Indian cement industry.

Secondary Objective

The second objective is to model commodity flows in a cement plant from sourcing raw materials to clinker manufacturing to cement grinding and dispatch to end user. This study will help identify the optimization gap for decarbonization potential in the logistics of cement manufacturing. The GMCNF framework identifies the optimization gap for the cement plant transportation/ logistics emissions while moving raw materials, fuels, commodities, and finished products for cement production.

Purpose

The purpose of this study is to identify the effective decarbonization strategies that can help limit the overall global warming to within 2 ºC by mid-century and look at opportunities beyond 2 ºC such as the net-zero, 1.5 ºC. This research will provide the reader a context of the background of the Indian cement industry, the dynamics involved, an overview of current and emerging technologies, and opportunities and strategies to effectively decarbonize the cement sector using systems thinking approach.

Organization of the Thesis

Chapter 1 - Introduction: This chapter introduces the research idea and the primary purpose and motivation behind the study. It includes the research questions, the primary and secondary objectives, and the approach and organization of the thesis.

Chapter 2 - Literature Review and Background: This chapter discusses the big picture of the Indian cement industry, emissions in the cement industry, economic factors, policies, and barriers that influence the ability of the cement industry to meet climate goals.

Chapter 3 - Decarbonization of the Indian cement industry: This chapter reviews the decarbonization strategies and emerging technologies in the Indian cement industry.

Chapter 4 - Methodology: It describes the scenarios and assumptions used to analyze the decarbonization potential and research questions for the Indian cement sector.

Chapter 5 - Results: This chapter presents the analysis results and key findings from the research methods, including a list of concerns and insights from the study. It shows the potential for decarbonization of the Indian cement sector for the scenarios chosen.

Chapter 6 - Conclusions and Future Work: The research gaps are listed here. This section also describes potential future work and the continuation of research ideas.

2 Literature Review and Background

2.1 Cement Industry Big Picture

Indian cement industry, similar to steel, is fundamental to India's economy. Cement is the most produced commodity in the industrial sector for India. It is the world's second-largest market not only for production but also for cement consumption. Today, the Indian cement industry is the second-largest emitter of CO_2 emissions, only next to Iron & Steel, and responsible for 8% of the nation's CO_2 emissions.[5] It is the second largest producer and consumer of cement next to China. Despite the Indian cement industry having the second-largest cement consumption globally, its per-capita cement consumption has been much lower than that of many nations at just 0.235 tonnes of cement per person. Compare this with China at a really high annual per-capita cement consumption of 1.5 tonnes in 2019 (Table 1). Economists and industry experts believe this India's annual per-capita cement consumption will grow and merge with those of developed nations by mid-century as India's economy improves and overall standards of living rise for its population (Table 2). Consequently, this will increase cement production and the sector's overall rise in CO_2 emissions. Past projections of historical CO_2 emissions from the Indian cement industry have pointed to an increasing trend (Figure 2) of future CO_2 emissions in a business-as-usual scenario. The Indian cement industry's emissions intensity (tonne of CO_2/tonne of cement) will undoubtedly lower due to the industry-wide decarbonization efforts. However, the CO_2 emissions will rise due to the projected increase in cement demand for infrastructure, increased per-capita consumption, and population growth. After all, cement demand growth stems from the essential goods required to advance governmental schemes such as housing, infrastructure advancement, and development projects in India over the next few decades. Considering that the cement industry is a hard-to-abate sector as low-carbon technologies are still nascent and available to pursue in unfavorable terms, combatting climate change is a monumental task for India. Compare this with situation in China where cement production and emissions will peak by 2030 and stabilize and being state-owned, has abundance of access to capital. China has just announced its Green Climate Deal to reach net zero by 2060 in September of 2020. It has a more concrete forward-looking plan and resources to battle the global war against climate change owing to its recent public, industrial and technological policy changes, shutting down outdated facilities, and widespread implementation of waste heat recovery systems (WHRS) for power generation. India has announced plans for net-zero transition in 2070. However, Indian cement industry being privately owned has limited access to low-cost capital for its cement industry and the industry has yet implement the full potential of Waste Heat Recovery and power generation across all its plants. There exists a large gap between potential and implementation due to lack of funding for capital improvements.

Table 1: Cement industry comparison of China, India and USA

Country/ Region	Year	Cement production (Million tonnes)	Population (Million people)	GDP (Million US dollars)	Cement per capita (kg of Cement/ person)	Cement per GDP (kg/USD)	CO_2 Emissions (MT)	CO_2 Emissions per capita (kg CO_2/ person)	Emission intensity (Tonne of CO_2/ Tonne of cement)
China	2019	2,200	1,400	$ 14,280,000	1,570	0.154	1300	930	0.591
India	2019	337	1,370	$ 2,870,500	240	0.118	194	150	0.575
United States	2019	86	330	$ 21,430,000	260	0.004	67	210	0.776

Sources:
US EPA U.S. Cement Industry Carbon Intensities (2019)
India Brand Equity Foundation; Crisil; Department for Promotion of Industry and Internal Trade (India); ICRA; CARE Ratings; TechSci Research; Statista
https://aeee.in/emission-reduction-approaches-for-the-cement-industry/
Note: Cement emissions include process emissions from calcination of limestone; For India, 2018 emission intensity value is used

Table 2: Per capita consumption of cement – India, China, and World

Country	Year	Annual Per Capita Consumption of Cement (in Tonnes)	Source
India	2018	0.235	[6] [7]
China	2018	1.700	[6] [7]
World	2018	0.520	[6] [7]
India*	2030	0.400	[8, p. 3]
India*	2050	0.465 – 0.810	[9, p. 13]
* Projection			

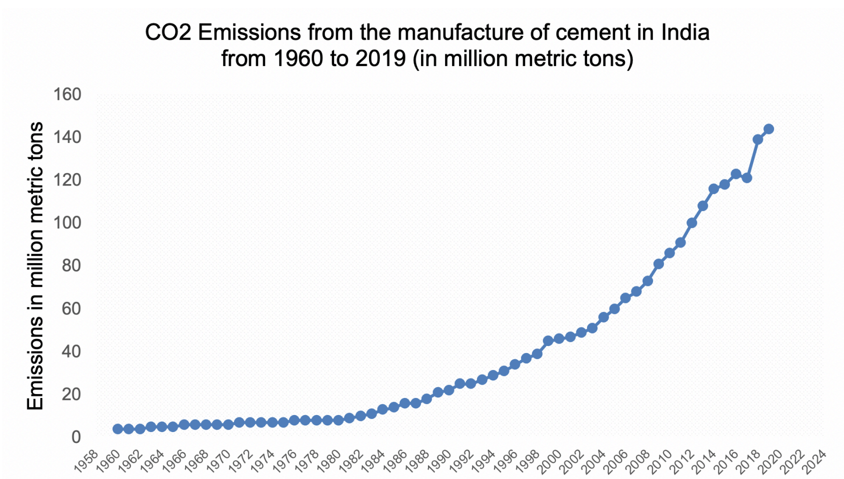


Figure 2: CO_2 emissions from the manufacture of cement in India (1960 - 2019) [10]

Despite increasing its overall CO_2 emissions, the Indian cement industry lowered its CO_2 emissions intensity (tonne of CO_2 per tonne of cement) over the past decade by adopting industry-wide standards (PAT scheme, see Section 2.1.13) for energy savings (Table 3).

It has lowered Indian cement industry emissions intensity (direct + indirect emissions) by 15% compared to China. [11, p. 55] The industry has improved its clinker quality and lowered CO_2 emissions from fuel-burning due to imported petcoke usage than coal. However, it is looking to reduce dependence on imports and utilize its more emission-intensive domestic coal in the future. The Indian cement sector is also looking to invest in a circular economy (i.e., using waste from one industry as raw material in another) and zero-water use. Companies are diversifying their product mix by introducing composite cement. Many Indian cement plants have started manufacturing composite cement. The industry aims to achieve the target emission intensity of 0.35 tonne CO_2/tonne of cement by 2050. While the cement industry professionals believe that achieving this target emissions intensity will mitigate climate change, the industry is susceptible to a range of macroeconomic factors that influence overall cement industry emissions. Due to this, the cement industry is on a long road to decarbonization. A SNAPFI country study identified several gaps in the Indian cement industry's regulatory, capacity and market areas that need policy interventions to achieve a low-carbon pathway, for example, innovative implementation models, incentivization, regulations, and access to finance for transformative technologies. [12] To summarize, the Indian Cement Industry needs a robust decarbonization strategy that will benefit from a transformative system thinking approach.

Table 3: Emission intensity of Indian cement industry vs. the global average

Industry	Year	Value (tonne of CO_2/tonne of cement)	Source
Cement, India	1996	1.120	CMA
Cement, India	2010	0.620 - 0.719	[3]
Cement, India	2017	0.719	[3]
Cement, India	2018	0.576	[3]
Cement, Global Average	2018	0.634	[3]
Cement, India (CSI and WBSCD roadmap)	2050	0.35	[13] CSI, WBSCD Low Carbon Technology Roadmap

2.1.1 Cement Production – India vs. World

Restructuring of the economy after World War II resulted in the second wave of industrialization and accelerated growth of global cement production (Figure 3). In the past couple of decades, accelerated growth resulted from rapid industrial development in China that led to increased cement production and consumption. Nearly 70% of cumulative global cement production has occurred in the decades following 1990, which led to a lot of CO_2 emissions. [14]

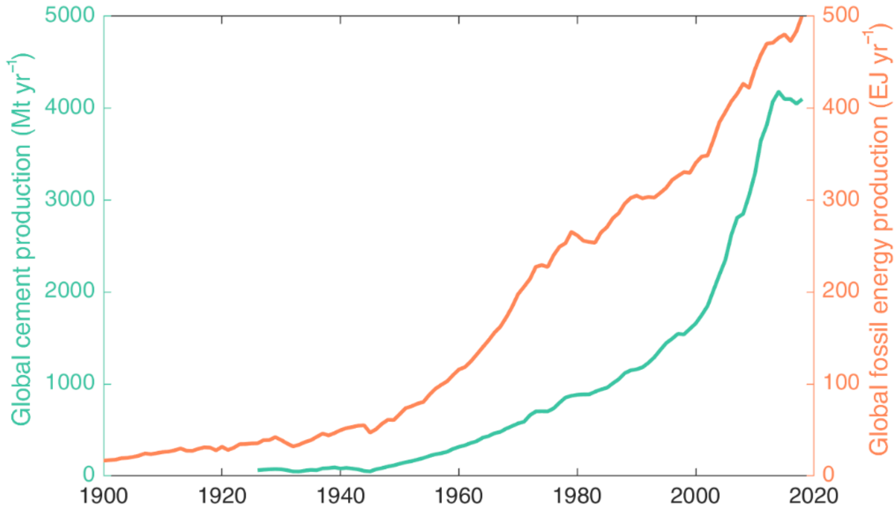


Figure 3: Global cement & fossil fuel production (the 1900s to 2019)[1]

Since then, due to the exponential cumulative CO_2 emissions, countries have prioritized reducing their overall CO_2 output. In India, the industrial sector contributes to a third of the nation's emissions. Therefore, India, too, in recent decades, has made it a priority to reduce overall CO_2 emissions by reducing emission intensity in the Industrial sector in their production of materials such as iron & steel and cement. At an 8% global market share, India is currently the second-largest cement producer next to China which accounted for 56.2% of global market share (Figure 4). The industry expects its CO_2 emissions to rise due to housing demand, infrastructure, rising living standards, and industrial migration from China (See Section 2.1.9). While China, the Northern neighbor to India, is miles ahead of India in terms of capacity and production, with more than 3500 cement producers, a majority of what China produces is of low-grade mortar quality cement of mark 32.5 while construction for columns, bridges, dams and slabs require higher grades of 42.5 or 52.5 cement[2].

[1] (Mohr et al., 2015; USGS, 2016, 2018; BP, 2019);
[2] https://www.business-standard.com/article/economy-policy/india-faces-headwinds-from-china-s-cement-success-117052300481_1.html

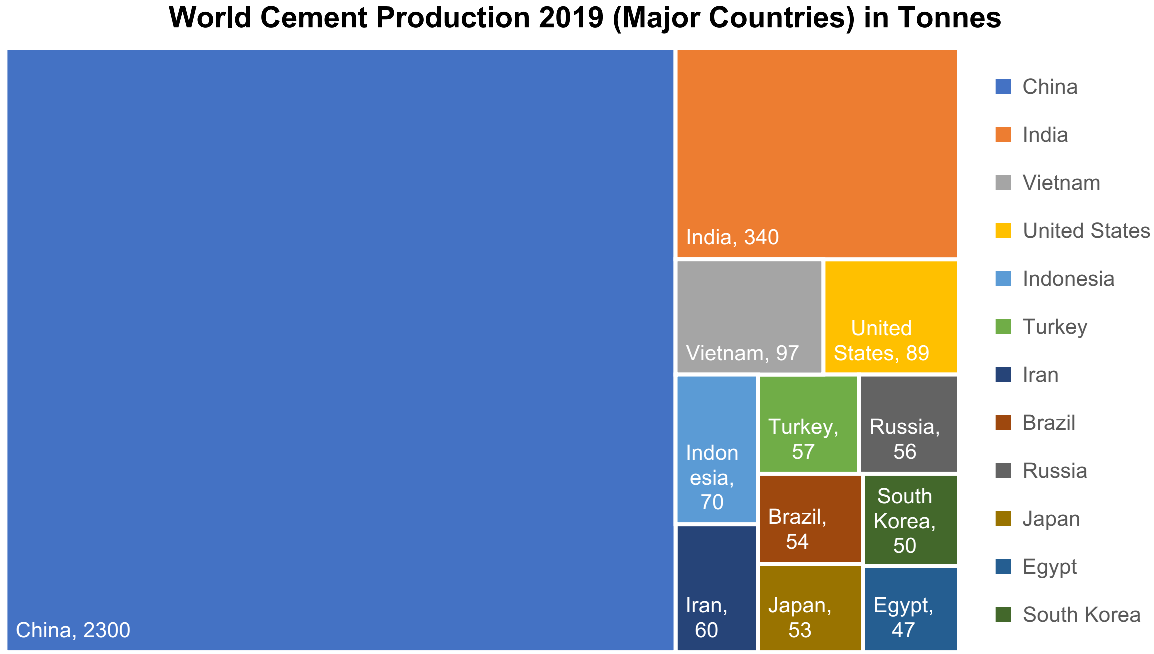


Figure 4: Cement production – India accounted for 7.8% of world production in 2019 [15]

2.1.2 Emissions Scenarios

Stated Energy Policy (STEPS): It is a conservative business-as-usual scenario that follows national and international agreements on CO_2 emissions reductions currently in place in India. This approach assumes that implementation is dependent on the availability of funds, measures, and real-life constraints such as financial, regulatory, and administrative barriers.

India Vision Case (IVC): This scenario relies on an optimistic economic recovery for India from the COVID pandemic and an assumption that it will meet the stated policies.

Delayed Recovery Scenario (DRS): Unlike STEPS or IVC, this scenario examines the implications of a prolonged pandemic and its lasting impacts on social, economic, and energy indicators. It assumes the same policy assumptions as STEPS except for slower economic growth.

Reference Technology Scenario (RTS): This base case scenario considers the existing energy and climate commitments under the Paris agreement. This scenario expects that direct CO_2 emissions will rise 4% globally by 2050. This scenario would result in an average temperature rise of 2.7 ºC by 2100 at which point temperatures are unlikely to have stabilized and continue to rise. [15][3, p. 44]

Sustainable Development Scenario (SDS): This scenario looks at the existing goals and specific outcomes for climate, clean air, and energy access, including the Paris agreement, and examines the combination of actions needed to achieve them.

6 Degree Scenario (6DS): This scenario considers no-effort on part of government, industry or public to curb emissions. It is understood that in the absence of any curtailing measures, the global temperature would rise to 6 ºC in the long term. [3, p. 44]

2 Degree scenario (2DS): This scenario aims to limit global rise in temperature by 2 ºC by 2100 with a 50% chance. To achieve it, IEA set out an energy system pathway and emissions reductions trajectory. It emphasizes that CO_2 emissions from fuel and industrial processes must continue their decline and energy system must reach a neutrality by 2100. [3, p. 44]

Net Zero Scenario (NZE): This is a utopian scenario where the cement industry contributes zero atmospheric CO_2 emissions across its entire value chain. The net-zero pathway for the cement industry requires all new capacity additions to be near-zero-emissions.

See Table 4 for carbon budget across scenarios, and Figure 5 for fuel supply and electricity generation across scenarios

Table 4: Target ambitions for IEA scenarios for India – STEPS, IVC, DRS, SDS, NZE

IEA Scenarios	Carbon Constraint	Carbon Constraint Budget	Source
BAU	None	N/A	IEA,[16, p. 463]
STEPS	None	N/A	""
2 ºC (2DS)	Yes	115 – 130 Bt CO_2 during 2011-2050	""
1.5 ºC (1.5DS)	Yes	<115 Bt CO_2	""

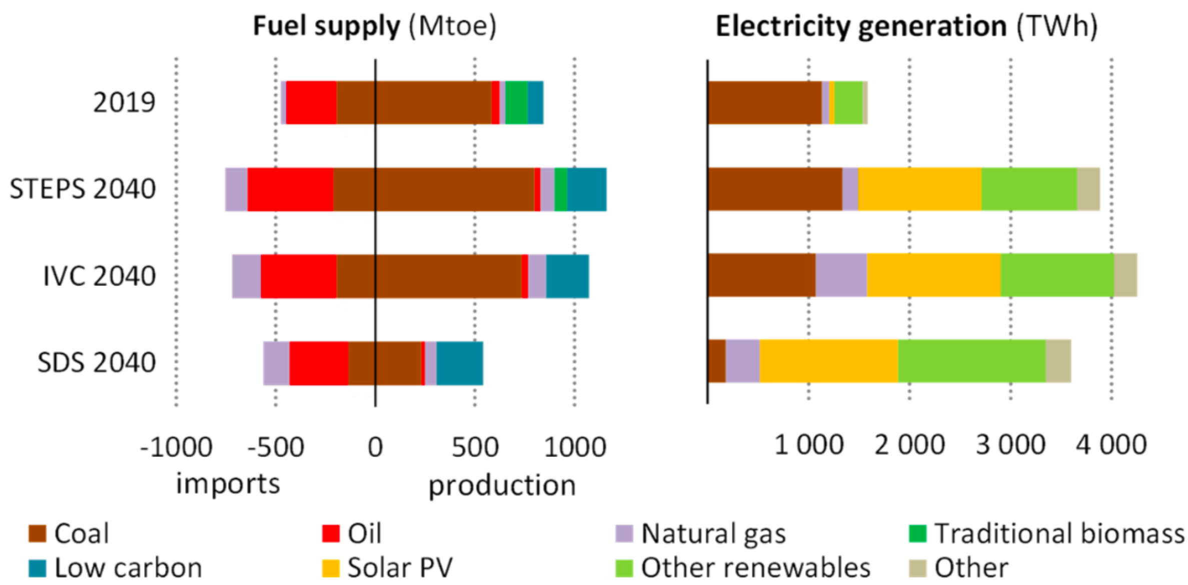


Figure 5: Scenario changes in fuel supply and installed electricity generation (2019 to 2040)

2.1.3 Cement Types Produced in India and Around World

Cement Production: Before Indian independence in 1947, the industry sold only one type of cement - Artificial Portland Cement[3]. Today, 23 types of cement exist specified by the Bureau of Indian Standards (BIS) (Table 5). The three most common cement types produced in India are Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), and Portland Slag Cement (PSC) along with minor amounts of other special-purpose cement. In recent times, India and countries around the globe have been marketing several low-carbon green cement types to decarbonize the cement industry. For CO_2 emissions for common cement types, refer to Section 2.1.10.

Green Cement Types: Many green types of cement are promising reductions in emissions and some of the institutions engaging in manufacturing them have advanced considerably in their work. [17] Examples of these types of cement include composite cement, Fortera cement (previously, Calix Calera cement), LC[3] cement, Belite rich cement, and other novel cement,

[3] https://datis-inc.com/blog/how-many-cement-plants-are-producing-in-india-2020/#Cement_Types_production_in_India

Geopolymer cements (GPC), Aether cement, Navrattan Green Crete[4] , JSW Concreel HD[5], Kiran Green Geobinder, Geocements & Geocretes, and Duraguard Silver. Out of these, LC[3] and Geopolymer types of cement have shown high potential[6].

Table 5: Cement types in India[7]

	Cement Type	Manufacturing	Properties	Applications/Use	Std
1	Ordinary Portland Cement 33 Grade	Low market availability	• Low compressive strength and low heat of hydration which helps lessen cracks	• Upto M20 Grade of Concrete • Plastering, flooring, masonry	IS:269
2	Ordinary Portland Cement 43 Grade	Widely used and high market availability	• Cement reaches a minimum compression strength of 43 mpa (Mega pascals) in 28 days.	• Upto M20 Grade of Concrete, precast elements • Plastering, flooring	IS:8112
3	Ordinary Portland Cement 53 Grade	Readily available in the market and widely used in the construction industry	• Cement reaches minimum compression strength of 53 mpa (Mega-pascals) in 28 days.	• Widely used general-purpose cement • Greater than M-30 concrete grade applications, PSC works, bridges, roads, multi-storied buildings	IS:12269
4	Portland Slag Cement	Available in select marketplaces	• Increases strength, reduces permeability, improves chemical attack resistance, and inhibits rebar corrosion.	• Applications include harsh environments, such as wastewater treatment and marine applications • High-strength concrete, such as high-rise structures or 100-year service life bridges	IS:455
5	Portland Pozzolana Cement	Readily available in the market	• Reduces permeability of concrete. • Denser than Ordinary Portland Cement. • Long-term strength, i.e., 90 days and above, is better than OPC.	• Hydraulic structures, i.e., dams & retaining walls • Marine structures • Mass concrete works, i.e., bridge footings under aggressive conditions • Masonry mortar and plastering	IS:1489 P-2
6	Colored Cement/White Cement	Readily available but more expensive than OPC	• Its color is white • Chemical composition and physical properties meet the specification of ordinary Portland cement	• Interior and exterior architectural decorations such as terrazzo tiles and floorings, ornamental concrete products such as idols	IS:8042
7	Sulphate Resisting Cement	Not usually available in the market regularly and expensive than OPC	• Results in premature hydration if kept in a wet place	• Recommended for places where the concrete is in contact with the soil, ground-water, exposed to the seacoast, and sea-water	IS:12330
8	Low Heat Portland Cement	Not usually available in the market regularly and can be obtained on specific orders.	• Generates less heat than OPC and thus avoids shrinkage cracks	• used in dams, water retaining structures, bridge abutments, massive retaining walls, piers, and slabs	IS:12600
9	Rapid Hardening Cement	Not usually available in the market regularly and expensive than OPC	• Low setting time than ordinary Portland cement • It acquires early strength	• Used in repairs and where there is a need for quick construction	IS:8041
10	Hydrophobic Portland Cement	Not usually available in the market regularly and expensive than OPC	• Setting of hydrophobic cement is slow initially because of the admixtures in cement • Strength after 28 days is the	• Construction of dams, spillways, under-water constructions • Used in cold weather conditions	IS:8043

[4] https://www.outlookindia.com/website/story/outlook-spotlight-green-cement-a-revolutionary-product-and-also-need-of-the-hour-of-this-decade/378962
[5] https://timesofindia.indiatimes.com/business/india-business/switch-to-green-cement-for-a-better-tomorrow/articleshow/83337585.cms
[6] High potential for India (https://aeee.in/emission-reduction-approaches-for-the-cement-industry/)
[7] https://civiljungle.com/23-different-types

			same as that of ordinary cement		
11	Extra Rapid Hardening Cement	Not usually available in the market regularly anymore d expensive than OPC	• Achieves hardening rapidly. Its one-day strength equals the three-day strength of OPC with the same water-cement ratio.	• Used where quick removal of formwork is needed to reuse it. • Used where there is need for high early strength • Used for constructing road pavements where it is essential to open the road up to traffic quickly.	
12	Quick Setting Cement	Not usually available in the market regularly and expensive than OPC	• Can be easily sculpted and molded as it sets • Product sets in 10-15 minutes.	• Used in under-water construction • Used in rainy & cold weather conditions • Used where quick strength is needed in a short time	
13	Super Sulphated Cement		• The heat of hydration is significantly lower • It is resistant to sulfate attack	• Used in the foundations where the chemically aggressive condition exists • Used In marine works, RCC pipes are used in sulfate-bearing soils.	IS:6909
14	Portland Pozzolana Cement (Fly ash based)	Not usually available in the market regularly but can be obtained on special orders	• Flyash-based blended cement has the properties required to be called blended cement.	• Used in low compressive applications such as plastering, flooring, grouting of cable ducts in PSC works	IS:1489 P-1
15	Portland Pozzolana Cement (Calcined based)	Not usually available in the market regularly but can be obtained on special orders	• Calcined based blended cement has the properties required to be blended cement.	Used in low compressive applications such as plastering, flooring, grouting of cable ducts in PSC works	IS:1489 P-2
16	Air Entraining Cement	Not usually available in the market regularly, and it is costly.	• Forms microscopic air bubbles during the mixture. • Decreases the strength of concrete	•Its heat and sound insulation properties make it ideal for use in lining walls and roofs	
17	Masonry Cement	Not usually available in the market regularly but can be obtained on special orders	• Better bonding between bricks or concrete blocks	• This mortar is used in brick, concrete block, and stone masonry construction also to produce stone plaster	IS:3466
18	Expansive Cement	Not usually available in the market regularly but can be obtained on special orders	• Shrinkage of cement occurs after mixing	• Grouting anchor bolts • Grouting machine foundation	
19	Oil Well Cement	Not usually available in the market regularly and expensive than OPC	• No chemical effect occurs on cement due to oils in an oil well.	• used for cementing work in high temperatures and pressures applications such as the drilling of oil wells	IS:8229
20	Rediset Cement	Not usually available in the market regularly but can be obtained on special orders	• Poor sulfate resistance of the cement • Shrinks rapidly, but the total shrinkage is similar to that of ordinary PCC.	• Very high-early strength concrete and mortar • Emergency repairs • Construction between tides • Palletization of Iron ore dust	
21	Concrete Sleeper Grade Cement	Not usually available in the market regularly but can be obtained on special orders	• It provides good tensile strength to concrete	• Used in prestressed concrete railway sleepers	IRS-R 40
22	High Alumina Cement	Not usually available in the market regularly and more expensive than OPC	• It develops 80% ultimate strength in 24 hours	• Used in cold water and under sea-water	IS:6452
23	Very High Strength Cement	Not usually available in the market regularly and expensive than OPC	• It has high compressive strength than ordinary Portland cement (OPC)	• Used to construct important buildings and infrastructure	

2.1.4 Raw Materials and Fuels in Cement Production

Raw materials: The primary raw material used to manufacture conventional cement manufacturing (OPC) is limestone. Other minerals are consumed, such as gypsum, quartz, bauxite, coal, kaolin (china clay), and iron-ore (Table 6). The raw materials used for making good quality OPC cement are mainly of three types, 1. *calcareous materials* such as limestone, calcareous sand, and seashells; 2. *argillaceous materials* such as clay, laterite (substitute: bauxite and flue dust from steel plants), shale, carbonate, bauxite & Iron ore, and 3. *gypsum*.

In India, limestone deposits occur in all states. The geological survey of India and other individual organizations are on the lookout for limestone reserves. In addition to using natural deposits as raw materials, the cement industry has been using industrial byproducts for manufacturing cement. For instance, the A.C.C cement company in India has used calcium carbonate sludge, a byproduct obtained from fertilizer plants, as raw material to substitute some of the limestone quarried from mines. [18]

Significant risks are present in the supply of raw materials. As noted in the 95th report on the performance of the Indian cement industry by the Government of India, the principal raw materials for cement - Limestone, Gypsum, and Sand, all presented risks, for example, the issue of availability of raw material reserves for limestone, shortages of gypsum, and soil erosion from sand mining. This committee recommended further research on non-limestone-bearing raw materials and binders and R&D, especially for developing geopolymer cement that requires chemical bonding instead of lime to lower CO_2 emissions. Although India has a mineral-rich economy, sub-quality limestone (sub-grade calcium oxide content) is abundant, which is not suitable for cement manufacture. Some estimates have noted that the combined reserve life of presently estimated stock is barely 3 – 4 decades, which is contingent on the pace of development of the mining sector. [19, p. 24]

Table 6: Raw material production (2019,2020) and reserves for India [6][8]

Raw Material	Production 2018-19	Production 2019-20	Total Reserves	Source
Limestone	379.974 MT	359.932 MT	203,224 MT of which 16,336 MT (8%) placed under reserves category & 1,86,889 MT (92%) placed under the remaining resources category.[9]	[17][20]
Bauxite	23,687,721 tonnes all industries; 2,075,100 tonnes for cement	Data not available	3,896 MT of which 656 MT placed under reserves category and 3,240 MT under remaining resources category	[21]

[8] http://ismenvis.nic.in/Database/Coal_Production_2020-21_Upto_Dec_2020_24869.aspx
[9] High quality limestone is much lower portion of these reserves

Shale	19.25 MT	Data not available	15.47 MT placed under reserves and 3.78 MT under the remaining resources category	[22]
Iron Ore	Hematite 22487 MT Magnetite 10789 MT	Data not available	Hematite: 5,422 MT placed under reserves and 17,065 MT under the remaining resources category Magnetite: 53 MT placed under reserves and 10,736 MT under the remaining resources category	[23]
Gypsum	4,369,300 tonnes	Data not available	1,330 MT, of which 37 MT placed under reserves category and 1,293 MT under remaining resources category. The majority of the grade (80%) is fertilizer or pottery grade. The cement or paint grade is 13%.	[24]

Fuels: The principal fuel used in the manufacture of OPC cement is clinker coal, petcoke, and some alternative fuels which are wastes in other industries. Indian coal has a lower energy density than imported pet-coke. To ensure energy security for India and reduce dependence on foreign imported coke, the emerging policies are being directed towards the use of domestic coal, resulting in higher CO_2 emissions. The percentage of free carbon in Indian coal ranges from 46.3% to 52.5% (Figure 6).

	Bengal Coal			Central Indian Coals	
	Selected A Grade I	Selected A Grade II	Selected B	Grade I	Grade II
% moisture	2.3	2.5	2.4	18.1	14.1
% ash	11.0	14.5	17.5	21.7	24.8
% volatile matter	36.5	25.8	30.4	29.0	28.9
% free carbon	52.5	49.7	52.1	49.3	46.3
Calorific Value					
Gross on dry	7000	6850	6250	6000	5650
Net on wet	6578	6423	5840	4600	4555

Figure 6: Indian coal analysis [18, p. 124]

India has the fifth-largest coal reserves globally at 319.02 billion tonnes of coal reserves concentrated in Jharkhand, Bihar, Odisha, West Bengal, Chhattisgarh, Madhya Pradesh and, Telangana (Table 7). Various grades of coking and non-coking coals exist at different mines across India, as noted by Ministry of Coal of the Government of India (GOI)[10] (Table 8). {Citation}

Table 7: Indian coal reserves

Fuel	Production 2018-19	Production 2019-20	Total Reserves	Source
Indian Coal	TBD	TBD	319.02 billion tonnes of coal reserves[11]	[25]

Table 8: Quality (grade specifications) of coal available in India across various coal mines

Gross Calorific Value (GCV) Grades of coal (non-coking)	GCV (Kilo Calories per KG)
G1	Above 7000
G2	6701 to 7000
G3	6401 to 6700
G4	6101 to 6400
G5	5801 to 6100
G6	5501 to 5800
G7	5201 to 5500
G8	4901 to 5200
G9	4601 to 4900
G10	4301 to 4600
G11	4001 to 4300
G12	3701 to 4000
G13	3401 to 3700
G14	3101 to 3400
G15	2801 to 3100
G16	2501 to 2800
G17	2201 to 2500

2.1.5 Cost of Production of Cement

Cement's manufacturing costs comprise capital expenditure (CAPEX) and operational expenditure (OPEX). The capital expenditure varies depending on whether the project type is a greenfield or a brownfield expansion. Typically, the CAPEX costs of setting up a greenfield

[10] https://coal.nic.in/en/major-statistics/coal-grades
[11] https://coal.nic.in/en/major-statistics/coal-reserves

cement plant are more than double that of setting up a brownfield expansion plant (Table 9). Currently, the most significant cost category for CAPEX is the 'Plant & Equipment' category, at 55% of the total CAPEX. However, 'land acquisition' costs are snowballing in many regions and thus will alter the CAPEX composition (Table 10). As land costs rise, companies may not have the financial means to deploy low-carbon technologies. The CAPEX costs vary regionally, with the southern region having a higher average cost of setting up a cement plant despite having the largest number of cement plants in the country (Table 11). In the OPEX, there has been a wide range in costs owing to variations in regional distribution of raw materials, quality of raw materials, availability of fuels, and freight distances (Table 12). Production costs can influence the cement production and growth potential of the industry. Cost management is critical during periods of low cement utilization, i.e., the amount of cement produced per total available capacity. Moreover, hikes in fuel prices lead to depressed margins for the cement companies.

Table 9: CAPEX for greenfield vs. brownfield expansion project

Expansion Type	**Average Costs**	**Unit**	**Lead Time**	**Source**
Greenfield	110-130	$/tonne	3-4 years	[26, p. 28]
Brownfield	50-80	$/tonne	2-3 years	""

Table 10: CAPEX breakdown by category

Capital Costs	2009 **Capital Cost (USD/t)**	2009 **Proportion**	2015 **Capital cost (USD/t)**	2015 **Proportion**	**CAGR (2009-2015)**	**Source**
Land	9	10%	21	16%	15%	[26, p. 28][12]
Plant & equipment	50	55%	62	48%	4%	""
Civil Works	17	19%	25	19%	7%	""
Pre-Operative Expenses	9	10%	14	11%	8%	""
Other	5	6%	8	6%	8%	""
Total	**90**		130		6%	""

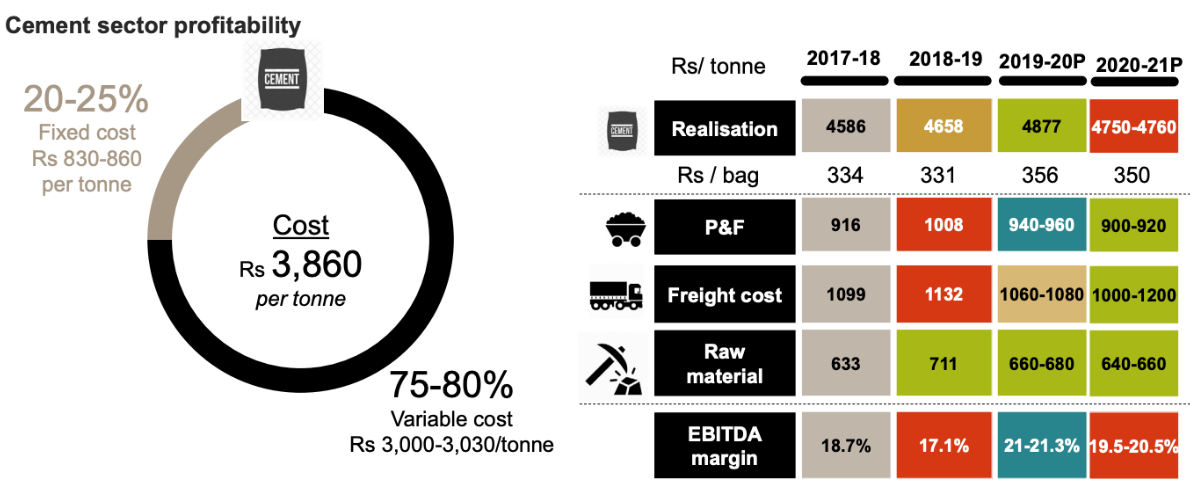
[12] Shree, JM Financial, Industry

Table 11: Average costs of setting up cement plant in India

	Unit	North	South	East	West	Central	Source
Average cost of setting up a plant (USD/t)	USD/ tonne	108	116	94	89	80	[26, p. 36]
Note: 1 USD = 65 INR							

Table 12: OPEX breakdown by category

OPEX Category	Unit	Low	High	Source
Raw material (24%)	INR/ tonne of cement	474	1461	[26, p. 33]
Freight (25%)	INR/ tonne of cement	535	1025	[26, p. 33]
Power & fuel cost (22%)	INR/ tonne of cement	500	1235	[26, p. 34]
Admin/employee cost (9%)	INR/ tonne of cement	196	418	[26, p. 34]
Other Fixed costs (20%)	INR/ tonne of cement	489	1006	[26, p. 34]



Source: CRISIL Research, industry, annual reports

Figure 7: Cement sector operational costs – fixed vs. variable

2.1.6 Cost of Manufacturing Cement by Type – OPC, PPC, PSC

Raw Material Costs: In the past, the cost to produce OPC was higher than PPC and PSC. PPC and PSC used waste from other industries as raw materials that offset costs. For example, fly ash, waste from power plants dumped into the ash ponds required higher expenditure to dispose of, found use in cement plants in making PPC cement. While cement companies obtained power plants to supply fly-ash at no cost initially, this changed when fly-ash was accepted to become a saleable commodity. Since then, surges in the pricing of flyash by powerhouses have had a detrimental effect on cement companies. Slag is not economically feasible for transporting over long distances. At times, the clinker is transported to a grinding and blending facility closer to iron & steel plants to use slag and for relative ease of clinker transport.

Furthermore, current regulations that mandate cement plants with captive power plants to supply 20% of their fly ash to manufacturers of fly-ash brick and tiles limit the amount of available fly-ash for cement plants and contribute to freight-related CO_2 emissions. Due to these factors, the cost of raw materials now for PSC is higher than PPC or OPC (Table 13). Moreover, the cost of electricity is lowest in PSC due to low clinker use and fly ash obtained as fine powder not requiring grinding (Table 14). After considering costs of raw material costs, fuel, and power, OPC cement has the highest manufacturing cost (raw material, fuel & power), followed by PSC or PPC cement types at INR 2143, INR 2053, and INR 1856 per tonne of cement, respectively.

Table 13: Raw material costs of manufacturing per cement type

Raw Material Costs	Unit	OPC	PPC	PSC	Source
Clinker requirement	Tonne of clinker per tonne of cement	0.9	0.67	0.41	[26, p. 113]
Limestone	INR/tonne of cement	687	511	313	""
Coal*/ Pet-coke** (Fuel)	INR/tonne of cement	683/599	508/446	311/273	""
Gypsum	INR/tonne of cement	200	100	120	""
Slag	INR/tonne of cement	0	0	557	""
Fly Ash	INR/tonne of cement	0	240	0	""
Total Raw Materials Costs	INR/tonne of cement	1570	1359	1574	""
* Includes mining cost and royalty payment to the government ** Coal cost is more than coke, and industry is moving to use domestic coal. Coal and not pet-coke is used in the total cost of cement					

Table 14: Power costs of manufacturing per cement type

Power	Unit	OPC	PPC	PSC	Source
Clinker Production	kWh/tonne of cement	50	38	23	[26, p. 113]
Cement Production	kWh/tonne of cement	28	30	42	""
Packing/Dispatch	kWh/tonne of cement	2	2	2	""
Other – Misc.	kWh/tonne of cement	2	2	2	""
Total Power Requirement	kWh/tonne of cement	82	71	68	""
Total Power Costs	INR/tonne of cement	573	497	479	""
* Cost of 1kWh = 7 INR/kWh					

2.1.7 Environmental Management Practices and Impacts

A study on the sustainable performance of the Indian Cement Industry in 50 large and mini cement companies noted that the Indian cement industry is on the path towards sustainability. It has made considerable improvements in waste heat recovery, efficient monitoring of particulate matter, energy efficiency, alternative fuel use, and reduction in CO_2 emission intensity. The companies leading sustainability efforts had a variety of improvements in mining technology, afforestation of mine areas, raw material sourcing and handling, waste management, energy efficiency, water use, and development of new technology and newer varieties of cement. [27]

The cement production generates numerous wastes such as solid, liquid, and flue gas emissions. Various non-renewable resources fuel the kiln and therefore are extremely energy and emission-intensive. There are numerous wastes and pollutants that occur across various activities (Table 15). They include:

- *Solid Wastes* such as during clinker production and spoil rocks during raw material preparation, dust and Fly Ash from the power plant, used oil, and scrap.
- *Particulate Matter Emissions* result from crushing and grinding of raw materials, storage, usage, storage of solid fuel, and other packaging and dispatch activities.
- *Liquid Wastes* such as stormwater flowing through coal stockpiles, stormwater flowing through coke stockpiles, stormwater flowing through waste material stockpiles
- *Wastes from fossil fuels and alternative fuels*, such as high Sulphur content in coal and petcoke, result in buildup on rings in the kiln due to high alkalinity at high temperatures. Alternative fuels to coal and petcoke such as used solvents, waste oil, tires, waste

plastics, and organic chemical waste result in heavy metal emissions such as Lead, Cadmium, Mercury.

- *Air Emissions* comprises flue emissions released into the atmosphere, which are ozone-depleting and include CO, CO_2, NOx, SOx, VOC. Several processes release air emissions (Table 15).

- *Noise Pollutions* encompass prolonged exposure to loud noise that may lead to hearing loss. The noise pollution arises from stone crusher, raw mill, kiln, conveyor, compressor, machine operating rooms, grinding, and blending equipment.

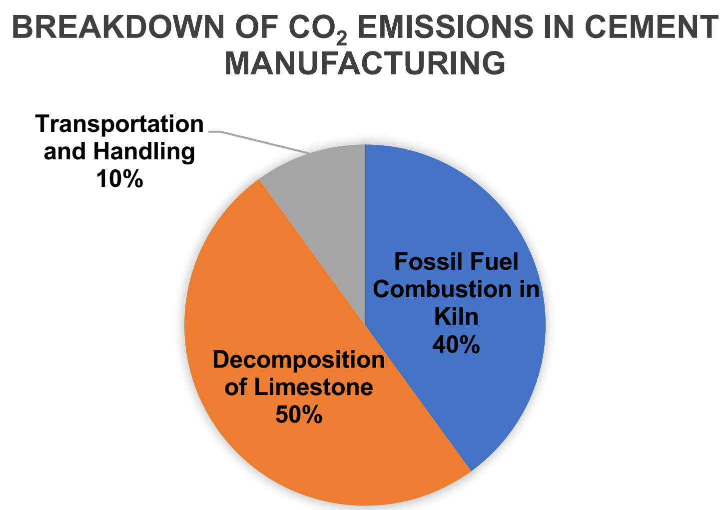


Figure 8: Emissions breakdown for cement manufacturing process

Table 15: Activity-wise breakdown of pollutants in cement manufacturing

Activity	Process Input	Process Output	Pollution	Impact
Crushing	Limestone Silica Clay Shale	Crushed Raw Material	Clinker Making Raw Material Dust	Noise Pollution (workplace) Air Pollution
Kiln & Clinker Cooler	Fuel	Clinker	Water Vapor Filter Kiln Dust	Noise Pollution (workplace) Air Pollution
Grinding	Clinker Gypsum Slag	Cement	Cement Making Raw Material Dust	Noise Pollution (workplace) Air Pollution
Packaging	Cement		Cement Dust	Air Pollution

Pollutants from cement manufacturing can affect resulting health, cause global warming and climate change, ozone depletion, acid rain, and create bio-diversity loss. Reduced crop productivity can also happen when the pollutants come into contact with the soil. Using alternative fuels may reduce CO_2 emissions but may affect clinker quality and release pollutants into the atmosphere and soil due to composition quality.

2.1.8 Cement Production Process

Cement production is a capital-intensive process and requires large machinery. The plants are close to the limestone mines or other raw carbonate mineral sources. The cement manufacturing process involves the following activities (Figure 10) [19, p. 9][28, p. 13]:

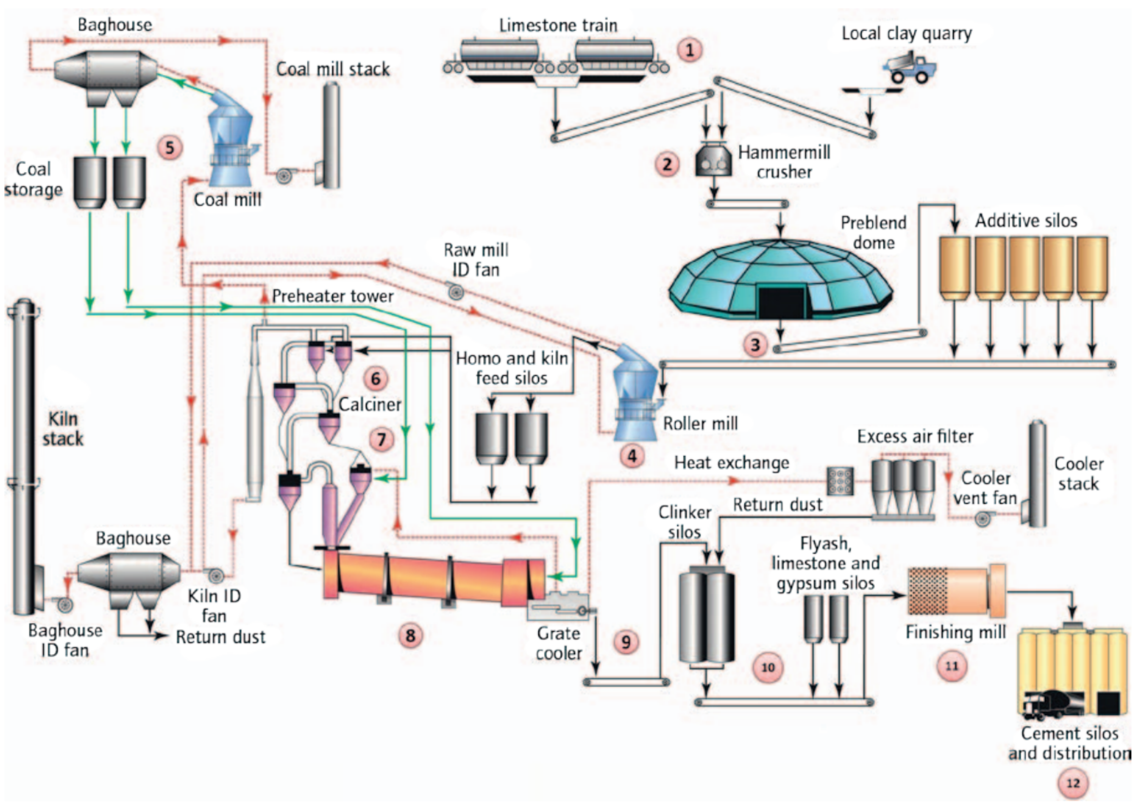


Figure 9: Cement production stages (adapted from Heidelberg cement) [19, p. 8]

1. **Extraction of raw materials:** Naturally occurring calcareous deposits, such as limestone, marl, or chalk, provide the calcium carbonate ($CaCO_3$) are extracted from surface mines/quarries.

2. **Crushing raw materials:** Quarried materials are fed through primary and secondary crushers, crushed to less than 10 centimeters (cm) in size, and transported to the cement plant.

3. **Raw meal prep & grinding:** Raw materials are mixed to achieve the required chemical composition, also known as pre-homogenization. Small amounts of corrective materials such as iron ore, bauxite, shale, clay, or sand may be added as needed to provide iron oxide (Fe_2O_3), alumina (Al_2O_3), and silica (SiO_2) to achieve the desired batch of cement. This material is then milled to produce a fine powder called the raw meal. The chemistry of the raw meal is also monitored to ensure the suitable composition of cement for quality and consistency.

4. **Preheating and co-processing:** It comprises a set of vertical cyclones through which the raw meal is passed. At this stage, the raw meal comes in contact with the hot kiln exhaust gases moving in the opposite direction. It captures some of the thermal energy from the kiln flue gases and preheats the raw meal before entering the kiln. The number of stages of cyclones is determined based on the moisture content in the raw material. It can have up to six stages of cyclones, and heat recovery increases at each recovery stage. The raw meal temperature is raised to over 900°C. The wastes generated from other industries and municipalities are used as materials for the raw mix or as fuels for pyro-processing. Wastes and byproducts vary widely in nature and moisture composition and have high material handling needs such as sorting, shredding, and drying before adding into the cement kiln.

5. **Precalcining:** Calcination is the chemical decomposition of limestone to lime and occurs in precalciner in most processes. During calcination, calcium carbonate ($CaCO_3$) decomposes at high heat to form Calcium Oxide (CaO) and Carbon Dioxide (CO_2). The precalciner is a combustion chamber located at the bottom of the preheater and is slightly above the kiln and partially within the kiln. The decomposition of limestone here produces 60% - 65% of the total emissions. The calcination reaction is exothermic and releases more heat which is used as inputs for clinker formation. The fuel combustion in the precalciner also produces emissions, accounting for about 65% of the remainder of total emissions, which is about 23-26% of total emissions.

6. **Clinker production in a rotary kiln:** The precalcined meal enters the rotary kiln. At the same time, fuel is fired directly into the kiln to reach high temperatures of 1450°C that results in further chemical and physical reactions and partially melts the meal into clinker. Also, any limestone or CO_2 combined minerals that did not complete calcination in the precalciner stage will complete the reaction in the kiln and emit CO_2. As the kiln rotates about three to five times per minute, the material falls towards the flame through progressively hotter zones.

7. **Cooling and storing of clinker:** Hot clinker from the kiln is collected on a grate cooler and cooled by blowing incoming combustion air, allowing thermal energy recovery from the hot molten kiln. Clinker once rapidly cooled on grate cooler from over 1000°C to 100°C with the aid of an air blower, is then stored in storage facilities on-site between kiln area and blending and grinding area.

8. **Blending:** Clinker is mixed with other minerals to make cement. Gypsum is a mineral that controls the setting time of the cement. Therefore, all cement types contain 4-5% of gypsum. In addition, cement producers use slag, fly ash, limestone, or other minerals to lower the clinker content for a given cement batch. They are inter-ground or blended to replace part of the clinker. The end product is called blended cement.

9. **Grinding:** The blended mixture of cooled clinker and gypsum is ground to form a grey cement powder known as OPC. It can be ground with other minerals to form blended cement. Vertical roller presses and vertical roller mills are used widely for grinding, unlike the more energy-intensive ball mill roller in the past.

10. **Storing in cement silos:** For future dispatch, the homogenized final product is stored in cement silos. Cement is packed in bags or loaded in bulk and transported to a packing station or directly to customers.

11. **Coal grinding/ kiln fuel prep:** Outside of these activities, coal is also ground into a fine powder and fed into the kiln as a fuel.

Direct vs. Indirect Emissions: Cement processing involves specialized equipment and processes (Figure 10). Energy is input in every stage, resulting in CO_2 and other greenhouse gases. Some of these emissions are direct, while some are indirect emissions (Figure 11). Direct emissions are those CO_2 emissions released as a result of the manufacturing activities and from sources that are owned and controlled by the reporting entity. Indirect emissions are those emissions that are a consequence of the activity of the reporting entity but occur at sources owned and controlled by another entity.[13]

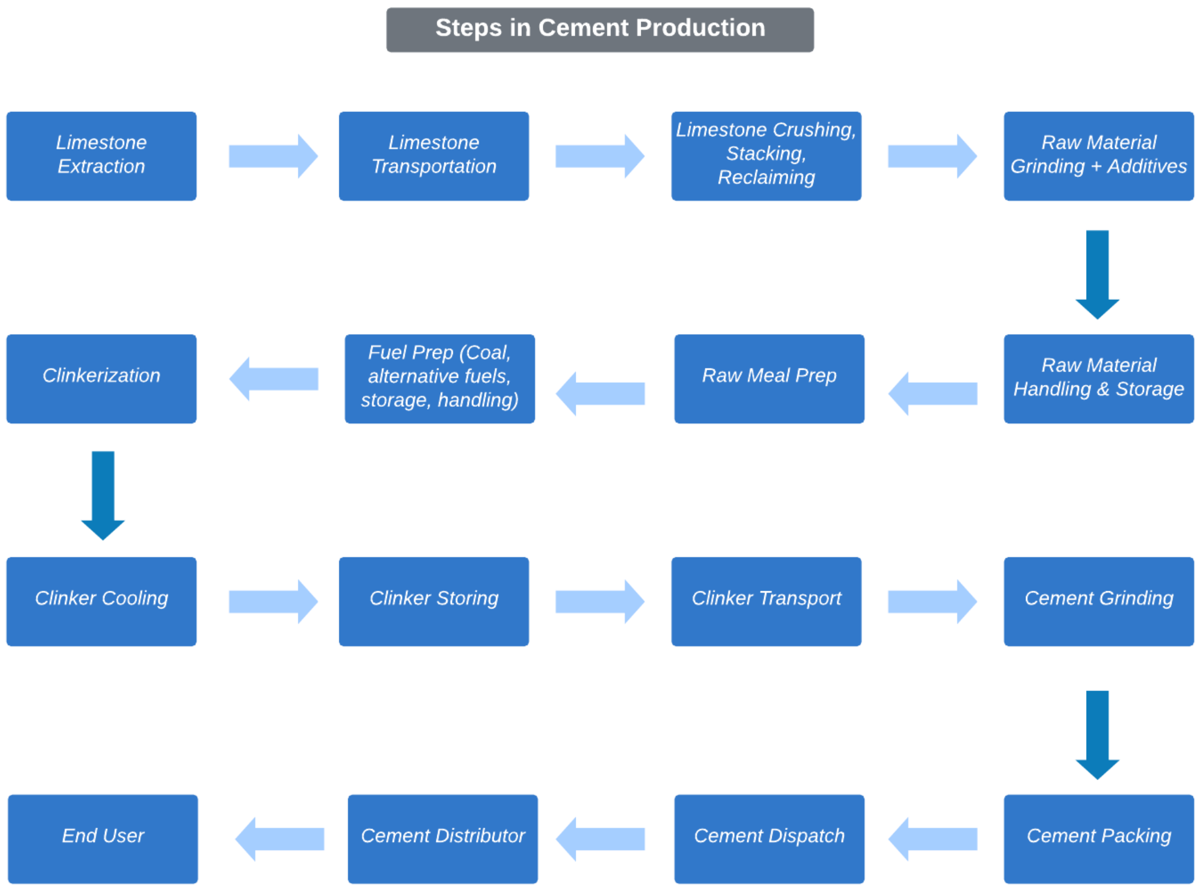


Figure 10: Steps involved in cement production from extraction to end-user

[13] https://ghgprotocol.org/calculationg-tools-faq

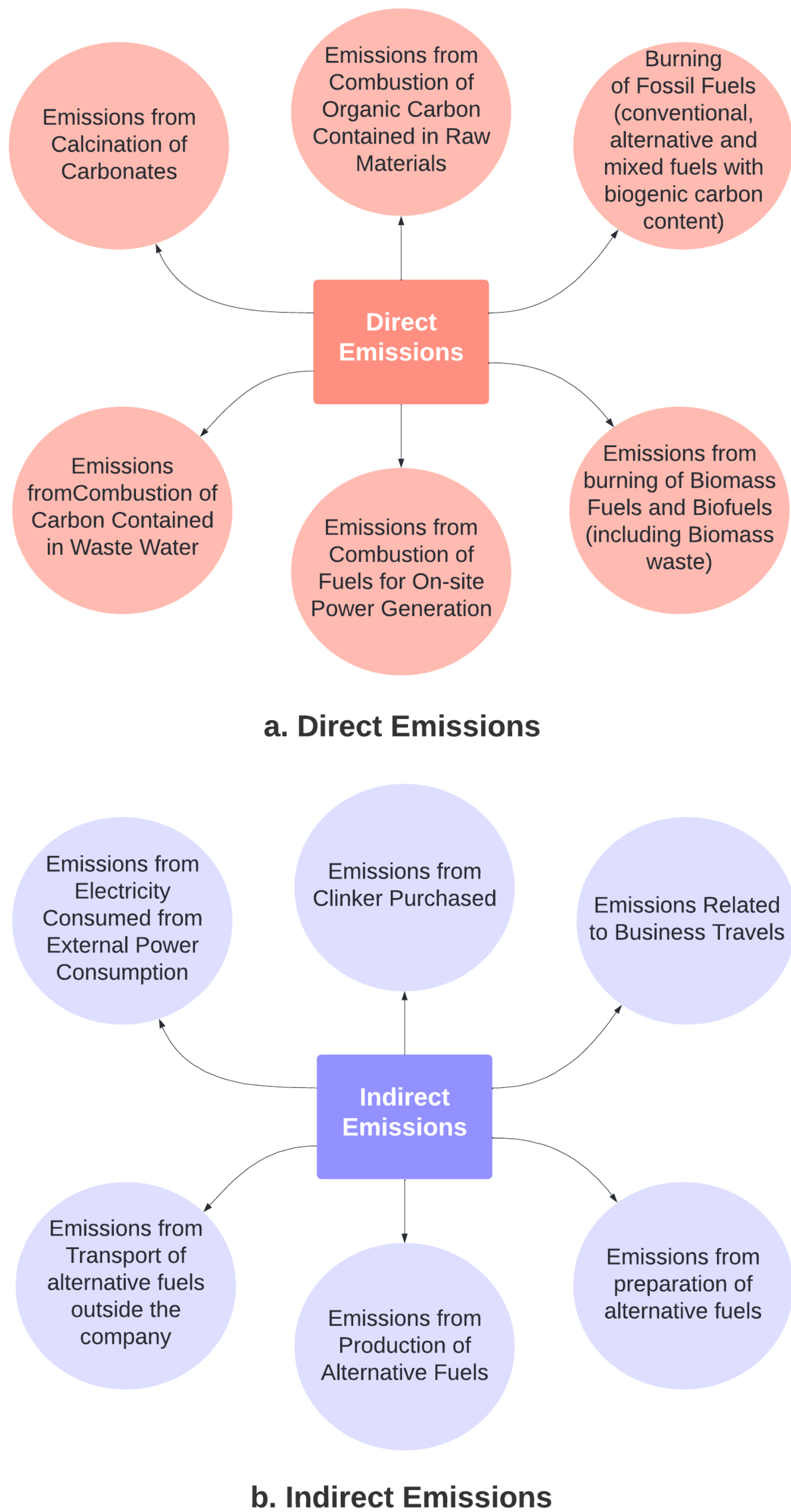


Figure 11: Sources of (a) direct and (b) indirect emissions in cement manufacturing

Energy and Emissions Flows in cement Production

Cement Manufacturing Process (Chemical decomposition – Calcination): Manufacturing processes of clinker produce CO_2 emissions. The chemical decomposition of limestone accounts for 60% to 65% of total emissions. [19, p. 9] The calcination reaction alone attributes to nearly two-thirds of process CO_2 emissions. [29][28][30]

Fuel Burning: Clinker production requires heating, calcining, and sintering at high temperatures. The burning of fossil fuels such as coal (Carbon) in the air causes emissions. Fuel combustion used to generate heat in the pre-calciner alone produces emissions in the range of 23-26% of the total process CO_2 emissions. Nearly one-third of process emissions are accounted for by burning carbon-intensive fuels such as coal and pet-coke to raise the kiln's temperature needed for calcination reaction.

Release of Trapped CO_2: The oceans and earth act as natural CO_2 sinks easing global warming. However, during the extraction of carbon from reservoirs for uses such as fuel for industrial or other purposes, the trapped CO_2 from underground is released into the earth's atmosphere, which would otherwise not reach the atmosphere, ocean, or soil.

Transportation (Raw Materials): Transportation of raw materials also releases emissions depending on the fuel source used for transportation.

Crushing, Grinding, Blending, Fuel Prep: These are various processes in cement manufacturing that release CO_2 directly or indirectly depending on the type of energy source.

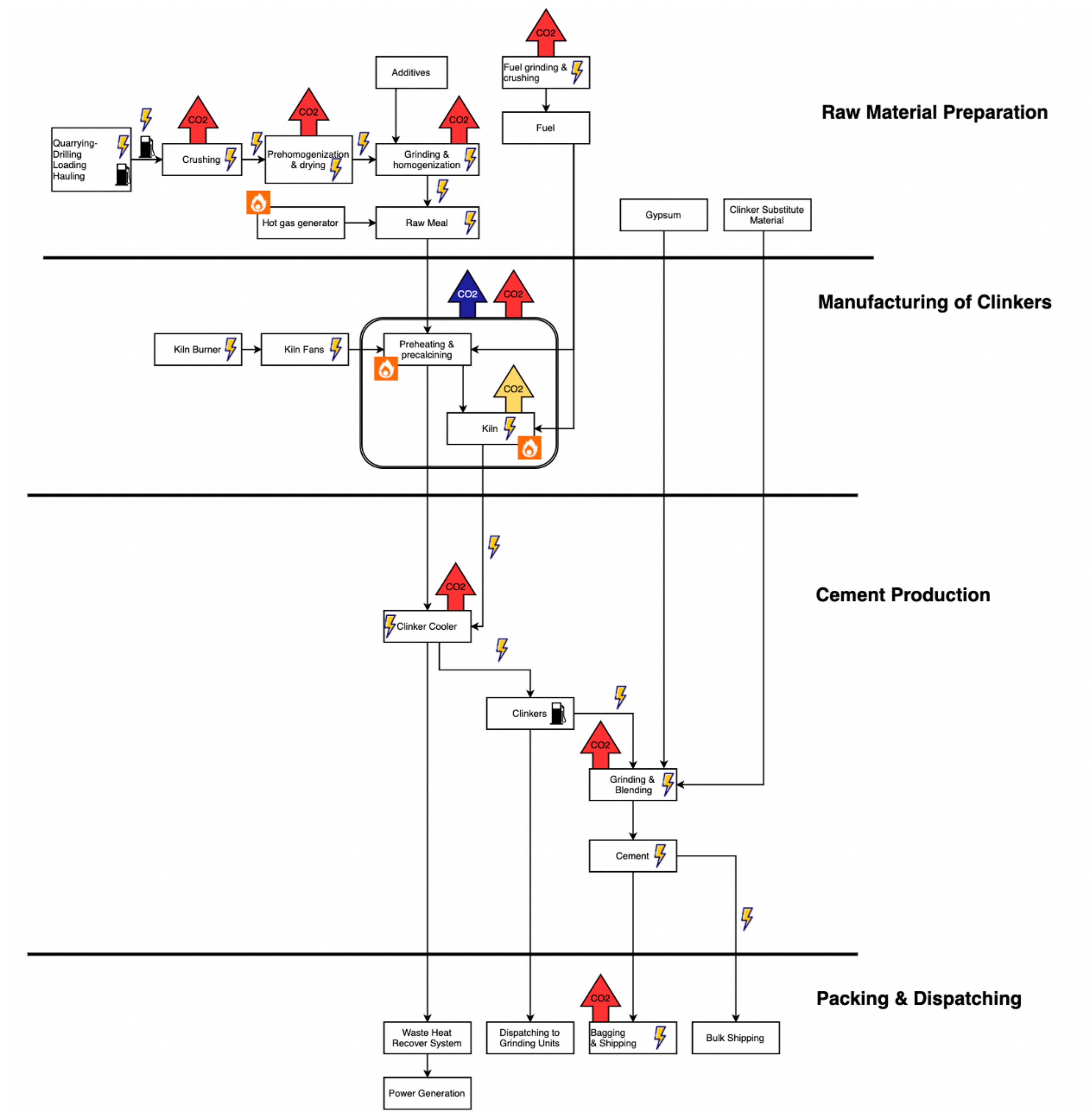


Figure 12: Schematic of emissions and energy flows in cement manufacturing

2.1.9 Economics Impacting CO_2 emissions

Business and Geographic Role of India: The Indian cement industry is 99% privately owned. These privately-owned plants are concentrated in India's Southern and Northern regions (Figure 13). Within these regions, cement plants are concentrated in Andhra Pradesh, Rajasthan, and Tamil Nadu because these are close to limestone deposits. Due to the production being limited to select states and regions, transportation emissions are a constraint for cost and decarbonizing the sector.

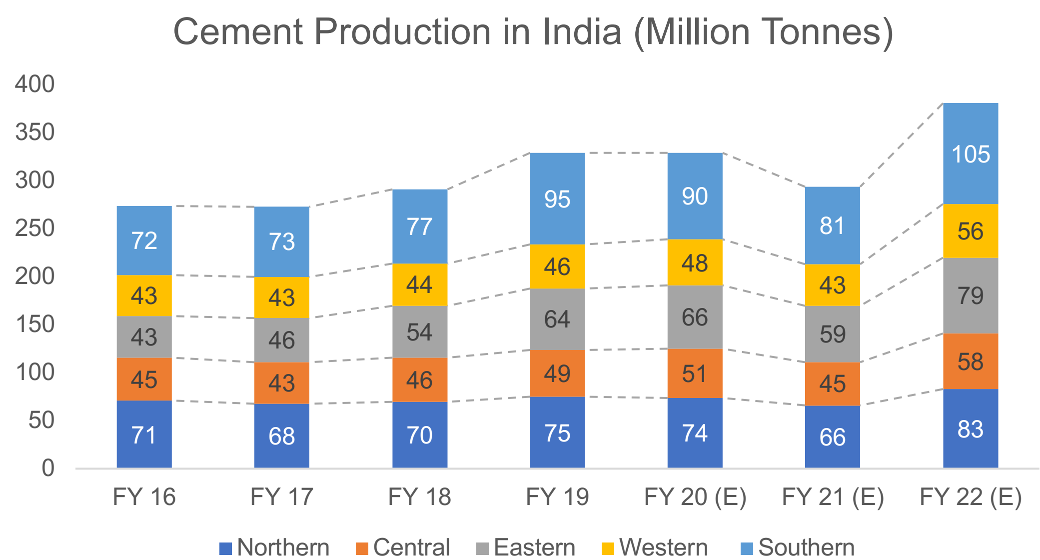


Figure 13: Breakdown of annual cement production in India by region - FY16 to FY22(E) [31][14]

Most cement production share happens in the larger cement plants [31] [32, p. 17] Smaller companies are typically disadvantaged in pursuing decarbonization due to a lack of capital, finance access, and pricing control. By contrast, larger companies are regulated and have better access to financial capital and pricing control to spend on decarbonization efforts. [31, p. 5]

[14] HDFC securities as noted in IBEF report; (E) indicates expected data where actual data is not available or occurs in future.

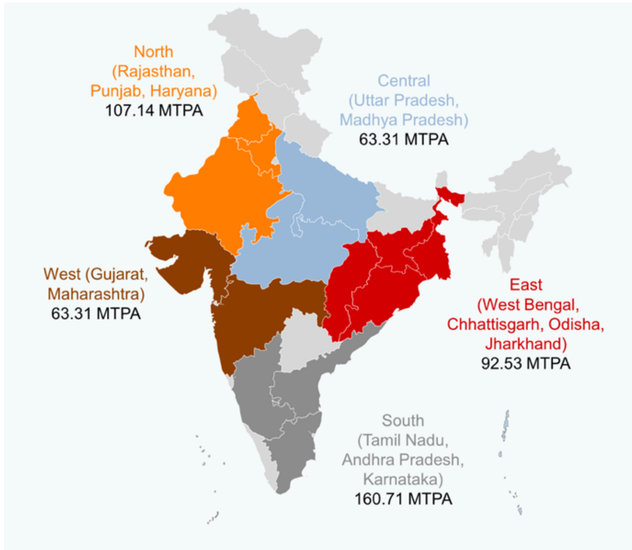


Figure 14: Installed capacity & key markets by geographic regions in India[15] [31, p. 10]

Cement Companies in India: Ultratech, the leading firm with the highest production market share (Figure 15), aims to deliver carbon-neutral concrete by 2050. Dalmia cement announced that it aims to be carbon negative as early as 2040.

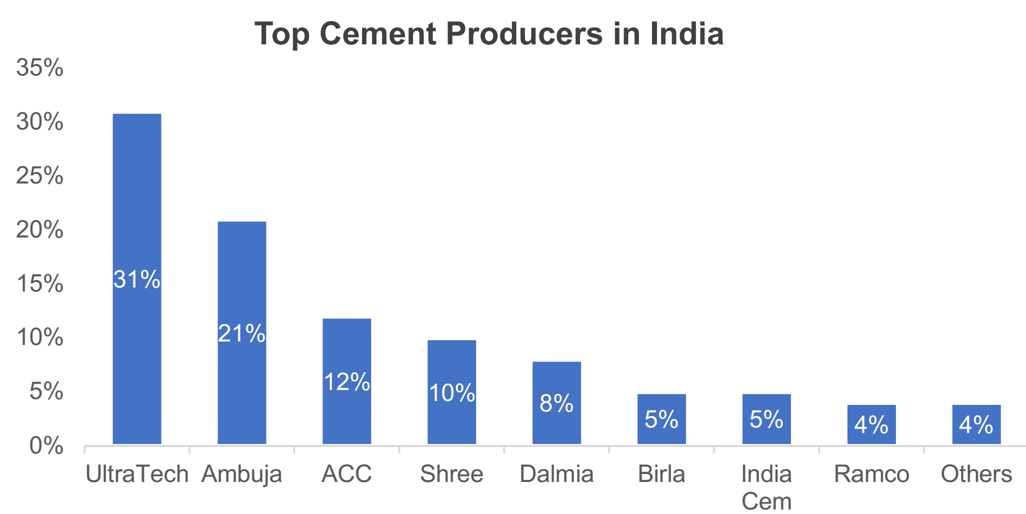


Figure 15: Top cement producers in India (by market share in 2020)[31][16]

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[15] Indian Minerals Yearbook by Indian Bureau of Mines; Ultratech Cement; IBEF Re

[16] Cement Manufacturers Association; USGS Mineral Commodities Summary 2020; Crisil; News Articles; IBEF report

Import vs. Export: Currently, India is a net importer, but this trend is expected to reverse, with India attempting to position itself as a net exporter in the future. This trend is observed in the compounded annual growth rates observed between FY16 and FY20, where the exports have been increasing at a higher y-o-y growth rate (CAGR%) compared to the imports growth rate (See Table 16). It is made feasible due to the number of capacity expansions in the Indian cement industry and China's expected decline in world market share. With cement being freight intensive, India exports it to nearby and neighboring countries such as Sri Lanka, Nepal, Bangladesh, or close locations connected by ports such as UAE and the US while conducting trade within India for cement export and import in FY 19, 20 and 21. [12, p. 13]

Table 16: Indian cement industry import vs. export in billion USD[17]

	FY16	FY17	FY18	FY19	FY20	CAGR FY-16 to 20
Cement Export from India (Billion USD)	1.85	1.93	2.22	2.23	1.98	**1.4%**
Cement Import to India (Billion USD)	2.58	2.17	2.52	2.85	2.62	**0.3%**

Cement Demand Factors: India's primary growth drivers for cement are housing and real estate (Table 17). [31, p. 14] It has several schemes in its pipeline such as Smart City Mission, Housing for All, Bharatmala Pariyojana, Pradhan Mantri Gram Sadak Yojana, Urban Transport Metro Rail Projects, Dedicated Freight Corridors, and ports, Make In India, Swachh Bharat Abhiyan, and Water transport. [33] [7] They will all contribute to the cement demand. Currently, the threat from cement substitutes is low and will see sustained cement use.

Table 17: Cement demand influencers

Sector	Cement Demand Share (FY2021)	Source
Housing and Real Estate	55%	[31, p. 15][18]
Infrastructure	22%	""
Low-cost Housing	13%	""
Industrial Development	10%	""

Nearly 75% of the buildings stock expected to be standing in 2030 are yet to be built, which will result in increased cement uptake. Government-led projects alone contribute to 35 – 40% of demand.[19] National infrastructure pipeline projects and opportunities in the Northeast region

[17] India Brand Equity Foundation; DGCI&S & Statista

[18] Source: Ministry of External Affairs (Investment and Technology Promotion Division), AT Kearney, CARE Ratings, NAREDCO and APREA, Union Budget 2021-22

[19] https://www.crisil.com/en/home/our-analysis/views-and-commentaries/2020/04/cement-cracks.html

which are experiencing a construction boom, are also contributing factors for cement demand growth. [34] The government of India's (GOI) adoption of cement and ready-mix concrete instead of Bitumen for rail-road projects is another contributing factor for cement demand and CO_2 emissions.[20]

While in many developed countries, market growth has been slow or nil, growth rates are rapidly increasing in developing markets such as India."[21][22] Several industry stakeholders and experts like IBEF, National Real Estate Development Council (NAREDCO), and other industry ratings such as CARE have all attested to strong economic growth for India that will result in the growth of the industrial sector, especially for India.

While rising GDP leads to growth in the cement industry, the growth in the Indian cement industry will, in return, contribute to the nation's GDP growth in terms of revenue generation and employment, and the purchasing power parity will rise as a result. It will, in turn, increase trends in consumption, more spending, larger housing, and other trends like nuclearization that will increase cement demand. Additionally, the population is expected to grow slowly, although it will peak around mid 21st century[23]. India's population is set to increase by 40% from 1.2 billion to 1.7 billion in 2050. [9, p. 13] All of this points towards greater demand for cement and cement industry emissions. The cement demand is rising due to the projected increase in per-capita consumption. As GDP improves and the overall living standards and purchasing power parity rise, the per-capita emissions will grow and merge with those of the developed nations, creating reinforcing feedback loops for CO_2 emissions.

Projections in Cement Demand Growth: The projected compounded annual growth rate for India's cement production between FY16-22 is 5.65%. [31, p. 8] The projected cement demand by 2025 is expected to reach 550-600 MTPA. [31, p. 15] Cement production is expected to increase 10-12%, and utilization will reach 65% in FY22. Between 2010 and 2050, cement production is projected to increase between 3.6 and 6.3 fold, which will cause energy consumption in the cement sector to grow between 2.8 and 5.0-fold. [7] Cement production in

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[20] IEA 2020; 2020 Report - India Brand Equity Foundation; AEEE 2008
[21] 2013 thesis Assessment of competition in cement industry in india.pdf", p. 1
[22] http://www.unep.fr/scp/csd/wssd/docs/further_resources/related_initiatives/WBCSD/WBCSD-cement.pdf
[23] https://www.thehindu.com/opinion/lead/indias-population-data-and-a-tale-of-two-projections/article32329243.ece

India is estimated to reach 780 million in a low-demand scenario to 1.36 billion tonnes in a high-demand scenario in 2050 (Figure 16).

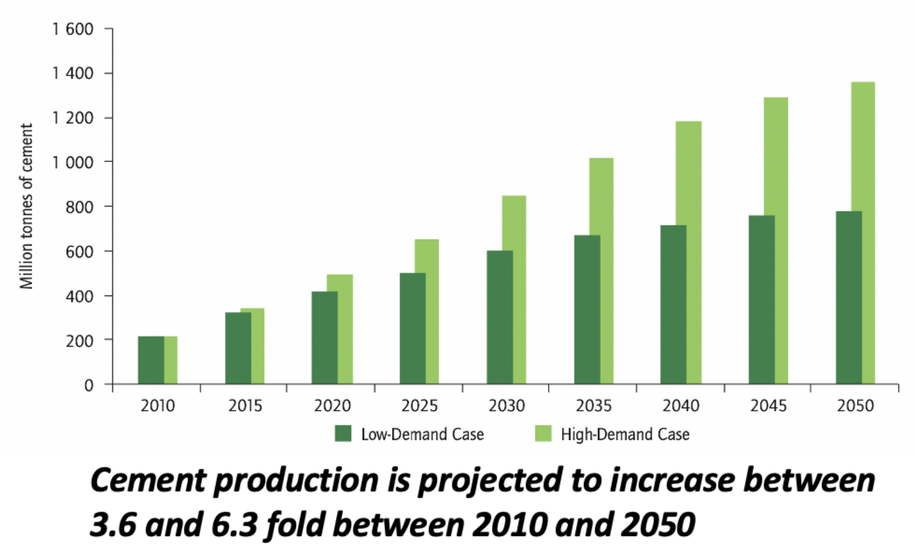

Figure 16: Cement production is expected to rise in the future [9, p. 13]

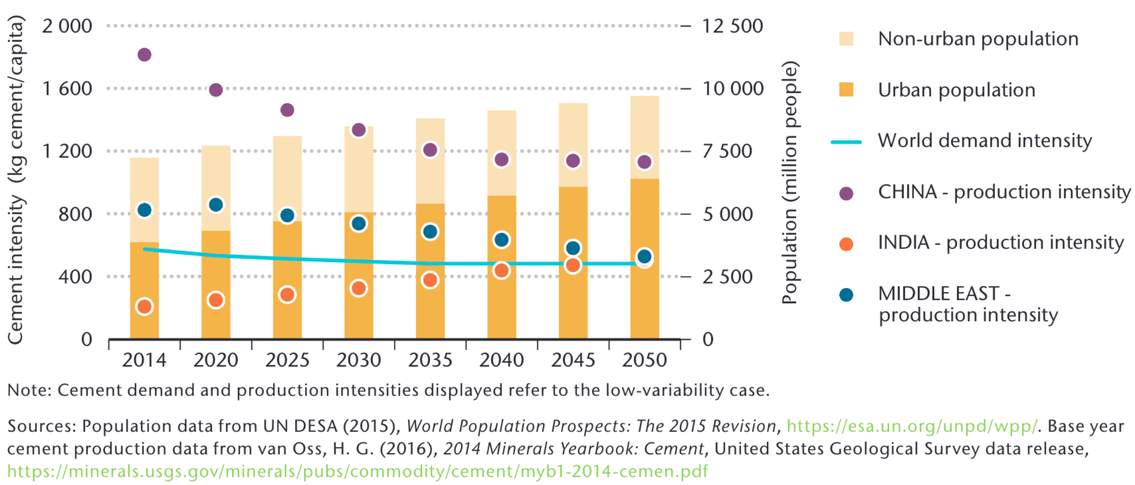

Figure 17: Global cement demand intensity projection 2014-2050 [28, p. 17]

The rise in global population and urbanization will result in the global cement production increasing between 12 to 23% by 2050 and is expected to grow by 34%. [28, p. 17] IEA projects that despite increasing efficiencies, direct carbon emissions from the global cement industry will rise by 4% globally by 2050 under the IEA Reference Technology Scenario (RTS). Limiting the more ambitious IEA's 2°C average global temperature rise by 2050 (2DS Scenario) or the 1.5°C scenario, which is more ambitious than the RTS scenario, is a challenging task given all the demand factors and growth projections.

Greenfield/Brownfield capacity additions: Cement players are opting for inorganic growth or brownfield acquisitions to ramp up their capacity expansion in a cost-efficient manner. [32, p. 17] See Figure 18 for capacity utilization projection across different regions in India. By FY 27, nearly all regions are expected to have greater than 80% capacity utilization.

Table 18: Greenfield vs. brownfield expansion potential across regions in India

	North	South	East	West	Central	Source
Expansion Potential (Brownfield)	57%	72%	27%	19%	0%	[26, p. 4]
Expansion Potential (Greenfield)	43%	28%	73%	81%	100%	[26, p. 4]

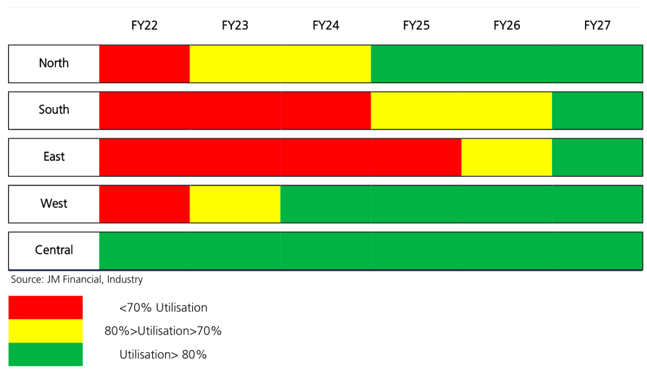

Figure 18: Projection of utilization spread by region [26, p. 4]

Cyclical economy: The cement sector in India is cyclical (seasonal) and dynamic and influenced by market and economic drivers. *Seasonal / Cyclical, i.e., e*ach year, there is a slight decrease in cement demand during the monsoon seasons, making it a seasonal or cyclical industry. *Dynamic nature,* i.e., various schemes and economics for example, government drivers such as infrastructure investments, freight corridors, pipeline projects, and airports boost cement demand. *Market and economic drivers depend on* real estate growth, urbanization, population, families (nuclear vs. joint), incomes, living standards, and PPP.

GDP: India is a lower-middle-income country. Its GDP per capita is 85% lower than that of advanced economies. India's GDP is projected to grow tremendously at 5.4% annually between 2019 and 2040. The long-term cement growth rate is estimated as 1.2 times GDP growth rate as economic growth leads to growth of the industrial sector. High GDP growth will result in high expected cement demand and an overall increase in CO_2 emissions. Typically, cement growth rate = 1.2 X GDP growth rate.

The overall growth of India's energy demand across all scenarios post-COVID (Figure 19)

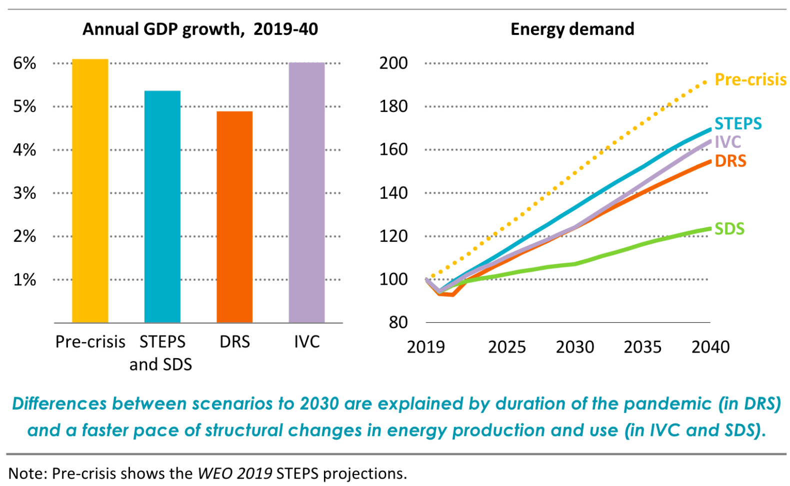

Figure 19: Growth in India GDP and energy demand to 2040 by scenario [11, p. 71]

Carbon Tax: Currently, India does not tax carbon emissions directly[24]. India implemented a CESS tax which started as a Clean Energy CESS tax on coal in 2010, which was realized at INR 50 per ton and was imposed on its domestically produced and imported coal, lignite, and peat. In 2017, this tax was increased to INR 100 per ton 2015[25,26]. The current Goods and Service Tax replaced the Clean Energy CESS tax since 2017, which levies INR 400 per ton of coal. The carbon tracker initiative noted that coal is both financially and environmentally unsustainable for India. The report calls for investors and policymakers to cancel all new coal projects and lay the foundations for a sustainable energy system. [35]

The International High-Level Commission on carbon prices noted that carbon pricing is most cost-effective in meeting climate goals while fostering growth. [36] It outlined the goal of a carbon tax of $40 - $80 per tonne of CO_2 by 2020 and $50 - $100 per tonne by 2030. The

[24] https://en.wikipedia.org/wiki/Carbon_tax#India
[25] https://www.financialexpress.com/opinion/controlling-emissions-explicit-carbon-taxation-needed-indirect-taxation-doesnt-help/2074347/
[26] https://economictimes.indiatimes.com/industry/energy/power/power-ministry-seeks-coal-cess-waiver-for-fgd-power-plants/articleshow/84473035.cms?from=mdr

commission also presented two major available policy options for introducing a direct carbon price in the economy. The first option is to impose a tax or fee on fossil fuels' GHG emissions (or carbon content). The other option is a cap-and-trade scheme that limits the total allowable volume of emissions in a particular time period from a specified set of sources (cap on emissions) and allows for trading their emissions rights. In India, despite not having a carbon penalty, some companies in the private sector have already started implementing Internal carbon pricing (ICP) in their estimates. Below is the cost penalty for CO_2 emissions of those companies sourced from TERI and CDP India report. Ultratech cement considered ICP at the rate of $9.93/ tonne of CO_2 (INR 680/ tonne of CO_2) in 2019, while Ambuja cement used $30.74/ tonne of CO_2 (INR 3313/ tonne of CO_2) [27].

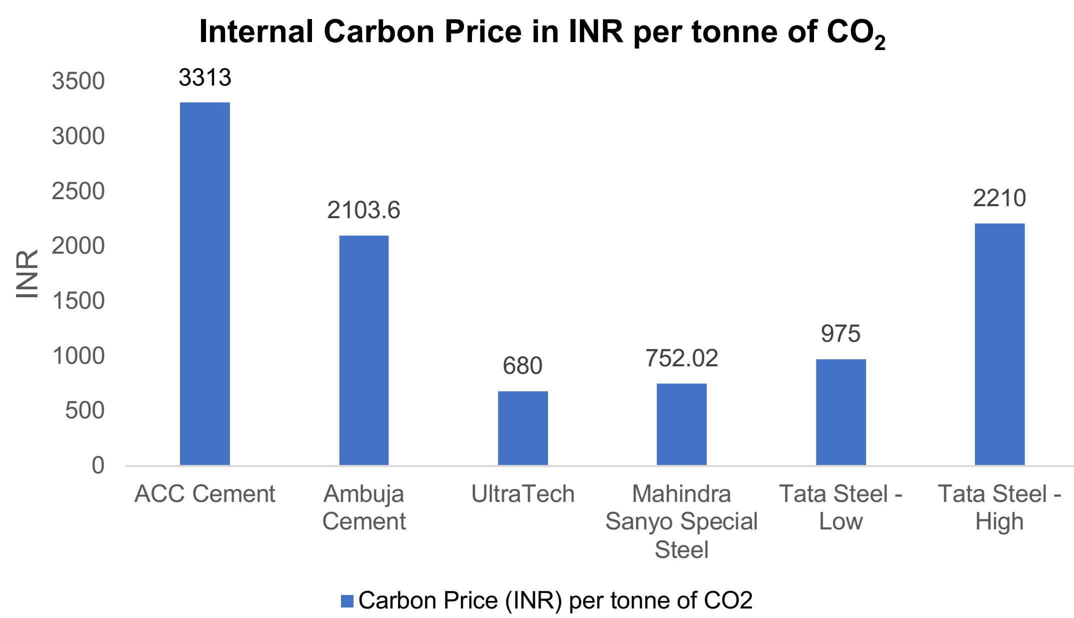

Figure 20: Internal carbon price of Indian cement and steel companies [37][28]

While the projections of India's cement production are expected to grow by 150-280% in the different scenarios, when a carbon tax is imposed, the production is expected to slow (1260 Mt in 2050 to just 800 Mt) due to higher costs. [38, p. 15] Additionally, incorporating CCS will result in a not so high decline in consumption, reaching 1000 Mt. Not factoring in carbon tax or CCUS

[27] Average exchange rate used: 1$ = INR 68.5
[28] Ambuja and Dalmia Bharat Ltd. have an internal carbon price but have not disclosed publicly

will disable the cement industry from being a significant contributor to India's economy and its path to SDG goals.

Table 19: Carbon tax scenarios from 2020 to 2050

Year	Low	Mean	High	Source
2020	$20	$50	$100	[39, p. 30]
2030	$30	$74	$148	[39, p. 30]
2040	$44	$110	$219	[39, p. 30]
2050	$65	$162	$324	[39, p. 30]

2.1.10 Emissions and Energy Consumption of Cement Types

Currently, the Indian cement industry is one of the most energy-efficient globally in energy intensity (See Section 3.4). India's cement plants have achieved Specific Energy Consumption (SEC) values comparable to the world benchmark (Table 20). The sector's best plants consumed 19% less energy than the global average. [32, p. 18] See Table 21 and Table 22 where the cement plant's electrical energy consumption is lower than the national and international benchmarks. Even though the Indian cement industry has dramatically reduced CO_2 emission intensity in the past decade through energy-efficient technology, employing this strategy further to achieve technology efficiency improvements will yield diminishing marginal returns. [9, p. 3]

Table 20: SEC (thermal and electric) benchmarking by CII

Reference year	Specific Thermal Energy Consumption (Kcal/tonne of clinker)	Specific Electrical Energy Consumption (kWh/tonne of clinker)	Source
2018-19	0.697	73.9	[40], J.K. Lakshmi Sirochi Plant
2019-20	0.697	73.87	[40], J.K. Lakshmi Sirochi Plant
2020-21	0.698	74.4	[40], J.K. Lakshmi Sirochi Plant
International Benchmark	0.660	63	[40], J.K. Lakshmi Sirochi Plant
National Benchmark	0.676	64	[40], J.K. Lakshmi Sirochi Plant

Table 21: SEC (electric) up to clinkerization and for overall cement

	Specific Electrical Energy Consumption – Up to Clinkerization (kWh/t of clinker)	**Specific Electrical Energy Consumption – Overall Cement (kWh/t of cement)**	**Source**
2018-19	46.03	34.72	[40]
2019-20	47.18	35.23	[40]
2020-21	48.02	35.95	[40]

Table 22: SEC (thermal and electric) - India vs. Global average

Region	**Specific Thermal Energy Consumption (GJ/tonne of clinker)**	**Specific Electrical Energy Consumption (kWh/tonne of cement)**	**Source**
India Best	2.83	64	[33]
India Average	3.1	80	[33]
Global Average	3.5	91	[33]

Average Specific Thermal Energy Consumption in Indian cement industry is 3.1 GJ/tonne of clinker vs. a global average of 3.5 GJ/tonne of clinker. The average specific electrical energy consumption in Indian cement industry is 80 kWh/ tonne of cement vs. the global average of 91 kWh/tonne.[29] Energy consumption for clinker, OPC, PPC, and PSC in a standard cement plant in India and around the world is listed in Table 23, Table 24 and Table 25. [41]

Table 23: Energy consumption for Clinker, OPC, PPC, and PSC cement

S. No.	Plant	Location	Capacity	Clinker Energy Intensity	OPC Energy Intensity	PPC Energy Intensity	System Boundary
1	Dry manufacturing, located near limestone mine	Ariyalur, Tamilnadu, India	1.6 MTPA	3990 MJ/ton	4015 MJ/ton	3077 MJ/ton	Gate-to-gate
2	Dry manufacturing, located near limestone mine	Ariyalur, Tamilnadu, India	1.5 MTPA	3626 MJ/ton	3821 MJ/ton	2733 MJ/ton	Gate-to-gate

[29] https://aeee.in/emission-reduction-approaches-for-the-cement-industry/

Table 24: Power consumption by section up to clinker

Power Consumption (kWh/t)	Plant										Source
	1	2	3	4	5	6	7	8	9	10	
Crusher Section	0.58	0.63	0.74	0.75	0.86	1.04	1.22	1.32	1.4	1.51	[40]
VRM Section	10.6	10.8	11.2	12.1	12.5	13.5	14.1	15.7	16.6	17.7	[40]
Kiln Section	15.4	18.5	19.9	19.9	20.1	20.8	21	21.3	22		[40]
Up to Clinker	42.6	43.2	44.0	45.6	45.7	48.9	49.5	49.9	50.6	50.8	[40]
% AFR consumption	30	15.2	15.1	13.3	12.7	10.4	8.63	4.55	1.58		[40]

Table 25: Energy use - Clinker, OPC, PPC (adapted)

Product	Input (MJ/ton)	US	Canada	Europe (excl. Switzerland)	Switz-erland	Rest of World	Source
Clinker	Thermal Energy	2442.6	3105.8	2495.63	1540.3	2403.9	Eco-invent v3, Simpro
	Electricity	652	450	643	1230	663	""
	Others	665.4	164.19	671.37	199.69	643.01	""
	Total	3760	3720	3810	2970	3710	""
Cement Portland (OPC)	Clinker	3420	3440	3460	2700	3380	""
	Electricity	627	228	417	444	420	""
	Others	63	62	63	46	60	""
	Total	4110	3730	3940	3190	3860	""
Cement Pozzolana + Fly ash (PPC)	Clinker	2610	-	2800	2180	2740	""
	Electricity	534	-	365	334	368	""
	Others	66	-	55	56	52	""
	Total	3210	-	3220	2570	3160	""

The industry achieved overall reductions of direct CO_2 emission intensity ($kgCO_2$/t cement) by 32 $kgCO_2$/t cement to 588 $kgCO_2$/t cement, a 5% reduction from 2010 to 2017 [32, p. 19]. The CO_2 emissions intensity including onsite/captive power plant (CPP) power generation reduced by 49 $kgCO_2$/t cement to 670 $kgCO_2$/t cement, a 6.8% reduction from 2010 to 2017. [32, p. 19]

Table 26: CO_2 emissions for Clinker, OPC, PPC, and PSC

S. No.	Plant Features	Location	Capacity	Clinker Emissions Intensity	OPC Emissions Intensity	PPC Emissions Intensity	System Boundary
1	Dry manufacturing; preheater & precalciner; located near limestone mine	Ariyalur, Tamilnadu	1.6 MTPA	849 kg CO_2/ton	802 kg CO_2/ton	606 kg CO_2/ton	Gate-to-Gate
2	Dry manufacturing; preheater & precalciner; located near limestone mine;	Ariyalur, Tamilnadu	1.5 MTPA	868 kg CO_2/ton	855 kg CO_2/ton	595 kg CO_2/ton	Gate-to-Gate

In 2020, the carbon intensity of cement production was 572 kgCO_2/ton of cement vs. a world average of 614 kgCO_2/ton of cement (Table 26). The breakdown of it is as follows for the three conventional types of cement (OPC, PPC, and PSC) [41]:

1. **Clinker Manufacturing CO_2 emissions:** 849 – 862 kgCO_2/ton of clinker
2. **Cement Manufacturing (OPC) CO_2 emissions:** 802 – 855 kgCO_2/ton of cement
3. **Cement Manufacturing (PPC) CO_2 emissions:** 595 – 606 kgCO_2/ton of cement
4. **Composite Cement CO2 emissions**: 56% CO_2 reduction potential from OPC [33]
5. **LC3 cement CO_2 emissions:** 30% CO_2 reduction potential from OPC [33]
6. **Geopolymer concrete CO_2 emissions:** 80% CO_2 reduction potential from OPC [33]

2.1.11 Stakeholders

World Business Council for Sustainable Development (WBCSD): It is a global organization that works with over 200 businesses and partners from various business sectors and economies. It aims to help its member companies transition to a sustainable world and maximize impact for shareholders, environments, and societies. WBSCD works with stakeholders across value chains and can thus play an integral role in the sustainable transition.

Cement Sustainability Initiative (CSI): CSI is a global voluntary effort led by 24 major cement producers (multinational or local) who collectively have operations globally in more than 100 countries with a combined cement production accounting for one-third of the world's cement production. The goal of CSI is to facilitate the sustainable development of cement. The CSI members voluntarily report independently verified energy and emissions information to the Getting the Numbers Right (GNR) database. (website: www.csi.org)

International Energy Agency (IEA): The IEA comprises 30 member countries, eight associate countries, and many more partner countries in emerging economies. It plays a critical role by advocating policies that enhance the reliability, affordability, inclusiveness, and sustainability of energy in those countries and guiding nations worldwide. It mainly focuses on energy security, efficiency, reliability for all fuels and energy sources while supporting economic development by encouraging free markets and promoting policies to create energy security. It promotes environmental awareness by analyzing policy options to offset the impact of energy production and use on the environment to tackle climate change and air pollution. IEA engages well with many nations to solve energy and environmental concerns. [3] (website: www.iea.org)

Confederation of Indian Industry (CII): It is a membership-based non-governmental, non-profit, industry-led, and managed trade association organization and advocacy group headquartered in New Delhi, India, founded in 1895. It actively engages with the industry, government leaders, academics, and civilians to strengthen the development of India through its 9000 members across public and private sectors that include both multinational companies and small and medium enterprises. Additionally, it is partnered indirectly with over 300,000 enterprises from around 265 national and regional sectoral industry bodies. Its 2021 theme of India RISE (Responsible, Inclusive, Sustainable, and Entrepreneurial) focused on accelerating India's growth and development through public-private partnerships by focusing on job creation, financing growth, and promoting next-generation manufacturing and sustainability corporate social responsibility, governance, and transparency. Its chief program is the IGBC rating system for green buildings. [3] (website: www.cii.in)

CII-Sohrabji Godrej Green Business Centre (CII-Godrej GBC): Established in 2004, it is CII's developmental institute on green practices & businesses and offers advisory services on conservation of natural resources. [37] (website: http://www.greenbusinesscentre.com)

International Finance Corporation (IFC): The largest global development institution focused on the private sector in emerging markets. It works with more than 2000 businesses using its capital and creates market opportunities worldwide. It is a member of the world bank group and a sister organization, the world bank. In FY 2018, IFC made $11.6 billion in long-term investments in 366 projects and mobilized $11.7 billion to support the private sector in developing economies. In FY20, IFC invested $22 billion, including $10.8 billion mobilized from other investors, including a $2.7 billion in long-term investment commitments for South Asia.[42] (website: www.ifc.org)

Cement Manufacturers Association (CMA): The apex representative body of large cement manufacturers in India who manufacture 1 MTPA and more. It plays the role of a trade organization and advocacy group to bridge the gap between the government and the Indian cement industry for shaping key policy matters. Knowledge of best-in-class innovations and advancements are disseminated through CMA, including environmental, energy and fuels, mines and minerals, logistics, waste matters, taxation, sustainability, and alternative fuels. (website: www.cmaindia.org)

Global Cement and Concrete Association (GCCA): In January 2018, seven major cement companies (including many WBCSD CSI members), GCCA works on cement and concrete sector sustainability issues. The GCCA and WBCSD have formed partnerships to facilitate sustainable development of the cement and concrete sectors and their value chains. This partnership was aimed to create synergies between work programs to benefit both organizations and their respective member companies. GCCA India is accelerating the Low Carbon Technology Roadmap (LCTR) for the Indian Cement sector, which aims to reduce the direct CO_2 emissions to 0.35 tonnes of CO_2/ tonne of cement by 2050. They achieve this through the identification of new technologies, supportive policy framework, public-private collaboration, financing mechanism, and social acceptance. The organization promotes increasing the use of alternative fuel, utilizing WHRS potential, lowering clinker factor in cement, promoting the usage of alternate cement such as low calcined clay cement (LC3), and developing carbon capture and use (CCU) solutions based on circular economy principle. (website: www.gccassociation.org)

Indian Concrete Institute (ICI): ICI is a non-profit professional organization promoting concrete technology and construction. ICI is focused on research on achieving sustainability through innovative materials and techniques. (website: www.indianconcreteinstitute.org)

National Council for Cement and Building Materials (NCB): It was founded in 1962 to promote research and scientific work connected with cement and building materials trade and industry. Their work spans the entire spectrum of cement manufacturing and usages, such as geological exploration of raw materials through the processes, machinery, manufacturing aspects, energy, environmental considerations, final utilization of materials in actual construction, condition monitoring, & rehabilitation of buildings and structures. (website: www.ncbindia.com) [28, p. 18]

Ministry of Railways: The cement industry is the fifth-largest contributor to India's economy, and its deliveries are Indian Railway's second-largest revenue source. [32, p. 18] The ministry of railways' primary initiative is the EE initiatives in traction and non-traction system.

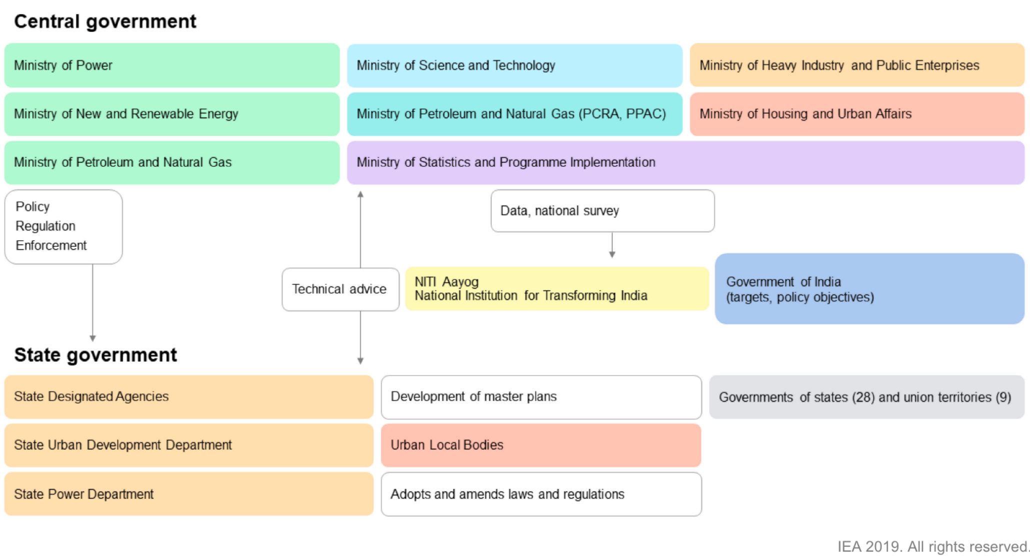

Figure 21: Key institutions involved in energy efficiency policy making & implementation [43]

2.1.12 Cement Initiatives

Low carbon technology roadmap (LTCR): This roadmap for the cement industry is promoted by IEA, CSI, and WBCSD. First published in 2009, the roadmaps were revised again in 2013 and the most recent roadmap in 2018. This LTCR roadmap envisions that CO_2 emissions are consistent with limiting global temperature increase by 2 ºC by 2100 with at least a 50% chance. This pathway uses a bottom-up least-cost technology analysis for possible feasible transition and aims to reduce the direct CO_2 emissions by 24% by 2050. Currently, this roadmap does not consider the CO_2 emissions across the whole construction value chain. [3, p. 3]

Net-zero by 2050 roadmap (NZE): It is a global roadmap by IEA and WBCSD to limit the rise in temperature by 1.5ºC. The roadmap guides what needs to happen, by when and how, spanning all, including cement.

SDG Roadmap for India: The World Business Council for Sustainable Development (WBCSD) for Cement Industry identified that cement sector emissions reduction is critical for progress in Sustainability Development Goals (SDG) goals. These SDGs are representative of the universal and unanimous commitment of world leaders towards achieving economic, environmental and social well-being. Innovations in cement technology, plants, and value chains (Figure 22) are necessary to achieving goals on water, energy, decent work, sustainable consumption and production, and terrestrial ecosystems (SDGs 6, 7, 8, 12, 13, and 15). [32, p. 5] The National Institute for Transforming India (NITI Aayog) highlighted that the private businesses across India would need to make changes to manage risks develop technologies and products to achieve SDG goals. United Nations Industrial Development Organization (UNIDO) further emphasized that cement sustainability goals across the entire value chain (Figure 22) are required in addition to energy efficiency achievements already in place for cement plants (Figure 23). In India's first-ever country-wide SDG roadmap initiative in 2019, nine cement companies have teamed up with WBCSD to identify impact opportunities, goals, and action items to reduce emissions by increasing alternative fuels and raw materials, creating a circular economy. [32, p. 15] The Roadmap highlighted eight impact opportunities and related actions that contribute to the high-priority SDGs for the sector: 1. Energy and climate; 2. People and communities; 3. Circular economy; and 4. Natural resources management. They highlighted human rights, a low-carbon economy, innovation in processes, products, services, and technology. [32, p. 9] The ones engaging in decarbonization efforts are low-carbon transportation and logistics, resilient and sustainable built environment, energy efficiency and clean energy, using waste as a resource, and natural resource management.

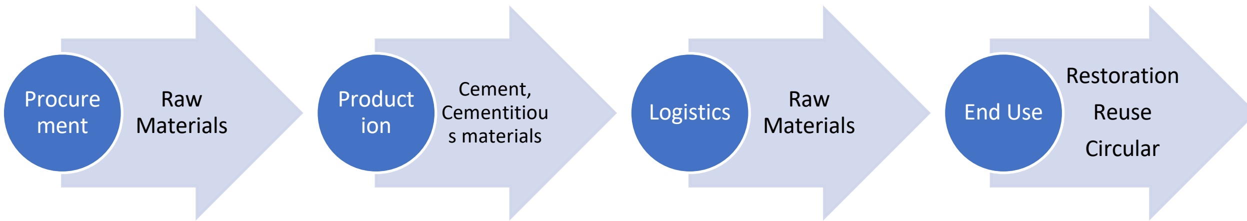

Figure 22: Value chain flow in cement manufacture

Figure 23: Goals adapted from Indian cement sector SDG roadmap report 2019 [32, p. 15]

2.1.13 Regulations and Policy Support Measures to Address Climate Change

The United Nation's SDG Goal #13 called for urgent action to combat climate change. The Paris Agreement (December 2015), as negotiated by the Conference of Parties (CoP) at UN Framework Convention on Climate Change (UNFCC), attempted to limit the rise in global temperatures to less than 2°C above pre-industrial levels by 2100. The most recent 26th Conference of Parties (COP 26) in Nov 2021 attempts to strengthen the previous 2015 COP global ambitions and action on climate building. [3, p. 9] India's per-capita emissions in 2020 are 1.77 tonnes of CO_2e, which is much lower than those of developed nations (US 14.24, China 7.41, World 4.47)[30] [31] as documented by the Global Carbon Project (GCP). India has made strides in energy efficiency regulations and policy measures that lowered its emission intensity (Figure 24).

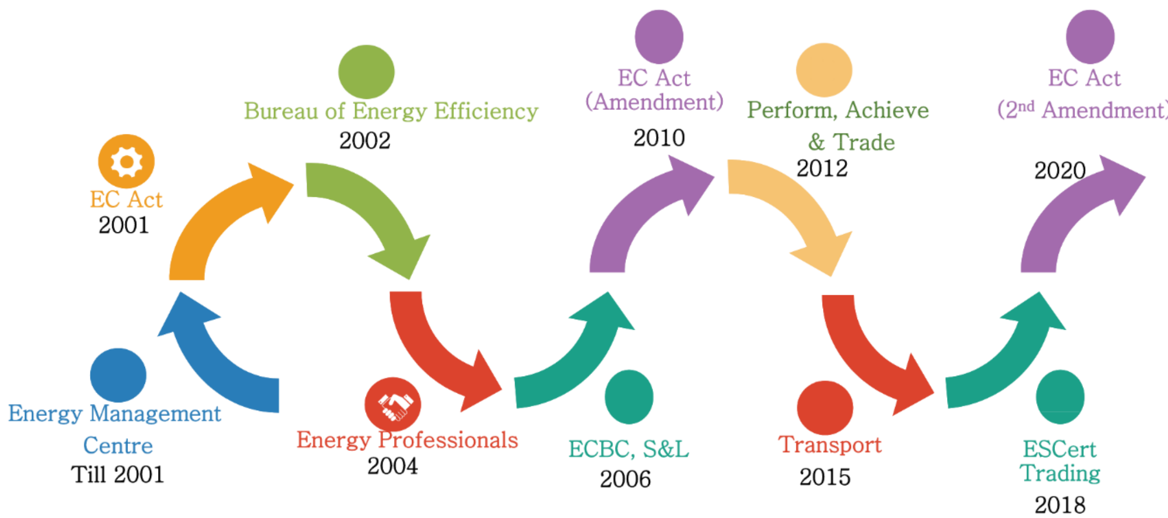

Figure 24: Chronograph of energy efficiency policies and programs in India [44]

With per-capita emissions in India projected to reach those of developed nations due to rising living standards in India, a robust emissions reductions strategy is still needed for decarbonizing the Indian Cement Industry and mitigating climate change. Moreover, there is a severe concern for economic damage once the global temperatures rise as quantified in Figure 25 as a percent of world GDP.

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[30] globalcarbonatlas.org
[31] https://www-statista-com.libproxy.mit.edu/statistics/270508/co2-emissions-per-capita-by-country/

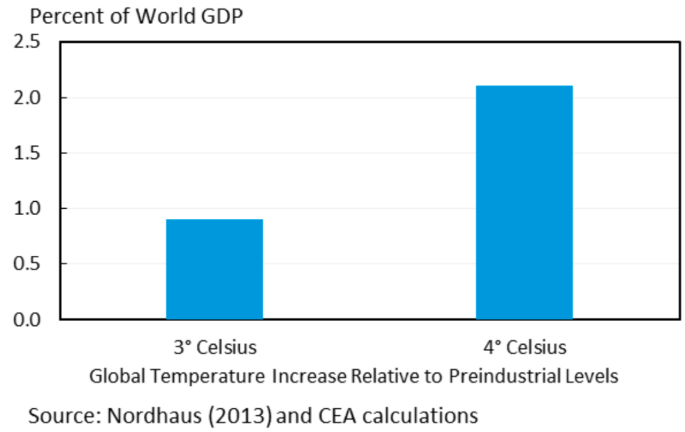

Figure 25: Economic damage from temperature increase beyond 2ºC [45, p. 5]

Below are a few policies support measures and regulations in place that reduce emissions in the Indian cement industry.

Funding Mechanisms: The cost of financing expansion or new development projects in India is higher than other Asian industrial nations such as China, Japan, or Korea. Being a capital-intensive sector, transitioning to green low-carbon production is easier through mobilizing funding mechanisms [12, p. 81]. The cement sector is looking to invest between $29 billion and $50 billion to achieve 2050 CO_2 emissions targets, move towards a circular economy (a concept where waste from one industry is used as raw material in another industry), and zero -water use.

Targeted Lending: This is an instrument designed to help specific sectors like agriculture, micro-enterprises, and renewable energy that have traditionally low access and undersupply of funding and promote access to funding based on their special development needs. Although the cement sector does not currently fall under the umbrella of this policy instrument, the industry could potentially lobby for it to be considered under a special categorization needs of green initiatives that promote green investments [12, p. 82].

Green Bonds: These bonds lessen the high capital cost needed for green investment initiatives by providing access to long-term finance for green investments. Their goal is to facilitate finance for climate change mitigation and adaptation. Starting with 2015, when the first green bond was issued, over a dozen green bonds were issued through September 2019. They have primarily benefited from renewable/green energy projects and only a few for green infrastructure projects like housing and transport, attributing to a lack of sector diversification and under-developed governmental regulation. Experts say these bonds can be utilized in the cement industry to promote a path to decarbonization.[32]

Tax incentives: There are no tax incentives for deploying green technologies in the Indian cement sector. If made available, they can be leveraged as a fiscal policy tool to compensate investors or consumers for producing or using green technologies towards decarbonization. [12, p. 83]

National Development Banks (NDBs): The Industrial Development Bank of India (IDBI) is a government-backed national development bank financial institution. It is the apex of development banking for industries in India. It has under its subsidiaries such as Industrial Finance Corporation of India (IFCI), Union Trust of India (UTI), Small Industries Development Bank of India (SIDBI). NDBs are seen as essential policy coordinators. They have not been found to support hard-to-abate sectors in their path to decarbonization.

PAT Scheme: First announced in 2008 by Govt. of India under its NMEEE mission in the National Action Plan on Climate Change (NAPCC), the PAT scheme evolved into a multi-cycle scheme launching in 2012 as an innovative market-based trading scheme offering Energy Savings Certificates (ESCerts) to Designated Consumers (DCs). The sector had a target of 0.815 Mtoe and achieved 1.48 Mtoe savings. This scheme achieved tremendous success for the cement industry as it surpassed the energy-saving targets by 80%. This scheme has contributed to positioning the Indian cement industry among the best globally in energy efficiency. PAT Cycle VI was notified in April 2020 (see Table 27). While appropriate pricing of Energy Saving Certificates (ESCerts) is crucial to ensuring the continued effectiveness of the PAT scheme, the industry needs new schemes for other areas of decarbonization as energy efficiency has marginal returns.

Table 27: PAT details till Cycle VI [44]

Sector/ No. of DCs	Till PAT Cycle II	PAT Cycle III	PAT Cycle IV	PAT Cycle V	PAT Cycle VI	Total DCs
Cement	111	14	1	12	37	175
Iron & Steel	71	29	35	23	5	163
Thermal Power Plant	154	37	17	17	-	225
Buildings	-	-	37	31	64	132

[32] TERI research

Waste Management Rules: This was introduced in 2016. It requires industrial units using fuel within 100 km of Refused Derived Fuel (RDF) plant to replace 5% of its fuel usage with RDF. It was adopted for co-processing to utilize the high calorific value present in the waste. Additionally, co-processing was the preferable method of hazardous waste disposal. Having better knowledge of the annual inventory of waste generated, recycled, utilized as co-processing, and disposed of is essential in understanding and availing the full potential of alternative fuel inventory. This data is published by the State Pollution Control Boards (SPCBs) for states and Pollution Control Committee (PCC) for union territories in India.

Fly Ash Utilization Policy (2009); Amended draft (2019): The MoEFCC in 2009 notified all thermal power plants (TPPs) to achieve 100% utilization of Fly Ash by 2014. It was further amended in 2019 to disallow the red clay brick kiln from TPPs and to encourage Fly ash brick manufacturing units. TPPs are mandated to provide Flyash brick manufacturing with Fly Ash at 1 INR/ tonne of Fly ash and also bear the transportation cost. In a captive power plant, where power plant is co-located with cement plant and generates power solely for a cement plant's use, this rule hurts the cement plants as it leaves less fly ash for the captive power plants to share Fly Ash with their cement manufacturing plants right next to them and creates logistical inefficiencies as well. [46, p. 14]

Timber Usage Notification: Although banned since 1993, timber use was recently lifted in July 2020. Using degraded land towards timber plantations will minimize the emissions from manufacturing energy-intensive materials like cement.

Construction & Demolition Waste Management: The waste generator collects and disposes of Construction and Demolition (C&D) waste at a designated location. Urban Local Bodies (ULBs) work together with their state agencies to monitor all activities related to the proper management of C&D waste and recommend Indian road congress use recycled C&D waste in road construction.

Bureau of Indian Standards (BIS) IS 16415:2015 policy: It permits for production of composite cement by adding fly ash and slag together in Portland cement. This standard allowed cement plants to produce composite cement by inter-grinding Portland cement clinker, granulated slag, and fly ash or thoroughly and uniformly blending OPC, finely ground granulated slag and fine fly ash with required addition of gypsum. Adding this policy to standards has reduced the public perception of viewing composite cements as poor quality adulterated cements. [3]

Solid Waste Management Policy: The solid wastes management rule implemented in 2016 in India engages in promotion of waste-to-energy in cement plants using co-processing systems. By mandating all industrial units located within 100 km of solid waste-based RDF plant to replace at least 5% of their fuel requirement by Refuse Derived Fuel (RDF), CO_2 emissions from the fuel consumption are reduced. This also helps divert all non-recyclable wastes having calorific value of 1500 kcal/kg or greater from landfill to generating energy at waste-to-energy plants or be given away as feedstock for preparation of refuse-derived fuel. Co-processing of wastes in cement plants is allowed with high calorific value fuels. In the Indian cement industry, solid waste comprises of 73% of alternative fuels used. [3, p. 18]

2.1.14 Barriers and Enablers to Achieving Climate Change Targets

Barriers: The main barriers for achieving climate change targets are low public willingness to pay a premium for green products, lack of awareness of benefits, and technical aspects of products on the demand side. Some of the past barriers to achieving systems transformation include attitude of short-termism, absence of critical mass of public and institutional opinion, lack of a push for an effective carbon price, not adjusting for shifts in timeframes or measures of success, transition costs, and effects on various stakeholders. [47, p. 92] Fuzzy analytical hierarchy process (FAHP) analysis studies have also identified top enabling factors of climate change targets as primarily government policy and regulatory barriers, followed by organizational and managerial barriers and economic and timeframe barriers, among others. There currently are green finance products and portfolios but diversification of sectors to include special decarbonization needs of cement sector green initiatives is still a barrier. The cement industry has been consolidating globally. Despite this, large international firms account for only 30% of the worldwide market. Smaller players are disadvantaged, creating challenges for transitioning to low carbon technologies without policy intervention and financial aid. Because the cement industry will be one of the most important contributing factors for the success of government schemes, it is on a tough road to decarbonization without the presence of substitutes or other mechanisms.

Enablers: Enablers of climate change targets include fostering awareness of potential litigation risks; health issues resulting from emissions; increased pressure from local public, societal and stakeholders for emission reductions; cuts in subsidies for conventional high-carbon fuels and hikes in taxes on fossil fuels; and market demand for low-carbon products and services. [48]

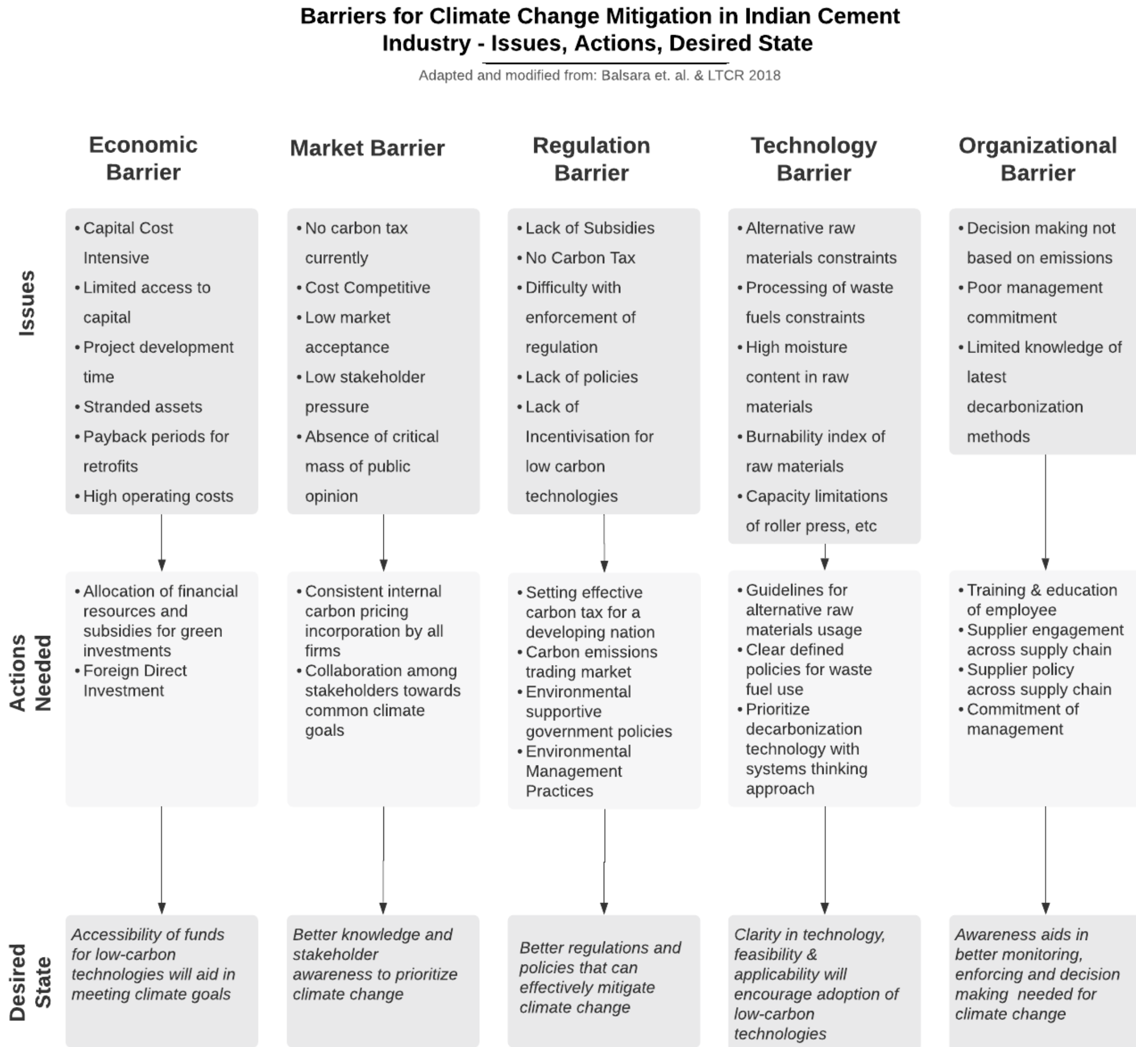

Figure 26: Actions to overcome barriers & reach desired state in Indian cement industry [48]

2.1.15 Covid Impacts on Economy and Industry

The government directed its spending on the most critical items halting its infrastructure projects during the pandemic. Most of the recovery budget was aimed at economic recovery rather than decarbonization. India's cement production volume prediction was estimated to reach 401 million tonnes in 2021[33]. The actual production volume was lower than estimated due to the COVID pandemic, which halted many activities. The first wave of COVID alone caused a -1% to -15% decrease in the cement sector in 2020, per the CRISIL report. The onset of COVID second wave observed a decline of 13% in overall industrial production from March to April 2021[34] attributed to demand growth decrease. Due to this, the overall CO_2 emissions lowered during the pandemic. These overall emissions are expected to rise due to the ramp-up of production activities once the pandemic subsides. The demand for affordable housing has gone up due to remote work and lifestyle changes resulting from COVID. Because housing and real estate sectors already account for nearly 65% of total cement consumption, this could mean that increase in demand in this sector imply greater CO_2 emissions in the future.

Other COVID impacts have included lower capacity utilization, non-availability of alternative fuels and raw materials, and shortage of personnel for day-to-day operations slowing down cement production activities. Lower utilization will result in poor returns on capital investments, leading to reduced adoption of low-carbon technologies. Thus, these factors have lowered the efficiency of cement manufacturing, thereby increasing the emission intensity of cement produced. In the future, strong growth in rural housing and low-cost affordable housing will amplify demand once the COVID situation eases and return to greater-than-before overall CO_2 emissions.

[33] India Brand Equity Foundation; Crisil; Department for Promotion of Industry and Internal Trade (India); ICRA; CARE Ratings; TechSci Research; Statista

[34] EY report – Economic Pulse, source: HIS Markit, DPIIT

3 Decarbonization Methods in Indian Cement Industry

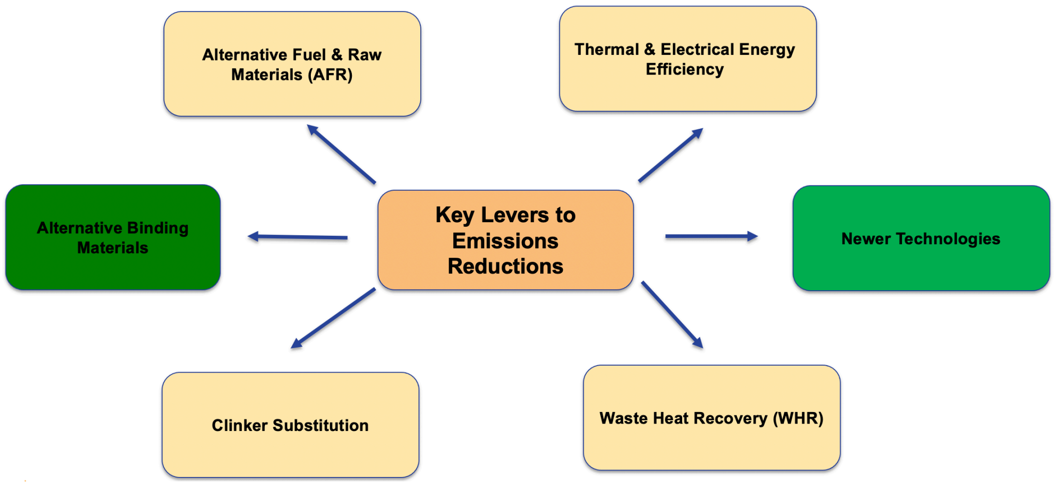

Figure 27: Decarbonization levers in Indian cement industry

Decarbonization methods for the cement industry are available on the *supply side*, *demand side,* and *operational side* of cement manufacture.

Supply Side: Those on the supply side include electrical & thermal efficiency, grid intensity, clinker factor, alternative fuels use (thermal substitution rate), waste heat recovery systems, captive power generation, renewable power generation, and CCUS.

Demand Side: The demand side decarbonization methods include material reuse, construction waste management, optimizing the use of concrete, optimizing recarbonization, net-zero building materials, maximizing the useful life of the building, reducing operational energy, and minimizing the albedo effect. Popular methods to reduce cement demand include blended (composite) cement, alternative (substitute) raw materials, industrial wastes that are raw materials, supplementary cementitious materials (SCM), green cement, cement substitutes.

Operational Side: The operational side include emissions from transportation and logistics, and capacity utilization. These decarbonization methods have varying levels of emissions reductions opportunities, cost constraints, technology constraints, and technology readiness levels.

Over the years, the concept of what it means to decarbonize evolved. The Indian cement industry has moved from the end-of-pipeline to cradle-to-grave approach to carbon footprint reduction, recycling and reuse, material efficiency, and a circular economy concept (Figure 28).

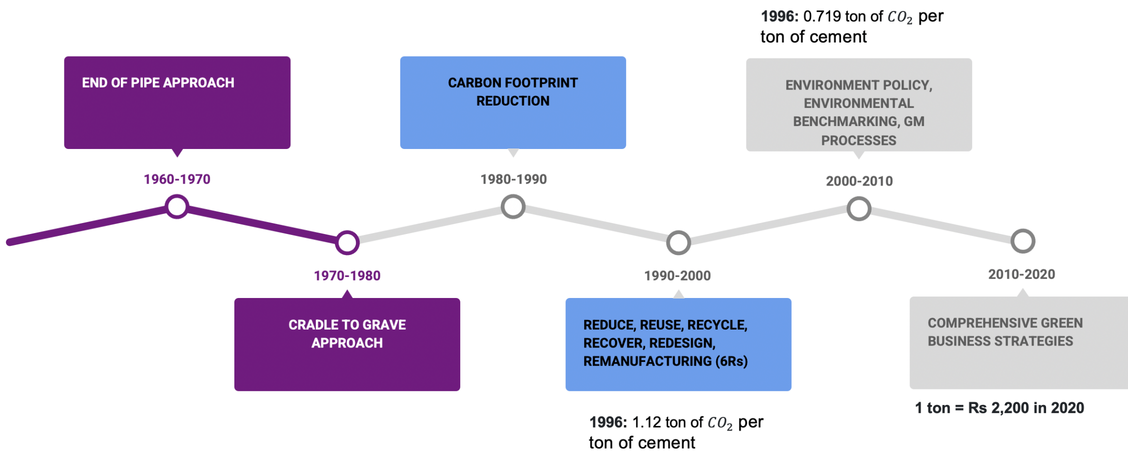

Figure 28: Green manufacturing adopted over the years for Indian cement sector [49, p. 428][35]

3.1 Circular Economy

This is a concept where natural resources are preserved by substituting raw materials and fossil fuels used in industrial processes like cement with other industrial byproducts and alternative fuels and wastes from different industries. It also encompasses preserving resources by recovering cement from construction and demolition waste to reduce the cement demand. [46, p. 12]. The CMA report highlighted the need for infusing circular economy concept focusing on increasing blended cements, composite cements, and optimizing use of alternative materials and waste products. Replacing virgin raw materials with alternative raw materials and substitutes such as construction and demolition (C&D) waste obtained through recycling efforts, foundry sand, crushed rock fines, refractory bricks and cement kiln dust using circular economy are beneficial. Innovation and R&D is needed in alternative materials. The report also

[35] Adapted and modified from Rehman et al.

highlighted essential skill building for masons as such proper practices and awareness will optimize the use of such materials much needed in a circular economy. [50]

3.2 Status of Decarbonization in Indian Cement Industry

The following decarbonization improvements were made in the cement industry:

Process Equipment: Almost 99% of the installed capacity in India uses dry process manufacturing, of which 50% has been built in the last ten years. The dry process has eliminated CO_2 emissions by removing fuel needs that would otherwise be necessary for heating to remove moisture from a wet mix process.

Auxiliary Equipment: Vertical conveyors, tri-lobe blowers, three-phase transformers for increased collection efficiency in electrostatic precipitators, lower-head pumps to cool water circuits with booster pumps for a specific application, aluminum piping to reduce the pressure drop, water-cooled condenser coils for packaged air conditioning, and the installation of screw chillers instead of compression chiller have been incorporated that are more energy-saving and thus lowering emissions.

Waste heat recovery: The excess heat from clinker that would have otherwise been dumped into the atmosphere is recovered and used to generate power, reducing global warming and emissions. The industry installed a 307 MW capacity of WHR. [32, p. 19] Due to this, the industry achieved 25% less electrical energy consumption. According to CMA, the Indian cement industry has additional potential for 800 – 1100 MW. The installed capacity is 307 MW. [32, p. 19]

Alternative fuel: The industry utilized coprocessing and preprocessing platforms to increase alternative fuel use. It utilized 1.2 million tonnes of alternative fuels in 2017. Using alternative fuels instead of conventional high carbon fuels has lowered carbon emissions. The Indian cement industry is looking to increase its share of alternative fuel use.

Clinker substitution: Indian cement industry is increasing its blended and composite cement production by using material resource efficiency and wastes such as fly ash and slag from sectors like power plants and iron & steel and partially substitute the high-emission intensive clinker. It has been the largest consumer of fly ash produced from thermal plants. It consumes nearly 100% of slag produced in India's steel plants.

Other: Intelligent motor control centers and energy management systems have been implemented.

While the above improvements have lowered emissions intensity, the Indian cement industry is not on track to achieving emissions targets and climate goals for a 2°C or the utopian 1.5°C world. This can pose several challenges. India's IEA 2018 roadmap report provided renewed guidance to achieve the low-carbon transition and meet its goal of achieving the industry's direct CO_2 emissions intensity to 0.35 tCO_2/ t of cement in 2050. Based on roadmap projections, it estimates that savings between 212 million tonnes of CO_2 ($MtCO_2$) and 367 $MtCO_2$ are achievable in 2050 from a business-as-usual scenario. [3, p. 4]

Below is a literature review of potential decarbonization roadmaps and technologies available for the Indian Cement Industry.

3.3 Roadmaps to Decarbonize Indian Cement Industry

India has pledged to achieve an electricity generation capacity of 40% by 2030 in its commitments to UNFCC from non-fossil fuel energy resources and to create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2e by 2030 to reduce the emissions intensity of its GDP by 33% - 35% by 2030 from 2005 levels. Other than these economy-wide targets, the Indian cement industry does not have any specific targets committed to decarbonizing its Industry sector, such as cement. The abatement of pollution measures has listed CCUS and Fly Ash Utilization Policy under Perform Achieve and Trade (PAT) and renewable energy certificates (REC) scheme. Already, the cement industry in India contributes to 30% of total GHG emissions from the industrial sector in the nation. Given that the demand for cement, capacity expansion, and consumption means this industry is headed towards high emissions, there is an urgent need for a comprehensive action plan. [12, p. 21] Because India does not have specific goals, the International Energy Agency (IEA) has partnered with leading firms. It has developed global and regional low-carbon technology roadmaps for the cement sector.

Globally, cement sector emissions reached 2.2 $GtCO_2$ in 2014. Global cement production is set to grow by 12-23% by 2050 from 2014 levels, and most of this is attributed to developing countries in Asia, primarily India. Emissions from the industry are expected to increase by 4% in the reference technology scenario (RTS) despite an increase of 12% in global cement production. To achieve a 2DS scenario, the CO_2 emissions need to be lowered by 24% in 2050 compared to 2014 levels and require significant measures as outlined by the global and regional roadmaps. [51, p. 1] In its global roadmap, IEA has also in its global roadmap recommended a whole life-cycle approach to work with the entire construction value chain. This will optimize emissions by offering opportunities beyond cement manufacturing. These include strategies on the demand and operations side, such as optimizing the use of concrete in construction by reducing waste, encouraging reuse and recycling, maximizing design life, and using concrete's properties to minimize operational energy of the built environment. The roadmap for Net-zero Concrete and Cement by GCCA has considered a life-cycle approach (Table 28).

Table 28: GCCA - net-zero global roadmap for cement sector [52, p. 10]

	Type of Lever	**Description**	**% of savings**	**Emissions Savings ($MTCO_2$)**
1	CCUS	Capture at cement plants	36%	1370
2	Efficiency in design and construction	Design optimization, construction site efficiencies, re-use, and extension of the useful life of buildings	22%	840
3	Concrete efficiency	Optimized mix design; Optimization of constituents in concrete production, industrialize manufacturing, quality control	11%	430
4	Clinker production efficiency	Alternative fuels, thermal efficiency, decarbonated raw materials, and hydrogen fuel	11%	410
5	Cement and Clinker Substitutes	Portland clinker cement substitutes, i.e., clinker binder ratio; Alternatives to Portland clinker cements	9%	350
6	Recarbonization	Natural uptake of CO_2 in concrete as a carbon sink	6%	240
7	Decarbonization of Electricity	Lower electricity emission intensity at cement plants and concrete production	5%	190

The IEA has provided strategic roadmaps to decarbonize the Indian Cement Industry since 2009. It considered two demand scenarios for cement production, a high-demand, and a low-demand, and provided a set of milestone targets (Table 29). [53] The roadmap has since updated its recommendations in its 2013 and 2018 reports (Table 30). Despite these latest recommendations, today, experts believe there exists a gap from the roadmap strategy to achieve required decarbonization targets by 2050 for climate goals and urge for a strategic action to decarbonize the Indian cement industry.

Table 29: IEA 2009 roadmap regional milestones for Indian cement industry [53]

Country	Scenario	Year	Energy Use (Mtoe)	Share of Alternative fuel Use	Clinker-to-cement Ratio	CO_2 Captured (MT)
India	Blue Low Demand	2030	29.9	23%	0.73	23.7
India	Blue Low Demand	2050	47.4	33%	0.71	99.8
India	Blue High Demand	2030	33.6	27%	0.72	28.8
India	Blue High Demand	2050	60.1	35%	0.72	173.1

In a business-as-usual scenario with no policy or technology developments, IEA predicts that CO_2 emissions (86 $MtCO_2$) in 2010 from the Indian cement industry will increase by 255% to 510%. [9, p. 3] In its regional IEA 2013 roadmap for the Indian cement industry, it outlined technologies, policy frameworks, and investments that have the potential to reduce CO_2 emissions by about half by 2050. It aims to reduce emissions intensity from 0.62 tCO_2/t of cement (2010 level) to 0.35 tCO_2/t of cement in 2050 (Figure 29). [53, p. 5]

Table 30: IEA roadmap for India (2DS) in 2013 [19, p. 16]

Country	Scenario	Year	Production (MT)	Per-Capita Consumption (kg/capita)	Clinker-to-cement Ratio	Share of Alternative fuel Use	Electrical Intensity of cement production (kWh/ t cement)	Thermal Intensity of clinker production (kcal/kg clinker)
India	Demand	2010	217	188	0.74	0.6	80	725
India	2DS - Low Demand	2020	416	309	0.7	5	76	709
India	2DS - Low Demand	2030	598	400	0.64	19	73	694
India	2DS - Low Demand	2050	780	467	0.58	25	71	680
India	2DS - High Demand	2020	492	364	0.7	5	75	703

India	2DS - High Demand	2030	848	565	0.64	19	72	690
India	2DS - High Demand	2050	1361	812	0.58	25	70	678

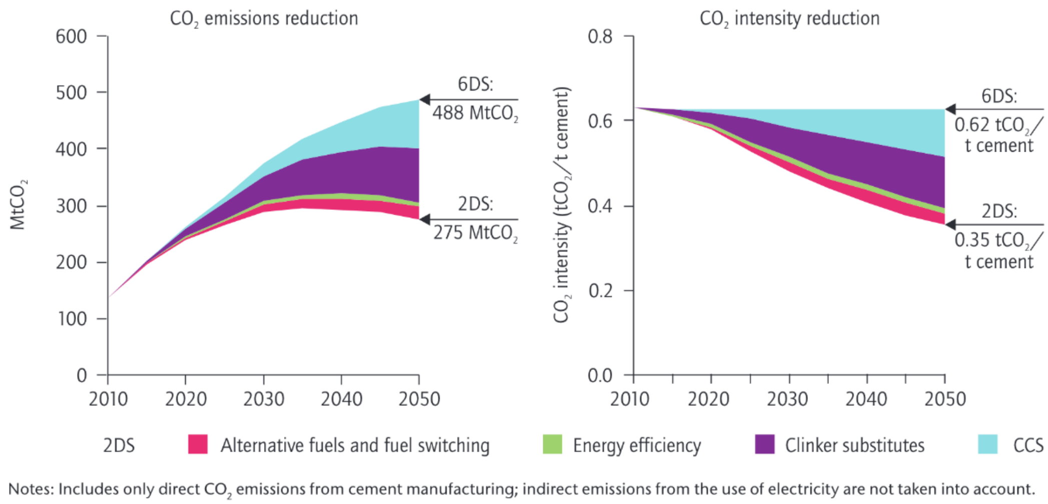

Figure 29: Savings potential in LCTR roadmap from 6DS to 2DS is 212 Mt CO_2 [19, p. 16]

To achieve the decarbonization goals for 2DS (2ºC) temperature rise, the IEA India roadmap requires deploying Carbon Capture as early as 2020. It aims to achieve an annual capture of 86 MT of CO_2 emissions in low demand scenario to 151 MT in the high-demand scenario by 2050 (Figure 30). Today, it is very cost-intensive to pursue carbon capture technologies, especially with the declining profit margins of the cement industry players.

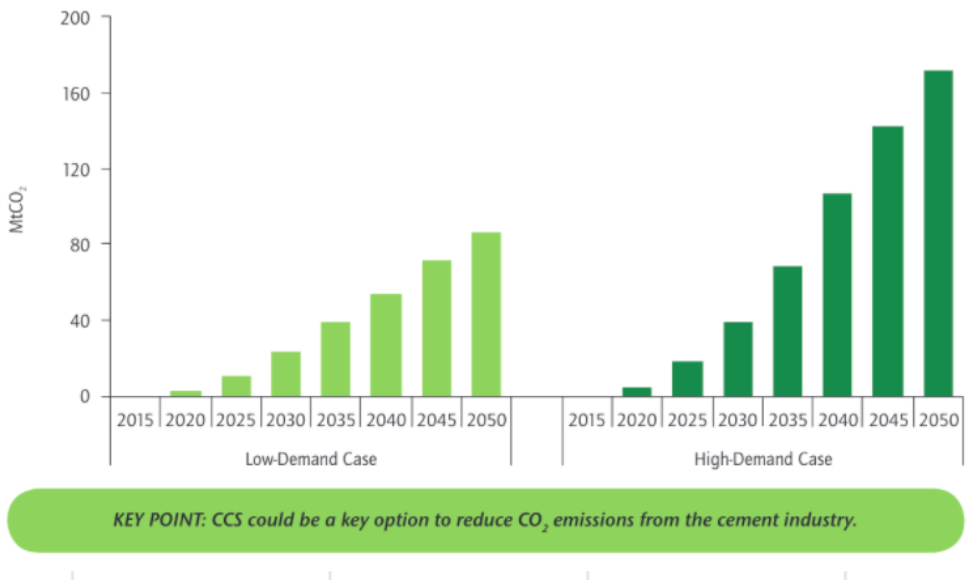

Figure 30: CCUS growth potential in high vs. low-demand for Indian cement in 2ºC [19, p. 15]

The key decarbonization levers identified by IEA 2012 and 2013 for the Indian cement industry include reductions in clinker-to-cement ratio through increased use of blending and raw materials other than limestone, higher usage of alternative fuels such as industrial wastes, sorted municipal wastes, and biomass to substitute for carbon-intensive fossil fuels, industry-wide adoption of waste heat recovery (WHR) systems and captive power plants to partially offset energy requirements and improve energy security in cement manufacturing. It also requires bringing in new technology development such as CCS, energy crop plantation, and carbon capture through algae growth, from research and development (R&D) to deployment. [9, p. 17]. Some of the newer technologies are in the early stages of the technology readiness level. There are constraints like the cost of setting up carbon capture and energy consumption of these low-carbon technologies. (Refer to Section 3.18 and Section 3.19).

In the cement industry, CO_2 emissions occur in various processes. Each of those processes and activities has varying decarbonization potentials and a set of specific actions necessary to achieve their emission reduction potentials (Figure 31).

Figure 31: Potential for decarbonization strategies – adapted from Balsara et al. [54]

The IEA 2018 global report for the cement sector has identified the decarbonization potential of different techniques lies in emerging technologies (48%), clinker-factor reduction (37%), alternative fuels (12%), and energy efficiency (3%). [46, p. 5] Many emerging technologies like Carbon Capture are expensive, especially in India, where the cost of financing is high, and India needs to explore the full potential of decarbonization alternatives.

3.4 Thermal and Electrical Energy Efficiency

Since the late 20th century, cement industry in India has increased. Most cement plants built in the past decade have adopted the latest pollution control and energy-efficient technologies thanks to the PAT scheme, resulting in reduced energy consumption and cost savings. (Figure 33). Other than capturing the current gap of 3% present between best plants in the sector vs. other plants, decarbonization efforts in energy efficiency have peaked for the Indian cement sector. Any new improvements will only yield diminishing returns. [3] India's best companies are already better than the global average for energy efficiency due to various measures implemented in the past few years. (Figure 32)

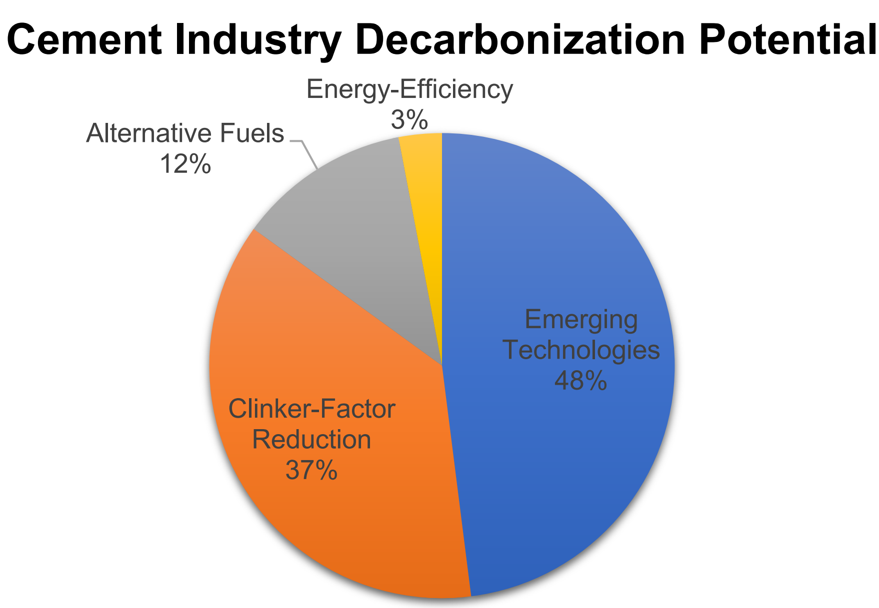

Figure 32: Decarbonization potential in cement Industry [46, p. 5]

Figure 33: Measures employed in the Indian cement Industry for thermal & energy efficiency

Table 31: Specific energy consumption in cement: India's best & average vs. Global [46, p. 4]

Specific Energy Consumption	Unit	Global Average	India Best	India Average
SEC - Thermal	GJ/tonne of clinker	3.5	2.83	3.1
SEC - Electrical	kWh/tonne of cement	91	64	80

3.5 Decarbonization of electricity

Currently the Indian cement industry has a grid emissions factor is 0.725 tonne of CO_2 per kWh of electricity. Due to the overall rise in cement production, it is expected that electricity demand will rise. In the coming years, the adoption of CCS technology will also increase electricity consumption. Due to this, the industry needs to decarbonize its power sector in the coming decades and reduce its grid emissions intensity to zero. Most plants are already equipped with the latest electrical systems such as intelligent Motor Control Centers (MCC) and Energy Management Systems (EMS) in addition to energy-efficient kilns and latest-gen coolers with high recuperation energy. Therefore, the cement sector needs to support further reductions by the increasing share of renewable energy in overall power production. Indian cement plants have ventured into solar power generation due to having access to nearby vast, unused unshaded arid land, making it ideal for the deployment of solar power generation. There are presently constraints for renewable energy such as wind and solar as they are both intermittent sources of power and require another power generation source for a reliable supply. [52, p. 27]

3.6 Capacity Utilization

The Indian cement industry production capacity reached 545 MT in 2018-2019. Several companies have increased production capacity considerably, relying on government support and growth expectations. However, delays in awarding infrastructure projects, decision-making surrounding the commencement of projects, land acquisition for construction projects, highway construction, and innovative city projects have resulted in lower capacity utilization. [36] Cement capacity utilization reduced by 4% from 2010 to 2017. [3, p. 9]. A lower utilization will result in operational inefficiencies and higher emissions intensities.

3.7 Clinker Factor

Clinker is the main component of most cement types. The 2018 IEA report identified lowering the clinker-to-cement ratio as having the 2nd-highest potential for emissions reductions (Figure 32). This is because it reduces the direct thermal emissions and lowers the process emissions from the calcination of limestone. Often, industrial byproducts require costly disposal methods. By substituting carbon-intensive clinker with suitable low carbon materials such as slag and fly

[36] https://www.prnewswire.com/news-releases/india-cement-market-study-2019-2024-size--share-production--consumption-trade-analysis-competitive-landscape-301008278.html

ash (byproducts of the steel industry and coal-fired power plant), the process and thermal energy emissions can be lowered.

For cements not commonly produced or regularly available, it is essential for end-users to know the properties, uses, and application and have design standards and other processes to help optimize cement usage for suitable applications. For instance, mixing ground clinker with 4-5% gypsum will allow the cement to react with water and harden. Similar hydraulic properties are observed when mixed with ground blast furnace slag (GBFS), a waste byproduct from the Iron and Steel industry, fly ash, a residue from coal-fired power stations, or natural volcanic materials. Additionally, when blast furnace slag cement with more than 50% of slag is used to replace clinker, the resultant blend can have good sulphate resistance but lower heat of hydration than PPC.[37]

Ordinary Portland Cement (OPC): Comprises of 95% clinker and 5% gypsum. It constitutes 70% of total cement production in India.

Portland Pozzolana Cement (PPC): Comprises of 60 - 80% clinker, 15-20% Pozzolana, and 5-10% gypsum. It constitutes 18% of total cement production in India.

Portland Slag Cement (PSC): Comprises of slag mixtures within the range of 25% to 60%. It constitutes 10% of cement produced in India.

The industry has been making progress in identifying new alternate materials with lower clinker consumption. [46, p. 5] New types of cement, such as LC^3, are reducing the amount of clinker needed for cement (See Section 3.8.2). In addition to lowering clinker use, several composite cements, geopolymer cement, belite rich cement, and other novel cements are emerging that have little to no clinker usage (See Section 3.8 and 3.10). [33] The use of OPC should also be restricted to special applications. [3, p. 25]. The WBCSD roadmap recommends that the rate of taxation be proportional to the CO_2 footprint of the cement to encourage blended cements that reduce clinker factor and aid in the sustainable transition. [3, p. 25]

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[37] Cement Manufacturers Association (CMA)
IL and FS, E, 2009. Technical EIA guidance manual for cement industry.
India Brand Equity Foundation
Indian Cement Industry

Since cement plants are located in various regions, geographic and widespread availability of alternate raw materials is desirable. Market availability and requirements are also an added constraint for consistent reductions in clinker usage. The GCCA roadmap noted that cement alternatives will comprise 1% and 5% of cement mix by 2030 and 2050, and also, the lowest technically achievable factor is 0.5. This does not appear to be an accurate estimate for India as it is looking to benefit from a growing circular economy. Many companies have already begun researching composite and other cement types.

Supply risks are present in sourcing fly ash and slag as these are byproducts of power plants and the steel industry, which are at risk for transition to achieve net-zero energy. Also, the amount of waste (fly ash and slag) output million tonnes per year varies depending on growth rate and industrial production. Although fly ash is currently favored by policy for maximizing use, fly ash will not be available if the coal plants are phased out in the future. In the coming decades, ground limestone and calcined clays are expected to compensate for the reduced supply of fly ash and GGBS. The share of blended cement remained constant until 2015 and rose by 5% in 2016 and 2017. WBSCD, in its roadmap, recommends that the clinker-to-cement ratio be lowered to 0.64 by 2030 for a sustainable transition. They suggest increased use of blended cements, clinker substitutes, including industrial byproducts such as the flag and fly ash in the short term. For the long-term, they offer calcined clay rather than industry byproducts, the reason being, decarbonization of power generation and iron and steel making reduce the availability of industrial byproducts like fly ash and slag.

3.8 Blended Cements

Blended cements are used to maximize the use of waste materials and for better control of cement properties. They are formed by blending Portland Clinker with Fly ash, Slag, or other cementitious materials. Clinker is ground finely with fly ash and slag along with the required amount of gypsum. It reduces limestone consumption, thermal & electrical energy consumption, and emissions intensity. These cements have lower CO_2 emissions due to reduced clinker use. Compared to OPC, Portland cements have a 56% reductions potential in emissions. Their emissions intensity is 0.36 tonne CO_2/ tonne of cement. [3]

It has been observed that composite cements have a considerably lower production cost. In a 1 MTPA, the cement plant required 57% less raw material and 52% less thermal energy than OPC production.

Applications for composite cements include pre-cast concrete pipes and blocks, civil works like dams and retaining walls, and in-building construction. This cement in India is now standardized by the Bureau of Indian Standards (BIS). The composite cement needs the availability of both fly ash and GBBS near the cement production plant. Logistical constraints plus the presence of both the materials and possible chemical composition inconsistencies make it more complex to manufacture, resulting in only a few manufacturers currently using it to lower carbon emissions (Hegde, 2020). Decarbonization efforts in the power and steel-making industry will limit the availability of fly ash and slag availability in the future.

Table 32: Blended cements, materials, and uses

Blended Cement	Blending Materials	Uses
Fly Ash Additive	Portland – Fly Ash Additive	To produce concretes for special application - alkaline and sulfate corrosion-resistant concrete; CO_2 reduction.
CEM II-S	Portland – silica flume cement	Workability, strength, durability; CO_2 reduction
CEM II-S	Portland – pozzolana cement Portland – fly ash cement	Workability, strength, durability; CO_2 reduction
CEM II-S	Portland – burnt shale cement	Workability, strength, durability; CO_2 reduction
CEM II-S	Portland – limestone cement	Workability, strength, durability; CO_2 reduction
CEM II-S	Portland – fly ash + limestone	Workability, strength, durability; CO_2 reduction
CEM II-M	Portland cement clinker, Slag, and Silica Flume[38]	Workability, strength, durability; CO_2 reduction
CEM II-M	Portland cement clinker + granulated slag + limestone	Workability, strength, durability; CO_2 reduction

These blended cements have lower thermal energy consumption, CO_2 emissions, workability, strength development, and durability. In the past, blended cements were considered to be

[38] **Silica fume** is an industrial byproduct. It's an ultrafine powder recovered from the production of silicon metals and alloys in electric-arc furnaces. Source: https://www.lehighhanson.com/products/cement/blended

adulterated cements and not quite popular. However, there has been wider acceptance of blended cements in the recent few years. Factors that influence blended cement are the market's growing acceptance of blended cement, awareness of sustainability concepts, availability of fly ash from thermal power plants or nearby, and cost matrix.

3.8.1 Slag

Iron Slag and Steel Slag can both be used as cement kiln feed. Although exact data is unavailable, global iron slag in 2020 from blast furnaces is estimated to be in the range of 25% to 30% of crude (pig) iron production and steel furnace slag may be estimated to be 10% to 15% of raw steel production. In 2020, global iron slag production was estimated to be between 310 million.

Table 33: Global production of steel and slag [6]

Global Raw Steel Production in million Tonnes (2020) in Million Tonnes (MT)	Global Steel Furnace Slag Production Estimate (2020) in Million Tonnes (MT)	Global Crude (pig) iron production (2020) in Million Tonnes (MT)	Global Iron Slag Production from Blast Furnace Estimate (2020) in Million Tonnes (MT)
1878	10% - 15% of raw steel production i.e. 187.8 to 281.7 MT	1319.9	25% - 30% of crude (pig) iron production i.e. 329.9 to 395.9 MT

Table 34: India's production of steel and slag [6]

Raw Steel Production in Million Tonnes (2020)	Finished Steel Production in Million Tonnes (2020)	Steel Furnace Slag Production Estimate (2020)	Iron Ore in million tonnes (2019)	Crude (pig) iron production in million tonnes (2020)	DRI production in million tonnes (2020)	Iron Slag Production from Blast Furnace Estimate (2020)
99.5	88.6	data not available	P-232.8 E-31.2 I- 2.1 C-203.7	Production 67.8 Exports 0.4 Consumption 67.4	Production: 33.6	data not available

Table 35: Production of steel by process [6]

	Million tonnes	Oxygen %	Electric %	Open hearth	Other %	Total %
Crude Steel for India in 2020	100.3	44.5	55.5	-	-	100

In the construction sector, ferrous slags compete with natural aggregates (crushed stone and construction sand and gravel) but are far less widely available than the natural materials. As a cementitious additive in blended cements and concrete, GGBFS mainly competes with fly ash, metakaolin, and volcanic ash pozzolans. In this respect, GGBFS reduces the amount of Portland cement per ton of concrete, thus allowing more concrete to be made per ton of Portland cement. Slags (especially steel slag) can be used as a partial substitute for limestone and some other natural raw materials for clinker (cement) manufacture and compete in this use with fly ash and bottom ash. Some other metallurgical slags, such as copper slag, can compete with ferrous slags in some specialty markets, such as ferrous feed-in clinker manufacture, but are generally in much more restricted in supply than ferrous slags.

3.8.2 Limestone Calcined Clay

LC^3 cement is a ternary cement[39]. It can achieve properties similar to OPC with a much lower emissions intensity. It uses 50% less clinker as the clinker factor in LC^3 ranges from 40-50%. It is a blend of low-grade clay (Kaolinitic clay), low-grade limestone, and gypsum. It is formed at a low calcination temperature of clay. It also does not require new manufacturing equipment as standard cement manufacturing plant equipment is sufficient for calcination of clays lowering its cost of production. Other feasible techniques include flash calcination, fluidized bed technology, and static calcination.

Successful pilot tests have been conducted. Pilot productions of LC^3 blends, lab tests, and successful field studies have resulted in LC^3 getting approved by BIS. The calcined clay is available in abundance in the country; some of the states where clay reserves are available are – Rajasthan, Kerala, West Bengal, etc. [46, p. 7]. Research is underway to determine the quantities of clay available in cement clusters in India. [46, p. 6]

[39] Ternary cement mixture is one that contains Portland cement and two other cementitious materials

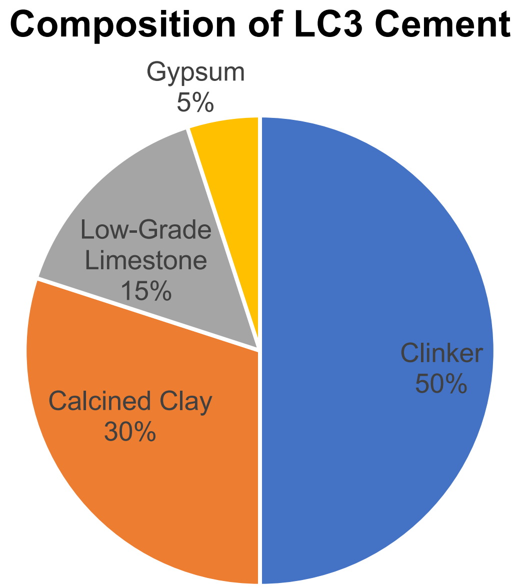

Figure 34: Composition of LC^3 Cement

Clay (kaolinitic clay) calcination temperature: 700°C – 850°C.

Kiln Type: Standard rotary kiln

Benefits:

1. Savings from 50% of clinker calcination reaction emissions avoided.

2. Calcination of Kaolinitic takes place at a lower temperature than limestone resulting in thermal energy savings due to less fuel and the ability to use low-grade fuel.

3. Calcined clays are softer than clinker and easy to grind, requiring less energy.

4. LC^3 is gaining popularity due to raw materials like calcined clay and low-grade limestone, which are readily available in India.

5. Lowered raw material risks - Reduced nation's dependency on imports for high-grade limestone for regular OPC cement. India imported 17.8 MT of high-grade limestone (lime content between 44% and 52% by mass) in 2015-2016 for OPC production. (IBM, 2017) [46, p. 7]

6. Increases lifetime of kilns lowering life-cycle emissions.

7. Abundant reserves of Clay, 2,941 MT, and Limestone, 16,366 MT in India (IBM, 2016) [46, p. 7]

8. Installation of clay calciners at clay mines allows moisture content to be removed at the site itself. It allows an addition of 15% of clay to be transported in the same load.

9. Pilot tests conducted in India and Cuba showed that the concrete produced by using LC^3 has similar physical and mechanical properties as OPC concrete (Scrivener et al., 2018).

Barriers: Uncertainty around the availability of power and equipment near mines etc., pose a few barriers, lack of economic reforms and tax incentives, and lack of a business case for essential stakeholders.

Changes needed: Shakti foundation noted that customer confidence building on benefits of LC^3, developing a business case for developers, contractors, and consumers by assessing techno-economic benefits of LC^3 vs. OPC, and economic reforms, tax incentives, and market mechanisms are key to bridging the gap for implementation of LC^3 to its mass commercialization. [46, p. 7] Recognized standards for LC^3 cement will help with fast adoption. [3, p. 25]

3.9 Composite Cements

A portion of the Portland clinker is replaced with industrial byproducts such as granulated blast furnace slag (gbfs) and pulverized fuel ash (pfa). This type of cement is referred to as composite cement. Today, the IS: 16415:2015 permits material proportion for composite cements as follows:

Table 36: Composition limits of composite cements per Bureau of Indian Standards [3, p. 24]

Composite Cement Composition	Proportion (% by weight)
Portland Cement Clinker or OPC	35-65
Fly ash	15-35
Granulated Slag	20-50

This cement is used in various applications like Precast concrete (pipe and block), Building construction, and civil engineering works, dams and retaining walls, etc. [46, p. 9] Requirement for and availability of both slag and fly ash at the same time is a constraint for widespread adoption.

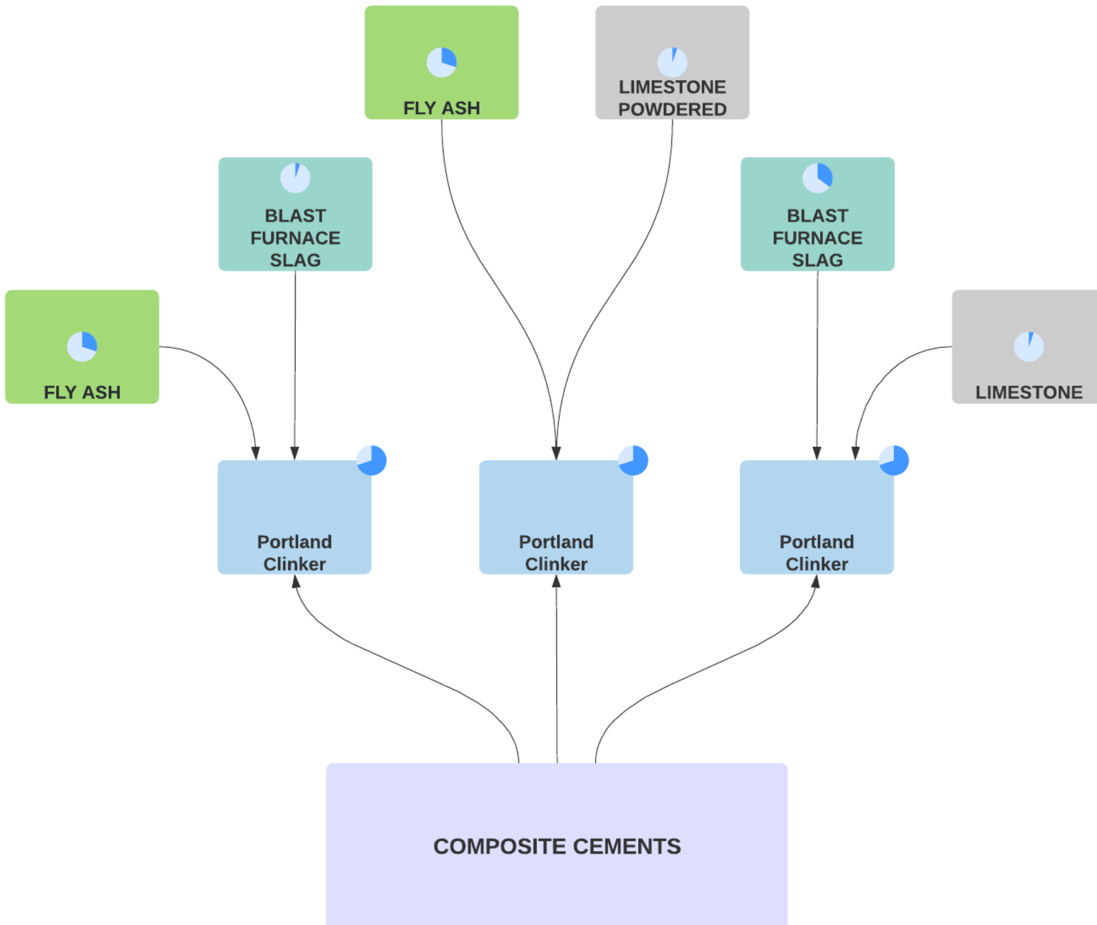

Figure 35: Composite cements – blend of Portland Clinker, Fly Ash, and Blast Furnace Slag

3.10 Cement Substitutes / Green Cements

Green cement is a form of cement produced with the help of a carbon-negative manufacturing process. [1] Companies recently have started marketing a range of types of cement claiming to be carbon negative, green cements. The traditional process involves the calcination of limestone, resulting in 60-65% of today's emissions. Because these cements do not use the traditional process of calcination of limestone nor the same raw materials as conventional cement, they are able to lower the emissions. While LC3 has 30% reduction potential, composite cements have 56%, and Geopolymers have 80% reduction potential (Table 37). LC3 and geopolymers have successfully implemented pilot projects in India. LC3 has been commercialized and authorized by BIS (Table 37). There are some constraints for other types of carbon-negative green cements like MOMS due to the scarcity of raw materials in India.

Table 37: SEC and emissions of global low-carbon & carbon-neutral cements vs. OPC clinker

Category	Alternative Cement	Direct CO_2 reduction potential	Energy Reduct-ion potential	Raw Material Availability in India	Technology readiness	Source
Low-Carbon Cement	Limestone Calcined Clay (LC^3)	30%	3%	Yes	Advanced	[46, p. 11]; [46, p. 10]
Low-Carbon Cement	Composite Cement	56%	57%	Yes	Advanced	[46, p. 11]; [46, p. 10]
Low-Carbon Cement	Geo-Polymer Concrete (Flyash/GBFS)	80%	42%	Yes	Advanced	[46, p. 11]; [46, p. 10]
Low-Carbon Cement	Belite-rich Portland cement (BRPC)	10%	15%	Yes	None in India; advanced globally – China & Japan	(Scrivener et al., 2017); [46, p. 9]; [46, p. 10]
Low-Carbon Cement	Calcium sulfoaluminate / Belite-Ye'elimite-Ferrite cements (BYF/CSA)	20%	38%	No, scarcity of aluminum-rich minerals	None	(Naqi & Jang, 2019); [46, p. 9]; [46, p. 10]
Low-Carbon Cement	Carbonatable calcium silicate cements (CCSC)[40]	30%	53%	Yes	None	(Sahu & Meyer, 2020); [46, p. 9] LafargeHolcim, 2019; [46, p. 10]
Carbon Negative Cement	Magnesium Oxide-based cements derived from magnesium silicates (MOMS)	100%	47%	No, scarcity of natural ore for producing magnesium silicates	None	(The American Ceramic Society, 2011); [46, p. 9]; [46, p. 10]

[40] Patented by Solidia Technologies, Inc. and partnered with LafargeHolcim; applications include concrete paver blocks

3.10.1 Geo Polymer Cement

Geopolymers are synthetic alumina silicate materials. They have the potential to decarbonize the cement industry. They have two-component binders – a reactive solid and an alkaline activator. They react with alkaline media to form a three-dimensional inorganic aluminosilicate polymer network form.

They have a relatively high strength of hardened product. The benefits of GPC are that existing cement plant production facilities, including kilns and grinding mills, can be used to produce GPCs. They also do not require high-temperature kilns. As clinkering temperature is lowered, fuel consumption too is lowered. This reduces the expenditure as well as emissions of fuels. Their widespread availability makes them very suitable to become cement substitutes.

There are two types of geopolymer cements, rock-based and fly ash based [55]:

1. **Rock Based**

Emissions: Rock-based GPC reduces emissions by 80% as it does not involve the process of limestone calcination. In addition, unlike traditional OPC, low-temperature heating results in lower emissions.

Quality: Similar to OPC

Cost: Less capital investment than OPC

Availability: Abundant

Properties: Greater thermal and chemical resistance and better mechanical properties than OPC. Since no limestone is used, GPC has excellent properties in an acid and salt environment. Moreover, seawater can be used to blend GPCs.

2. **Fly Ash Based**

Composition: 50-80% Fly ash, 10% Slag, 10% Potassium Silicate. Fly ash is obtained from thermal power plants produced at 1200 -1400 °C.

Emissions: Reduce CO_2 emissions by 90%

Properties: Greater thermal and chemical resistance and better mechanical properties than OPC. Since no limestone is used, GPC has excellent properties in an acid and salt environment. Moreover, seawater can be used to blend GPCs.

Process: Geopolymerization involves the alkalization of NaOH and KOH. Fly-ash-based GPC binds with coarse and fine aggregates to form GP Concrete.

Table 38: SEC and emissions comparison of GPCs' vs. OPC

	OPC	Glass	Carbunculus	Carbunculus nat.	Source
Manuf. Temp (ºC)	1400-1500	750-1350	750-800	20-80	[55]
Energy %	100	64	40	30	[55]
CO_2 Emissions %	100	35	20	10	[55]
Source	[55]	[55]	[55]	[55]	[55]

3.10.2 Novacem Cement

Novacem cement (not in business anymore)

Process: Novacem is a CO_2-absorbing or carbon-negative cement. It uses magnesium silicate (talc) as raw material in cement production. There is an abundance of talc (10,000 billion tons) to produce plenty of cement. The process involves magnesium silicate converting into magnesium carbonate under elevated temperatures (180°C) and 150 bar pressure. Decomposition of carbonate occurs at low temperatures of 700°C to produce MgO, then made into cement. This cement absorbs and stores CO_2 from the air as it hardens within concrete mixes.

Emissions: 0.75 tons of CO_2 is used to produce 1 ton of Novacem. Due to calcination occurring at low temperatures, this process facilitates better use of alternative fuels (biomass), reducing CO_2 emissions.

One ton of Novacem absorbs 100 kg more CO_2 than it emits.

Total typical emissions in making Novacem are 50 to +100 kg/ton of cement as compared to 800 kg/ton for OPC.

Energy: Novacem consumes 60-90% of the energy typically required for OPC.

Quality: Novacem claims the quality to be equal to OPC

Cost: Novacem claims costs of production to be on par with OPC.

3.10.3 Calix Calera Cement[41]

Traditional carbon capture and sequestration involves using carbon capture and storing it underground or in other industries. In this Calix Calera, the sequestration process includes converting CO_2, SO_2, fly ash, brines, and wastewater into economically viable products such as building materials, clean flue gas, and freshwater. The inputs for this cement are calcium carbonate cement are CO_2 and smokestack pollutants like SO_2, fly ash, brines, and wastewater. The outputs of the process result in producing clean flue gas, building materials, and freshwater. It involves seawater and CO_2 to produce calcium carbonate or limestone. A demonstration project has been built in Moss Landing, California. It captures 30,000 tons of CO_2 per year (the equivalent effluent of 10 MW of natural gas power plant). Scaling this to capture the effluent of 100 MW of natural gas power plant (an equivalent of 300,000 tons of CO_2 per year), it can produce valuable building material worth 550,000 tons per year[42]. It estimates the price of a metric ton of Calera cement between \$50 - \$100. It aims to provide fresh water while producing building materials. In Latrobe Valley in Victoria, Australia, the Calera Yallourn project is anticipated to capture more than 300,000 tons of CO_2 and produce more than 1 million tons of building material per year, along with 2 million gallons of freshwater per day.

The process involves using seawater to scrub the CO_2 from the flue gas. The concentrated CO_2 is further mixed with water to form hydronic acid H_2CO_3. It is processed further to strip the Hydrogen Ions and mix them with calcium and magnesium ions to form calcium carbonate and magnesium carbonate. The precipitated carbonates are separated out of the water (called supernatant). This water is filtered using a reverse osmosis desalination plant to achieve potability. Co-locating cement plants near natural gas power plants will be beneficial economically.

Calera has since become Fortera. During clinkerization of limestone in traditional cement production, about 44% of the limestone fed into the process is decomposed into CO_2 nearly 1.7 tons of limestone yields 1 ton of clinker. One ton of OPC uses 0.95 tons of clinker, therefore 1.58 tons of limestone is used to prepare 1 ton of OPC.

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[41] https://golden.com/wiki/Calera-PBRJAD
[42] https://www.greentechmedia.com/articles/read/calera

Regulations: Fortera can be used as supplementary cementitious material, and regulations are now allowing its use of up to 35% either co-blended with Portland cement or as a substitute.

Cost: It costs 10% less than traditional cement without sacrificing quality or performance while utilizing CO_2.

Emissions: Since Fortera does not release CO_2, every ton of feedstock results in one ton of sellable product, creating an economic advantage while minimizing CO_2. It has the same curing workability as that of Portland cement.[43]

The raw material mix is prepared by first grinding and mixing the materials in the accurate proportions, and then passing the mixture through different stages of the Clinkerization process. The raw feed is then passed through the preheater stage. In this stage, most of the limestone is decomposed, and the raw mixture is heated up to 800°C. Then the raw feed enters the kiln for clinker production, where it is heated to even greater temperatures (1450-1500 °C). This causes the raw feed to break into Alite (C3S), Belite (C2S), Tricalcium aluminate (C3A), etc., and the composition of these materials is called clinker.

The clinker formed at the exit of the kiln is passed through the cooler, reducing its temperature to 200°C. After cooling, the clinker is ground and mixed in the required proportions of the final product with gypsum, fly ash, or slag. This final product (Cement) is then packed for dispatching in 50 kg bags.

3.11 Supplementary Cementitious Materials (SCMs)

These are pozzolans like fly ash, calcined clay, and silica fumes (Table 39). They are siliceous materials. The SCMs are either mixed with OPC to form blended cements or added separately in the concrete mixer. By themselves, they do not have cementitious value; however, when mixed with ground clinker and water, they react with Calcium hydroxide to form compounds with cementitious properties. Because some of the clinker or OPC is replaced with the pozzolans, it reduces the emissions intensity of cement.

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[43] https://forterausa.com/product/

Table 39: Supplementary cementitious materials (SCMs)

Supplementary Cementitious Materials (SCMs)	Source
Fly Ash	[46, p. 12]
Blast Furnace Slag	" "
Zinc Slag	" "
Copper Slag	" "
LD Slag/Steel Slag	" "
Low-Grade Limestone (Filler)	" "
Calcined Clay	" "
Natural Pozzolan	" "
Pond Ash	" "

Fly Ash: It is a byproduct of power generating plants obtained by burning coal. The fly ash is the fine dust-like powder that comes out with the exhaust gases from the burning zone in the boiler. It is collected by using electrostatic precipitators or bag filters. When mixed with Portland clinker and water, it forms calcium-silicate-hydrates and calcium aluminum hydrates. The fly ash is ground together with Portland cement to produce Portland Pozzolana Cement (PPC).

In 2018-19, nearly 27% of fly ash production was utilized by cement companies, another 51% by other industries, and 22% of fly ash remained unutilized. The permissible amount of clinker substitution by fly ash per Indian Standard IS 1489-1:2015 (Portland Pozzolana Cement fly ash based) is 35%. The European standard permits 55% substitution with fly ash. There is potential for fly ash percentage to be increased in India, and research is underway to achieve it. [46, p. 13]

Blast Furnace Slag: Blast furnace slag is a non-metallic industrial byproduct that is generated in the manufacturing process of pig iron from iron ore in the blast furnace. The slag comes out in liquid form, then cooled to form granules, and finally, grounded to suitable fineness to produce a powder to be mixed with the ordinary Portland cement. Currently, India produces 27 million tons of blast furnace slag, and its production is expected to increase to approximately 45-50 million tons by 2030 (NITI Aayog, 2018). Increasing the percentage of slag would help decrease the clinker content of cement and the associated emissions. In 2017, India produced only 23% of OPC, and the rest, 73%, are blended cements comprising 63% PPC, 9% PSC, and 1% other types such as rapid hardening cement, composite cement, and low heat cement. (Figure 36).

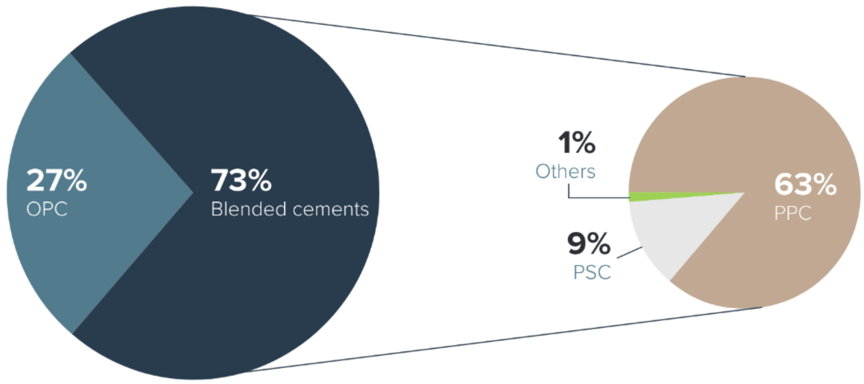


Figure 36: Share of different types of cement in India's cement mix (2017) [46, p. 14]

Low-grade limestone as a filler: Fillers are finely ground particles that are used as a partial replacement for clinker and other SCMs. Low-grade limestone is a popular filler due to its lower cost of production and emissions savings and is used widely around the world. Since it does not require calcining and only grinding, it has lowered emissions. Low-grade limestone is mixed with clinker to produce Portland limestone cement. The permissible levels of limestone substitution are 5-35% in various standards (Figure 37). India allows for 5% of limestone for performance improvement in OPC according to IS 269: 2013 (BIS, 2013). Recent studies show that a replacement of 70% clinker by low-grade limestone (filler) can be achieved without impacting the strength. Moreover, fillers can be used with all new binders, including LC^3, geopolymers, carbonation-hardening cements, and cement made with clinkers such as BYF and CSA (John et al., 2017). LC^3 cement composition consists of 15% of low-grade limestone. In India, low-grade limestone is heavily available for use as a filler in Portland limestone cement, which is produced in Europe. [46, p. 15] Substituting a portion of high content clinker with limestone will proportionately lower the process emissions from conventional process of calcination of limestone. This will lower embodied energy and overall emissions of cement.

PERMISSIBLE LIMESTONE FILLER LIMITS ACROSS COUNTRIES (5% - 35%)

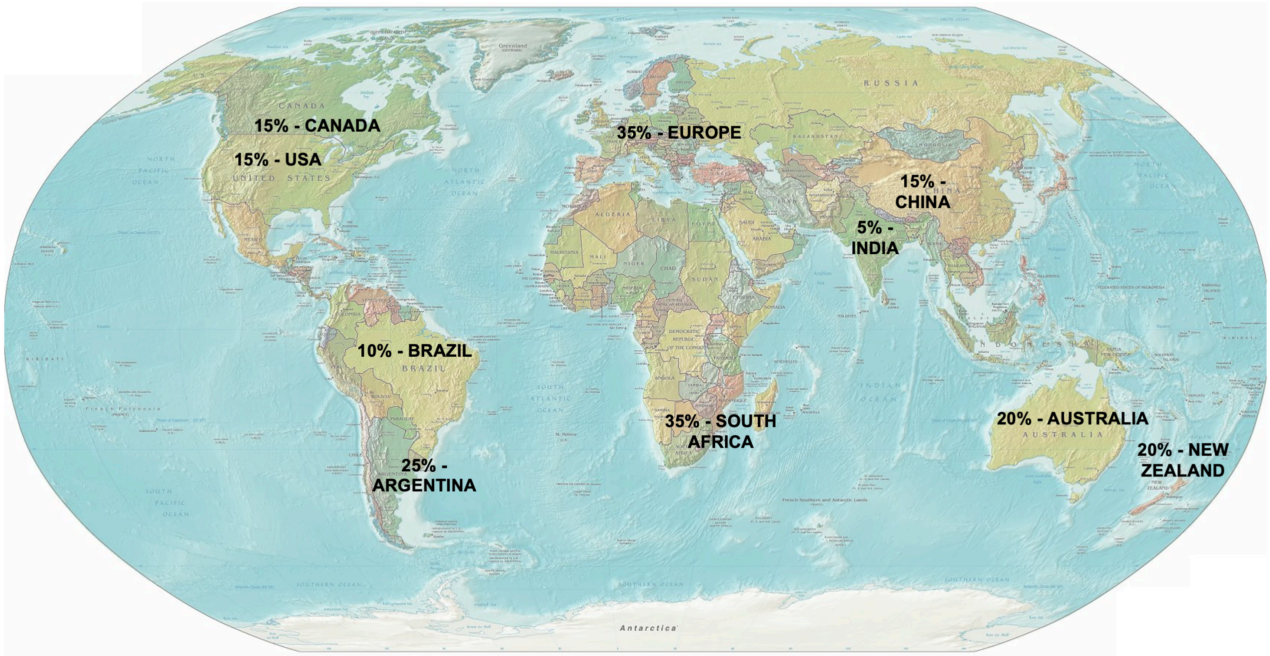


Figure 37: Limestone filler limit by region as adapted from John, et al., 2017 [46, p. 15]

Calcined Clay:

When clays containing kaolinite undergo calcination at 700°C-850°C, they produce reactive materials that can replace some of the clinker and other supplementary cementitious materials such as fly ash and slag. A clay with kaolinite content as low as 40% can be used as SCM in cement production (Scrivener, et al., 2018). With plans to phase out coal-fired power plants to transition to renewable generation and the introduction of a national steel scrap policy that promotes the generation of scrap-based steel, it is expected that the availability of fly ash from power plants and production of BF slag will lower over time. Calcined clay can gradually overtake these SCMs in clinker replacement, as clay is abundantly available in India. Further, only high-quality clay is used by the ceramic industry, resulting in a significant amount of clay being stockpiled as waste. Currently, the LC^3 cement is being produced commercially, which uses calcined clay in cement production. [46, p. 15]

Pond Ash: Pond ash is formed when unused fly ash at the Thermal Power Plants (TPPs) is dumped into the landfills, called ash ponds. Around 1/3rd of the fly ash produced remains unused and deposits into the ash ponds. This leftover ash has accumulated and resulted in an environmental hazard for the country. A much better alternative would be to utilize this pond ash to produce PPC, composite cement, or geopolymer cement since it is naturally pozzolanic.

Utilizing pond ash can help India reach its waste utilization target and allow for the implementation of circular economy principles. Research is underway to find the use of industrial byproducts such as LD slag (a byproduct of steel production), Natural Pozzolan, Silica fumes, Copper slag, Zing slag, byproducts from the aluminum industry, bauxite as SCMs in the Indian cement industry to reduce waste and environmental hazards.

3.12 Alternative (Substitute) Raw Materials and Additives (Ars)

The most important distinction between Alternative Raw materials and composite or blended cement is that the addition that happens is during the pre-clinkering stage. It is relatively easy to add the ARs because they only require the addition of a hopper and a sub-meter.

The CO_2 reductions can be achieved by using decarbonated raw materials and sustainable waste materials (alternative fuels) to replace fossil fuels (See Section 3.14). Using decarbonated raw materials to replace part of the limestone in the kiln reduces the total emissions resulting from decarbonation of the limestone. Unlike fossil fuels, decarbonated material, such as fine material from recycled concrete, will not emit CO_2 when heated since CO_2 was already removed from its processing. Thus, decarbonated material can provide a 2% reduction in total emissions worldwide from the sector. This 2% reduction considers the potential increase in the thermal energy demand that will likely occur as a result of substituting alternative fuels. [52, p. 25]

The potential of alternative fuels has been proven by cement kilns currently operating while using 100% alternative fuels (i.e., biomass, non-primary materials). The industry is a well-established consumer of non-recyclable waste-derived alternative fuels from various sources such as municipal, agricultural, chemical, and food production. Supply chain logistics and infrastructure are implemented to ensure these are managed in a safe and environmentally sound way.

Alternative (Substitute) Raw Materials and additives (ARs) are essential because too much raw material consumption can lead to unsustainable depletion of natural resources. See Figure 38 for a list of such materials listed sourced from CII. [56, p. 19]

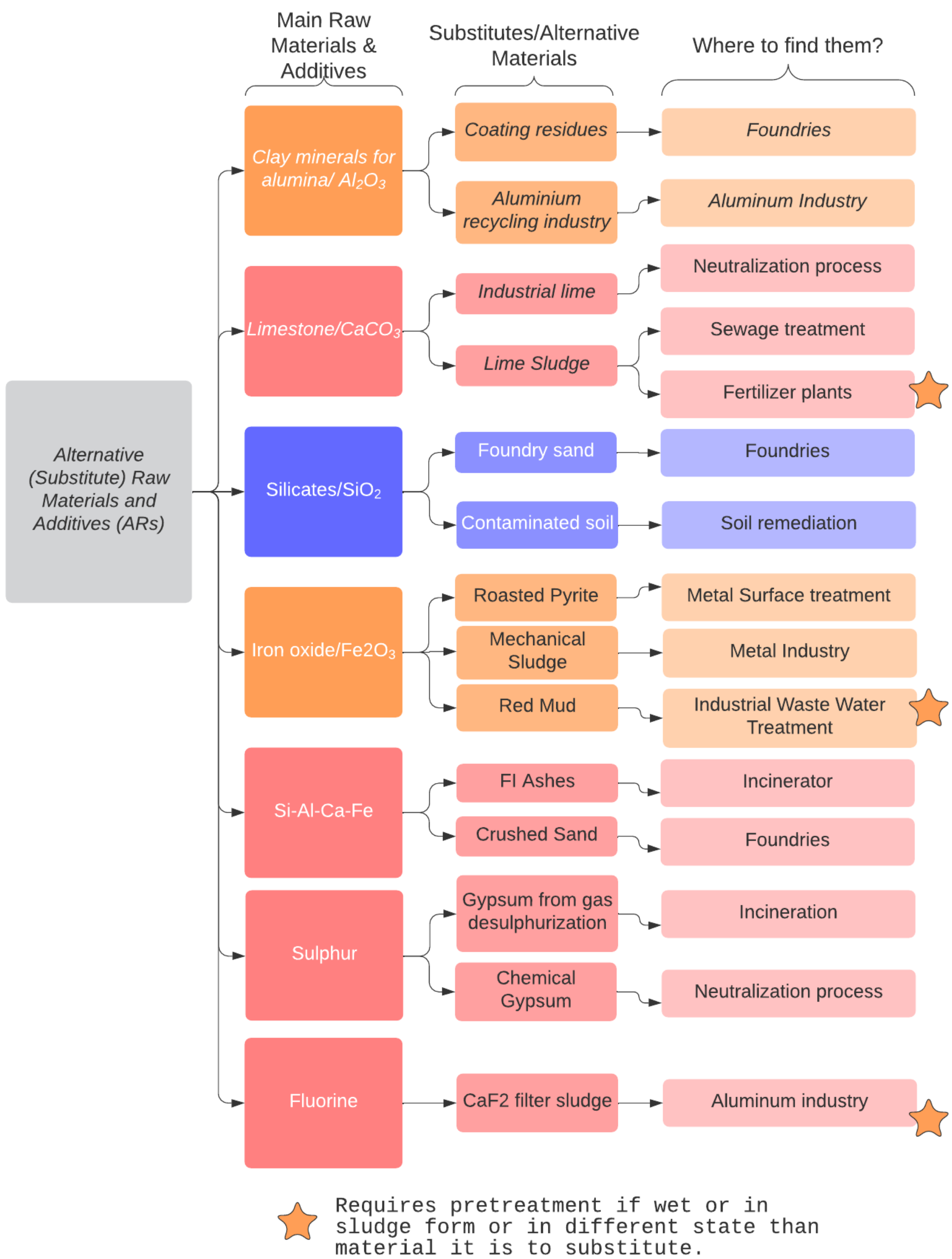


Figure 38: Alternative raw materials and Additives (ARs)

3.13 Alternative Binding Materials

Binder refers to all material in concrete such as cement, fly ash, GGBS, limestone that is permitted as cementing material in the local jurisdiction.

Table 40: Process CO_2 emissions from calcination of raw material by clinker compounds

Clinker Compounds	**Process CO_2 Emissions (from calcination of raw materials)** [kg CO_2/tonne of material]	Source
Alite (Ca_3SiO_5)	579	UNEP (2016); [28, p. 42]
Belite (Ca_2SiO_4)	512	UNEP (2016); [28, p. 42]
Tricalcium Aluminate ($Ca_3Al_2O_6$)	489	UNEP (2016); [28, p. 42]
Tetracalcium Alumino-ferrite ($C_4Al_2Fe_2O_{10}$)	362	UNEP (2016); [28, p. 42]
Lime from Limestone (CaO)	786	UNEP (2016); [28, p. 42]
Wollastonite ($CaSiO_3$)	379	UNEP (2016); [28, p. 42]
Ye'elimite ($Ca_4Al_6SO_{16}$) from calcium sulphate	216	UNEP (2016); [28, p. 42]
Periclase from magnesium carbonate (MgO)	1100	UNEP (2016); [28, p. 42]
Periclase from magnesium silicate rocks (MgO)	0	UNEP (2016); [28, p. 42]

3.13.1 Aether™ Cement clinker

It is a cement clinker developed by Lafarge that has properties similar to OPC. It has 25-30% lower emissions than OPC clinker and can be produced in existing cement plants. Loss of ignition in Portland raw mix is 35%, whereas, in Aether™ raw mix, it is 29%. Aether clinker is produced in standard cement kilns. Its sintering temperature is 1225-1300ºC. Energy consumed for grinding Aether clinker is lower than OPC. Aether clinker can be blended with other blending materials such as fly ash and slag to produce blended cements.

Table 41: Chemical composition of OPC clinker

Chemical Composition of Portland Clinker	Percentage	Source
Alite (C_3S)	65%	[28, p. 42]
Tricalcium Aluminate (C_3A)	6%	[28, p. 42]
Belite (C_2S)	15%	[28, p. 42]
C_4F	12%	[28, p. 42]

Table 42: Chemical composition of Aether^{TM} clinker

Chemical Composition of Aether^{TM} clinker	Percentage	Aether^{TM} clinker (Example)	Source
Calcium Sulfoaluminate ($C_4A_3$$)	15-35%	25%	[28, p. 42]
Belite (C_2S)	40-70%	55%	[28, p. 42]
Ferrite (C_2AF)	5-25%	20%	[28, p. 42]
Minor phases	0.1-10%	0.1%	[28, p. 42]

3.13.2 Belite Clinker

It is an alternative binding cement material available commercially. It contains little to no Alite. It is commercialized in China and Japan and used in dams and hydropower projects due to its low heat of hydration. They have been found to have been used in mass concrete and high-strength concretes. They can be produced at lower temperatures (600-900°C). The heat of hydration refers to the heat released due to the exothermic reaction between cement and water. It needs to be limited in mass concrete applications to reduce the risk of thermal cracking.

Table 43: Composition of Belite clinker

Chemical Composition of Belite Clinker	Percentage	Source
Belite (C_2S)	40-90%	(Gartner and Sui, 2017); [28, p. 42]
Alite (C_3S)	<35%	(Gartner and Sui, 2017); [28, p. 42]

3.13.3 Calcium SulphoAluminate Clinker/ Belite-Ye'elimite-Ferrite Cement Clinker (BYF/CSA)

This calcium sulphoaluminate clinker contains ye'elimite as the primary constituent. The presence of this constituent drastically reduces the process CO_2 emissions due to low calcination emissions (Table 40).

3.14 Alternative Fuels Use or Thermal Substitution Rate (TSR)

Cement production is very energy-intensive. Added to that, cement demand and fuel prices are rising. The Indian cement industry is increasingly moving towards positioning itself at the heart of the circular economy to benefit from the use of waste materials. It uses industrial and municipal waste from various waste streams to reduce energy consumption and emissions generated. By reducing carbon-intensive fossil fuels and replacing them with less intensive alternative fossil fuels, biomass fuels and other industrial wastes, and hazard wastes, alternative fuels are gaining momentum. Madras cement's Alathiyur plant has used bioenergy by burning coffee husk & cashew nut shells and achieved a savings of USD 1.7 million. Dalmia plant has adopted plant matter, and refuse-derived fuel (RDF) for 100% of its fuel needs to transition to renewable power by 2030. Lafarge's Arasmeta plant also substituted 10% of coal used in kilns with rice husk to lower carbon emissions. Also, a Dalavoi plant uses Low Sulphur Heavy Stock (LSHS) sludge as an alternative fuel and realizes annual savings of USD 6500. [34]

Thermal Substitution Rate (TSR): is the amount of alternative fuel used by the plant or industry to substitute fossil fuels. From the TSR level of 0.6% in 2010 to 3% in 2017, the Indian cement industry targets to achieve 25% TSR by 2025 and 30% by 2030 (CMA, 2020). Presently, more than 24% of total alternative fuels are consumed as biomass. [3, p. 5] Nearly 73% of alternative fuel use is solid waste which mainly includes carbon black, tire chips, refuse-derived fuel (RDF), captive power plant (CPP) bed ash, and dolachar. [3, p. 19]

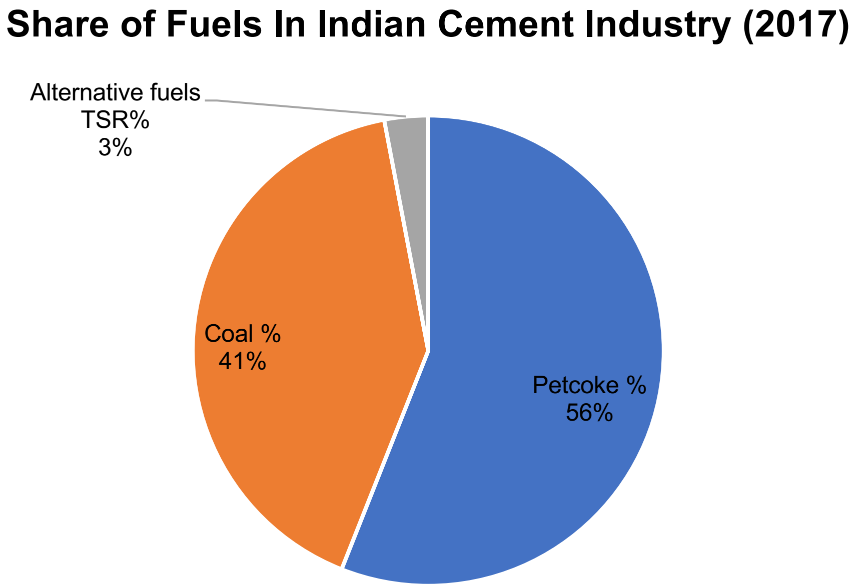
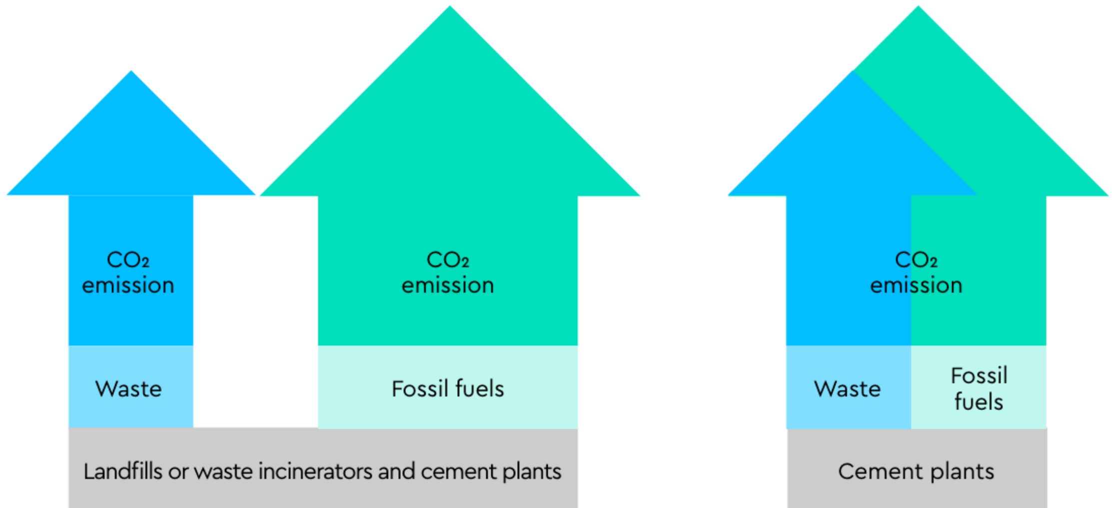


Figure 39: Share of fuels including alternative fuels in Indian Cement Industry in 2017

Petcoke calorific value (8,000 kcal/kg) has twice the energy density of Indian coal (3,500 – 4,500 kcal/kg). It also costs less to transport than coal, leading to savings in transportation costs. As the industry is moving towards Indian coal, some of the benefits of petcoke are lost. At the same time, India is looking to achieve energy security through domestic production. The use of Indian coal requires slightly higher-grade limestone, unlike imported petcoke, which is known to work with the marginal grade of limestone with a low lime saturation factor. There is a gap in the best plants using alternative fuels vs. others. Some plants to date consume more than 95% of petcoke.

The RDF derived from Municipal Solid Waste (MSW) has a high potential to be used as an alternative fuel. About 80% of the estimated 62 million tonnes of MSW generated in India is disposed of in dumpsites. There are some challenges associated with alternative fuel use, like the segregation of MSW, collection of Biomass, handling of hazardous waste, etc., but it reduces land needed for landfill.

Co-processing of industrial waste has been found to have issues during the implementation phase. While alternative fuels usage is greatly exercised within the manufacturing industries of Europe whereby an 83% thermal substitution rate can be achieved by utilizing a range of low-carbon, combustible material, it is also important to note that policymakers and cement companies in Europe have integrated change over many years to demonstrate a 13% vol. of CO_2 emissions reductions from 1990 to 2011. (Ariyaratne, 2014a; del Mar Cortada Mut, 2014; Nielsen et al., 2011; VDZ, 2009) [57]. Some challenges of integrating alternative fuels into kilns exist (Figure 41).



Utilisation of waste fuels in cement plants results – according to the Greenhouse Gas Protocol – in CO_2 and even GHG emission reductions at landfills and incineration plants.

Figure 40: Waste fuels utilization in cement plants for lowering emissions [52, p. 25]

CHALLENGES IN INTEGRATING ALTERNATIVE FUELS INTO CLINKER KILN	
As properties, process stability, efficiency, etc. differ from conventional fuels	*Generates products of incomplete combustion*
Direct contact of raw meal with fuel	*Causes decrease in calorific value*
Due to lack of knowledge or testing; it is not straightforward	Potential to inadvertently generate new pollutants
It is not process efficient, fuel uncertainties	Uncertain fuel needs as it depends on quality of alternative fuels
Based on fuel heating values, hydrogen carbon-ratio	Instability of Stochiometric Ratios
In presence of moisture, ash, chlorine, suphur, alkali metals	Pollution forming catalysts
Due to variability in process stability and chemical properties variations	Reduction in heat transfer, effecting material temperatures and clinkerization properties
Due to variability in heat transfer and clinkerization	Lower clinker production rate, and increased costs in operation due to reduced clinker production rate

Figure 41: Challenges in integrating alternative fuels into clinker kiln

3.15 Captive Power Plant (CPP)

Captive Power refers to the generation of its own power by the cement manufacturing facility exclusively for its internal consumption. A captive power plant is located next to a cement plant. Coal is the primary fuel (as oil and gas are not economical in India). In some cases, power produced from wind farms and solar are also used to supplement captive power.

Most cement plants in India have a captive power plant next to them to operate with 100% captive power generation and avoid high grid electricity costs, power shortages, and power failures. Overall, cement plants use captive power plants (CPPs) to meet nearly 60% of their electrical power requirements. To reduce emissions from CPP, renewable energy and efficiency improvements are essential. Onsite/CPP generation reduces the emission intensity of cement by 49 kgCO_2/ t of cement.

3.16 Waste Heat Recovery Systems (WHRS) Technology

Waste heat recovery is a proven efficiency measure in Indian cement plants. It reduces CO_2 and aids in mitigating GHG emissions while enhancing the overall system performance. Cement plants have waste heat available in kiln exhaust gases and vent air from clinker cooler. This waste heat is captured and used to preheat raw materials and raw meal in preheater stages. In addition, waste heat can also be used for power generation using Cogen. Waste heat recovery and cogeneration is a promising addition to existing captive power generation.

For Cogen of power, Steam Rankine cycle (SRC) with waste heat recovery boiler is employed for capturing high-grade temperatures greater than 600 ºC. To capture medium grade temperatures in the range of 250 - 600 ºC, a waste heat recovery boiler with Organic Rankine Cycle (ORC) system is needed. Low-grade temperature recovery of less than 250 ºC is challenging to achieve economic feasibility. This is where a Waste Heat recovery boiler with a Kalina Cycle system has been found to be useful.

The Indian cement industry has potential to produce more than 800 MW through co-generation of power using WHR, of which only about 40% is being tapped. The WHRS offers a cost-effective way to reduce fuel demand; however, there are high investment costs upfront. Data reveals that co-generation of power using waste heat meets 25-30% of total cement plant power requirements. Energy costs for fuels such as coal and grid electricity also have observed an increase due to the additional tax called the Clean Energy CESS tax for the use of coal. This tax increased by 700% by 2017 from when it was first introduced in 2010. These rising costs have prompted for the use of more imported petcoke as well as adding WHRS in some cement. While these systems were installed in Indian cement plants, they were primarily self-financed and used a Rankine cycle, except for a few that used an Organic Rankine cycle. [3, p. 16]

3.17 Logistics

Logistics is the activity that links cement from the point of extraction of raw materials for cement and its production until reaching the hands of the ultimate consumer. In recent years, logistics have emerged as a function of critical importance for the cement sector. The logistics have to concern themselves with balancing various functions such as supply and demand of cement, the demand of users, and support cement manufacturing needs such as acquiring and bringing raw materials and fuels to the manufacturing site from mining sites or stockpiles to cement manufacturing plants and maintain timely deliveries. Each of these functions has unique constraints.

Generally, the bulkiness and weight of limestone and cement make it very difficult to transport these materials over long distances. Its high weight-to-volume ratio makes it a freight-intensive industry. Due to this, the cement industry is divided into five distinct regions for cement manufacturing. This is why cement plants are also located next to limestone deposits.

To balance freight costs, demand and supply factors, and industry structures, the Indian cement industry is also fragmented into five regions from north to south and east to west and northeast. Figure 42 represents cement production and market across different regions in India. [58] Limestone that is quarried in a region and cement produced in a region is consumed mainly in that region.

CMA 2020 report identified key challenges and opportunities for logistics and transportation emissions reductions which are illustrated in Figure 43. [50, p. 11] There is a need for quantifying emissions reductions opportunities in the transportation and logistics of cement.

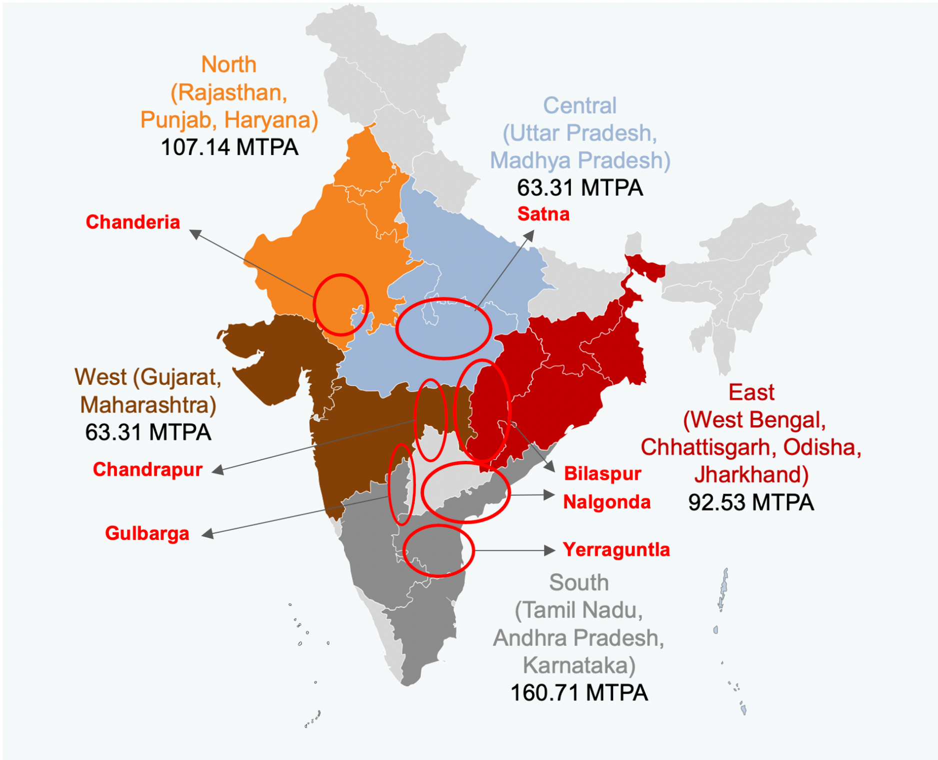


Figure 42: Regional breakdown of cement manufacturing (cement clusters in red) [59, p. 16]

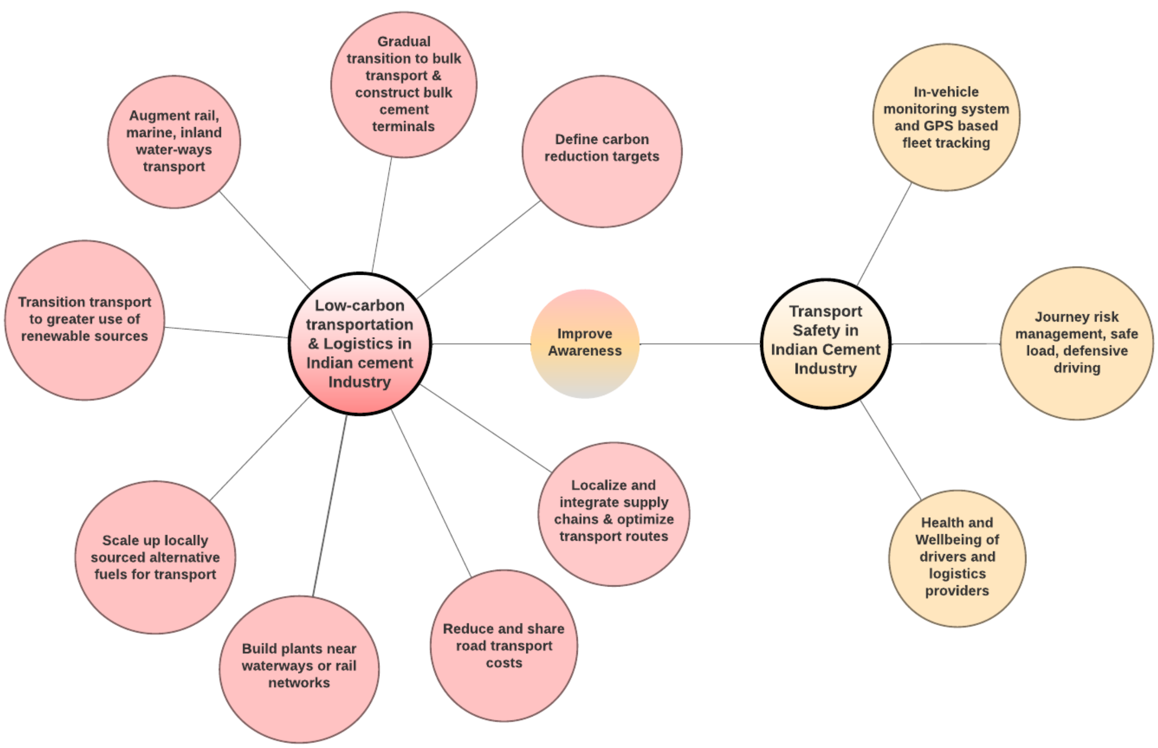


Figure 43: Sustainable development goals in transportation and logistics of cement

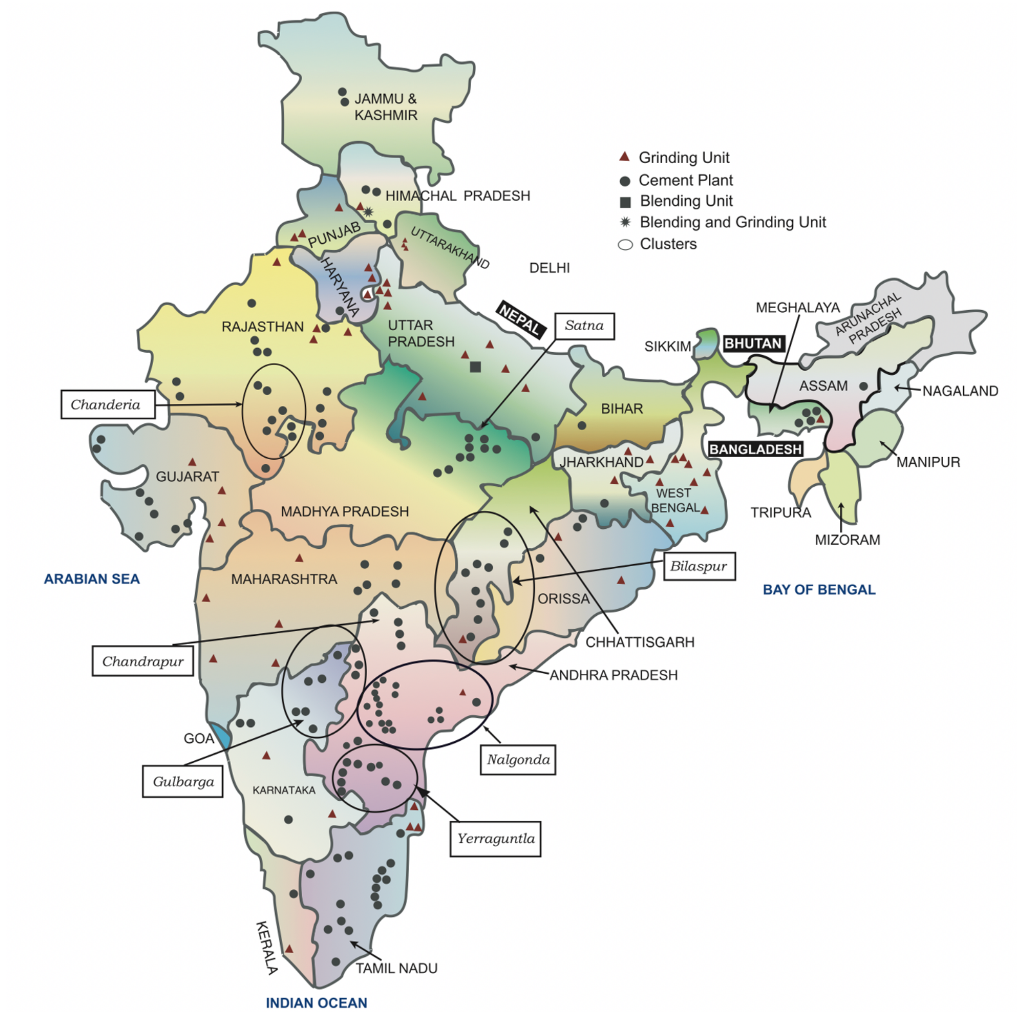


Figure 44: Spatial layout of integrated, blending, blending and grinding, grinding unit in India[44] [45]

Since the location of limestone mines is concentrated in certain states, cement and clinker have to be transported to those locations farther from mines. Cement companies are setting up long-term contracts with freight companies are being set up to lower operational costs and secure preferential allotment of racks for the transport of cement bags. To further combat the issue of cost, the government is also planning on expanding railways and facilities for handling and storage. Railway siding proposals play an essential role in the future expansions and considerations of cement companies.

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[44] Cement Manufacturers' Association Basic Data 2012
[45] 2012 Technology Roadmap - Low-Carbon Technology for the Indian Cement Industry

Road transport has also gained popularity in the last few years due to the construction of new highways and road maintenances. This has resulted in the majority of cement plants having their own fleet of trucks to transport the cement bags directly to distributors, dealers, and franchises. The extensive demand for cement calls for more than one mode of transportation. Plus, the railway station may or may not be in the vicinity of the cement plant. Overall multi-modal transport is the standard for logistics in India to readily meet high demand. [60] Another strategy being employed by cement companies is trying to locate themselves nearby power plants to utilize fly ash available as a clinker substitute. [61, p. 15] This has two benefits. First, it has emissions savings from cement substitutes, and secondly, the cost of transporting fly ash is virtually close to zero.

Being freight intensive commodity due to its weight, cement supply via land transportation is quite expensive. It is generally limited to an area within 300 km of any one plant site. [59] Typically, the mode of transportation holds about 20% of the retail price of cement. Over the years, the operating costs of Indian cement companies have also grown at a CAGR of 7.03%, from INR 1330 per tonne in FY05 to INR 1868 per tonne in FY10. If we look at the breakdown of operational costs of Indian cement companies, raw materials, and freight costs have gone up significantly (10.7% CAGR and 12.9% CAGR respectively) while the fuel costs went up by a slight amount (3% CAGR) and power costs have gone down (-0.5%).[59, p. 15]

During logistics handling, cement companies have incurred losses due to bag bursts and seepages. Due to this, companies have been promoting bulk cement suppliers who deliver cement in bulk at construction sites in specially designed vehicles. This has been incredibly beneficial for large construction sites such as infrastructure development sites and multi-story building construction sites. This has been a favorite procurement option for developers as it is economical and no moisture seeps in. [60]

Raw material is more available in the Southern region, which also has the largest number of cement manufacturing companies compared to any other region. Nearly 37% of large cement plants (i.e., 77 out of the 210 large cement plants) in India are located in the states of Andhra Pradesh (South), Rajasthan (North), and Tamil Nadu (South). Freight costs and emissions intensities will be greater for plants that have complex logistics needs.

A cement blending unit may be onsite, in which case it is an integrated unit. Sometimes it is located off-site in a separate unit and about 100 km away. See Table 44 for an example of logistics in the cement manufacturing process.

Table 44: Example logistics of a cement plant

Materials	Sources	Transportation	Distance	Requirement
Limestone	From adjacent captive limestone mines	Covered conveyor belt	0.05 km	12000 Tonne per Day (TPD)
Bauxite	Nearby Districts	Truck/Rail	100 km	300 TPD
Iron Ore	Nearby Districts	Truck/Rail	130 km	150 TPD
Gypsum	Nearby Districts	Truck/Rail	1000 km	330 TPD
Fly Ash	Generation from CPP	Closed Conveyor Belt	0.05 km	900 TPD
Fly Ash	CPP purchase from thermal power plants nearby	Closed Tankers	200-300 km	900 TPD
Coal	Coal from nearby coal mine for clinker	Truck/Rail	375 km	300 TPD
Coal	Coal for CPP	Truck/Rail	250 km	650 TPD
Petcoke	Pet Coke for clinker from a nearby refinery	Rail	1200 km	660 TPD

In the future, India aims to be a net exporter in the world in the next decade. It expects to export clinker and gray cement to the Middle East, Africa, and other developing nations in the world. Therefore, those plants located near ports such as Gujarat and Visakhapatnam have added competitive advantage and will logistically be well-armed from other regional competition in India. [61, p. 15]

3.18 Newer Technologies

It is estimated that newly emerging and innovative technologies will provide a total cumulative savings of 48% by 2050 compared to the RTS scenario. The global technology roadmap for the cement industry estimates a total of 3.7 Gt CO_2 savings by 2050 in the 2DS compared to RTS.

3.18.1 Renewable Power Generation

The cement sector has the potential to lower emissions from electricity production by increasing the share of renewable power in its overall energy consumption. Most cement plants in India are located in dry and hot areas around unused arid lands, making them quite suitable for solar power generation in India. The renewable energy power generation installed capacity (wind and solar) in cement plants in 2017 was 276 MW, consisting of 42 MW Solar and 234 MW Wind.

3.18.2 Material Savings and Demand Reduction Technology – SmartCrusher

This technology, developed and patented by Koos Schenk in 2011 out of the Netherlands, is being developed to reuse concrete for incorporating it into the circular economy. The SmartCrusher technology recovers sand, gravel, hydrated and unhydrated cement (accounting for 30-40% of the initial cement used) from concrete. Working on the principle of separating materials based on their individual crushing strength, this technology has been lab-tested, and pilot demonstrations were conducted in the Netherlands. This technology uses 10% of the energy of a traditional crusher. The sand and gravel recovered is better in quality and can save up to 25% of the cement in the new constructions. The Shakti report recommends a country-level assessment for the suitability of this technology in the Indian conditions as well as the economic feasibility due to being a patented technology. [46, p. 16]

3.18.3 Solar Concentrators and Heaters for Preheating and Drying Raw Materials

Input raw materials and fuels such as coal, limestone, petcoke, and additives have an average moisture content of 5% to 10%. Using technology harnessing solar power such as solar concentrators and heaters can lower the heat input needed for preheating raw materials and fuels. [3, p. 28]

3.18.4 Concentrated Solar Power (CSP) for Clinkerization

Successful pilots have been conducted to produce clinker from heat derived from concentrated solar radiation. In this pilot study, the clinker production process was set up near a very high concentration solar tower and connected with the solar receiver that delivered temperatures beyond 1,500 ºC. The process involves the solar receiver heating up a gaseous heat transfer fluid and providing the necessary heat required for calcination reaction of limestone and clinkerization. Due to the calcination process utilizing renewable source of heat instead of conventional or alternate fuels, nearly 1/3rd of process emissions resulting from conventional and alternative fuel burning are eliminated. Since it is a newer technology, there needs to be analysis on its techno-economic feasibility. Moreover, India generates large quantity of wastes that can be currently integrated into cement kiln to avoiding landfills[46]. When a CSP is used instead of alternate fuels, the current waste management rules may need another solution for managing wastes such as industrial and MSW.

3.18.5 Use of Bamboo as Alternative fuel

Since bamboo has been recently categorized as grass in India, it can be mass planted on mining land or part of social forestry programs and community farming and used as an alternative fuel. [3, p. 28]

3.18.6 CCS

Medium to long-term Decarbonization Strategies include Post-Combustion CCS and cryogenic CCS. (See Section 3.19)

3.18.7 Hydrogen as a Fuel for High-Temperature Heat

Use of Blue and Green Hydrogen for high-temperature heat (where Blue Hydrogen is obtained from natural gas with CCS; and Green Hydrogen is obtained from renewables via electrolysis). On a global average, alternative fuel use is projected to increase from 6% (currently) to 22% by 2030 and 43% by 2050. Innovations such as the use of hydrogen and kiln electrification are expected to play a small role from 2040. [52, p. 25]

3.18.8 CO_2 Curing

It is a method of utilizing CO_2 to reduce emissions. Here early-age cement paste is placed in a CO_2 chamber/ pressure vessel. This accelerates its strength development. By measuring gas pressure loss, the CO_2 uptake can be quantified. Researchers have looked at material efficiency and identified that the efficiency of the CO_2 curing is superior when a 20% concentration of CO_2 gas is supplied at a relative humidity of 75%. [62, p. 1]

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[46] https://synhelion.com/news/cemex-and-synhelion-produce-the-world-s-first-clinker-with-solar-energy

3.18.9 New Cement Types

Materials substitution of cement with increasing variety of low carbon substitutes can lower emissions. For a low carbon transition, the new cement types require characteristics such as durability, early strength development, workability, cost and low environmental impacts, and compliance with norms such as carbonation resistance and chloride penetration resistance. [3, p. 25]

3.18.10 Synthetic Slag Derived from Low-Grade Limestone

This is a laboratory scale developed slag derived from low-grade limestone and mine-rejects. This slag has been found to achieve a glass % of 92% which is greater than that specified in the Indian Standard Specification (IS 12089-1987) of 85%. This is an early-stage technology that is dependent on being able to be mass produced at industrial scale. Indian cement industry now has a high material supply risk of limestone due to rapidly depleting cement grade limestone, with only 8949 MT remaining. Since synthetic limestone is made with low-grade limestone which is abundant in India, and the lab results have been promising, there is potential for this technology[47].

3.19 Carbon Capture Utilization and Storage (CCUS)

Carbon capture is the process of capturing and storing CO_2 emissions from cement production. The Carbon Capture Utilization and Storage is an emerging emissions reduction lever, so its contribution is projected to become significant beyond 2030 when commercial viability and necessary infrastructure have been established. Some cement companies have implemented CCUS technology. Once the CO_2 is captured, it can either be stored or utilized within the cement and concrete industry or used in other industries as a raw material. The utilization option in cement includes injection into wet concrete, curing hardened concrete, and manufacturing aggregates from waste products. Further research, development, and expansion of all three of these potential uses of captured CO_2 are underway.

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[47] https://www.ncbindia.com/centre-for-cement-research-and-independent-testing.php

The calcination of limestone in cement manufacturing results in process emissions. As long as cement is derived from the calcination of the limestone process, these emissions are hard to diminish. This is where the CCUS is very useful to the cement sector to mitigate CO_2 emissions and meet the climate goals. Exploring new cement types that capture CO_2 and technologies available in CCUS for capturing emissions from the cement plant and improving the maturity levels for these new technologies will be very beneficial. Raw material alternatives and CCS technologies should be evaluated as a demonstration, and pilot projects and tests should be conducted to ascertain their scalability. The costs to incorporate CCUS are currently high, but a long-term view is needed.

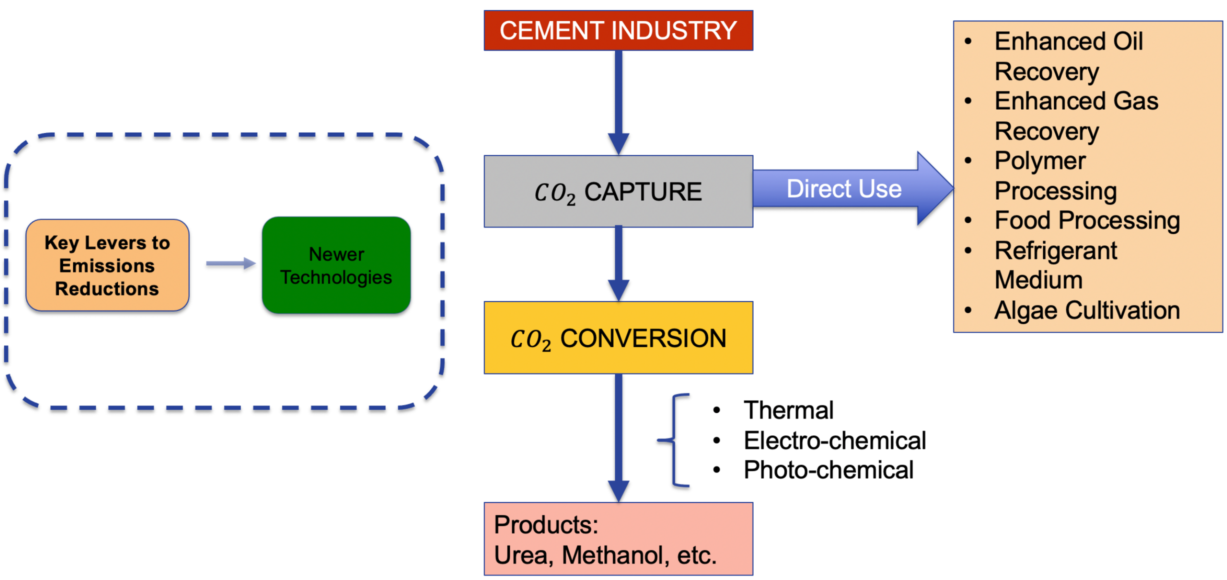

Figure 45: CO_2 capture and utilization pathways

The roadmap for CCUS comprised of research and development for the early 2000s. This R&D roadmap included oxyfuelling, gas cleaning oxyfuelling, and chemical looping. The period of 2015-2025 marks the stage of demonstration projects of chemical absorption plants. The mitigation costs for such projects are estimated to be 125 USD/tCO_2. Further along, in 2020, the roadmap included a demonstration of three oxyfuel demo projects and three chemical looping demo projects. By 2030, the roadmap consists of the addition of CCS to all large new kilns. As the technology progresses and becomes more economical, the price of carbon capture is estimated to drop to 100 USD/tCO_2 post-combustion and 60 USD/tCO_2 for Oxyfuel. Between

2030 and 2040, it estimates at least 50-70 major kilns to have CCS. The CO_2 mitigation costs for post-combustion are also at 100 USD/tCO_2, with a slight reduction of oxy-fuel expenses at 50 USD/tCO_2. With this level of CCS deployed, it is predicted that 0.11 to 0.16 Gt of CO_2 is captured, accounting for 10-12% of CO_2 emissions. As 2030 to 2040 marks the period of commercialization, the report outlined an estimated 100-200 cement kilns with CCS. It was further estimated that in 2050, 220-430 cement kilns will incorporate CCS with a mitigation cost of 75 USD/tCO_2 for post-combustion and 40 USD/tCO_2 for oxyfuelling. This was calculated to achieve a total captured Gt of CO_2 to be 0.5 to 1.0 Gt with a net capture of 40-45% of CO_2. [53] In the future, the CCUS technology will aid in mitigating emissions that are otherwise unattainable due to technology, policy, or implementation gaps in a target vs. actual realized emissions.

Researchers are currently investigating ways to overcome the major barriers to mass adoption of CCUS, which are lack of economies of scale and water availability. Some cement plants in India have started pilot projects for carbon capture through algal growth and use as biofuels. For instance, one cement plant co-located with a paper manufacturing unit has managed to successfully use CO_2 from the cement and lime kilns to produce calcium carbonate. This is used in the paper and pulp unit as a filler, indicating that companies could develop many customized CCU solutions to abide by local requirements. Collaborative efforts between the cement and paper sectors could help scale such circular economy solutions.

Oxygen enrichment can significantly improve combustion efficiency, reducing energy requirements in the kiln between 84 and 167 MJ/t cement. This process has been widely implemented in industrial sectors (i.e., steel, copper, etc.) but has not yet gained popularity in the cement sector. Oxygen enrichment can also reduce combustion gas or preheater exit gas volumes, which has shown to have a net decrease in energy usage of the overall system. For instance, it is estimated that a 2% increase in the oxygen level in the burning zone (kiln combustion) can reduce the preheater gas volumes by 8%. This can lower SEC by 0.5 kW/t clinker or an equivalent increase in production or effective use of alternative fuels.

At present, the main drawback is the higher initial investments needed to deploy this technology. If the higher operating costs to produce, store, and use oxygen can be compensated by reduced costs from using alternative fuels, perhaps the Indian cement industry will begin to adopt this technology widely. A carbon tax could potentially motivate the industry to adopt CCUS to lower CO_2 emissions. [3, p. 28]

3.20 Demand Side Reductions

3.20.1 Efficiency in Concrete Production

The CO_2 emissions reductions in concrete production are achievable by shifting concrete production from small project batching to industrialized processes due to improved efficiency and optimization, adherence to mixing specifications, quality control, and loss of cement due to bag spillages. In India, where the vast majority of concrete production occurs on project sites, there is a huge potential to transition to industrialized production, as seen in other countries. The industrialized production allows for the utilization of admixtures improved processing of aggregates, which can lower CO_2 emissions. It is estimated that optimization of concrete production in terms of binder utilization can lead to binder demand reductions of 5% and 14% in 2030 and 2050, respectively. [52, p. 26]

3.20.2 Recarbonation

Some of the atmospheric CO_2 is re-absorbed by concrete structures during their lifetime as it reacts with cement to form H_2O and $CaCO_3$. This naturally occurring process is known as recarbonization. It has recently been considered in carbon accounting in the IPCC 6th Assessment Report. It absorbs 105 kg CO_2/ tonne of clinker, a conservative number that considers a 20% recarbonation of the theoretical maximum of 525 Kg CO_2/tonne. Over the next few decades, the clinker-binder ratio will be slightly lower due to reductions in the clinker content replaced by clinker substitutes. Due to the reduced clinker-binder ratio, the forecast for recarbonation is 319, 318, and 242 Mt CO_2 in 2020, 2030, and 2050, respectively. The reduced clinker per m^3 of concrete slightly lowers the recarbonation over the coming decades. Research is in the works for a more detailed evaluation of recarbonation and the efforts to enhance recarbonation through active exposure of crushed concrete to CO_2 at the end of life. [52, p. 27] Also, carbonation has been found to increase corrosion risk in rebar. There may be some scope to further evaluate any potential for tradeoff of reduced carbonation with increased durability of rebar within concrete, or potential ways to maintain durability for varied recarbonation levels.

3.20.3 Utilization of Construction and Demolition (C&D) Waste

During construction, renovation or demolition, there is a lot of construction waste generated. This waste (usually wood, concrete, steel, etc.) is dumped on the roadside, public areas, or municipal bins. There is an estimated 100 million tons of annual C&D waste generation in the country (BMTPC, 2018). The current practices for utilization of C&D waste include salvaging recoverable items like metal rods, pipes, fixtures, wooden frames, etc., that leave behind rubble comprising concrete, stones, and sand, among others that have potential applications such as landscaping, earthworks, aggregates in concrete. Recycling the rubble waste and reutilizing it in the newly constructed buildings and infrastructure can lower some of the concrete and cement demand. [46, p. 16]

3.20.4 Design Optimization Technologies

Building design influences the amount of concrete used. By reducing cement demand, emissions are lowered. Lowering demand and improving environmental degradation are two focus areas. Following are some of the techniques available on the design optimization side to lower cement demand.

Voided concrete slab technology/ Bubble Deck Technology: This technology involves the creation of engineered voids in the slab and filling them with spherical or oval or hollow cubical structures derived from recycled plastics. Since the slab is where the highest amount of concrete is used, creating voided slabs and using bubble decks can reduce concrete consumption. Additional benefits include lowered strain on a slab, thus allowing longer span lengths, lighter foundation, and framework of building due to decreased burden, overall materials savings due to thinner columns and voided slabs, waste reduction, and lowered emissions due to reduced concrete usage. [46, p. 17] In slabs with spans greater than 7 meters and thickness of slab is greater than 20cm, voided slabs are used along with post-tensioning. Using this technology has lowered 25-30% of concrete savings and 10% on reinforcement. [46, p. 18]

Confined Masonry: It is a construction technique wherein masonry walls are load-bearing walls. These walls are additionally enclosed by horizontal and vertical Reinforced Concrete (RC) elements such as tie beams and tie-columns to provide confinement & strength for the walls and support against seismic loads. Due to load-bearing walls, they are constructed first, unlike in a conventional technique where RC frame is built first, and walls added later. Due to confined masonry carrying some loads, the RC ties used here are smaller than those in the RC frame construction technique. (Borah et al., 2019). In case studies where confined masonry technique was used rather than conventional RC frame with masonry infill, it was found that the average concrete usage was lower than 50%, with a net 0.30 - 0.36 m^3 of concrete/ m^2 area in confined masonry vs. a 0.86 m^3 of concrete/ m^2 area in conventional RC frame with masonry infill technique. In addition to material savings, additional benefits of confined masonry include reductions in steel consumption, cost savings, and emissions reductions. The construction methods for this technique are also included in guidebooks by EERI, SDC/Humanitarian aid unit, and competence center for reconstruction. This technique is an excellent choice for low-rise buildings with simpler shapes. [46, p. 19] Improving builders, architects, and homeowners' awareness of sustainability and climate change issues and their technical knowledge of sustainable design and construction techniques in addition to adding incentives or tax credits can result in its widespread implementation across traditional housing construction.

Cross-Laminated Timber (CLT): It is a prefabricated and engineered wood panel developed in the 1990s in Europe. It is made by drying the timber boards and placing them over each other with timber grains perpendicular to each other. These glued timber boards or lamellas are then hydraulically pressed against each other for strength and used in the construction of walls, floors, roofs, and any type of building, residential, commercial, industrial, and multi-story building construction. (Beyond Zero Emissions, 2017) Increasing the share of wood in construction can significantly lower concrete usage and thus emissions from the construction sector. Its benefits include material savings, reduction in construction time, flexibility in design, improved thermal performance. Timber in India was initially banned from construction services in 1993. Recently, this was lifted off since July 2020 to encourage timber use in India to construct housing and related activities (CPWD, 2020). With this change, it is expected that an increase in timber demand will encourage farmers to add a green cover to degraded land, helping to realize NDC's target of creating 2.5 – 3 billion MT of CO_2 equivalent increase in green cover. Technical and economic analysis of the use of timber in construction for India is needed, along with a better understanding of its performance across climate zones. A system for monitoring timber stock in the country, time to grow, sustainable usage, and standardizing emissions calculations is necessary and must be established. [46, p. 19]

Design for Deconstruction (DfD): It is a design technique where buildings are constructed to permit disassembly and reuse for some other purposes and in new constructions. This upfront flexibility can lower wastage when the building use case changes.

3-D Printing: Three-dimensional structures are created through computer-controlled sequential layering that permits faster and more efficient construction with minimal material wastage. [46, p. 20]

Literature summary: The literature review and status of decarbonization methods outlined in Chapters 2 and 3 helped to identify various technological, social, economic, policy, and logistical factors that affect the overall Indian cement industry's emissions outcomes. It is expected that over the next few decades, India will witness an exponential cement demand and production growth trajectory as observed in the case of China, whose rapid development and urbanization over the past few decades owing to similar reasons of industrial growth, GDP, infrastructure, rising urbanization, and living standards has led to exponential cement consumption. To provide a perspective, China consumed more cement between 2011 and 2013 (6.4 Gt), than the U.S. did in the entire 20th century spanning from the 1900s to 2000[48]. Much of this was attributed to rapid urbanization widespread use of concrete, a similar situation likely to happen in India as well. India, too, will witness a strong demand for cement with phenomenal growth in demand for houses, roads, and bridges to accommodate the rapid urbanization. With more people relocating to cities in India and the nuclearization of families, the market and emissions are only expected to grow. Added to it, any lower construction standards will lower building lifespans resulting in its contribution to rising cement demand. In China, the cement industry is plagued with excess capacity and through-the-roof per-capita consumption. While the Chinese cement industry is primarily state-owned, has access to financial capital, and has brought 100s of millions of Chinese citizens out of poverty, rising pollution concerns have also forced its president Xi Jinping to order shutting down of hundreds of steel, coal, and cement plants resulting in loss of jobs to many. India needs a more strategic approach to meet its rising cement demand learning from the invaluable lessons of China's dark path of emissions for its cement industry and the problem of having to deal with a reactive environmental management situation. Fixing down the road is easily understood when we reference software development,

[48] https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/

where the cost to fix bugs grows exponentially the later it gets detected in the process. The same is true for India’s economic development and costs of reducing emissions. Suppose the entire value chain's construction standards, innovations, and emissions requirements are not in place upfront and well-integrated in the value chain. In that case, it is not only a costly affair but a significant environmental, socio-political, and climate detriment for the nation. This thesis aims to reiterate this concept and come up with effective strategies for pathways to decarbonize the Indian cement industry.

4 Methodology

From the climate-based research questions outlined in Chapter 1, the broad system problem statement (SPS) was first arrived at to identify decarbonization pathways and low-cost levers that can lower the cement industry's CO_2 emissions.

Table 45: System problem statement (SPS)

SYSTEM PROBLEM STATEMENT	
To	Meet the climate goals and carbon budget targets set for the Indian cement industry
By	Lowering emissions intensity of cement manufacturing
Using	Potential decarbonization levers across the value chain

The path to decarbonization of the cement industry requires designing of an engineered system for mitigating climate change by evaluating carbon-intensive processes, emerging technologies, material science, and decarbonization levers across the entire value chain of the construction industry, as well as the ability to reliably integrate them into decarbonization pathways to achieve desired climate goals.

In the case of the Indian cement industry, low-investment decarbonization pathways are needed to ensure that smaller players and many others with limited access to capital are also able to source, produce and deliver cement with reduced emissions. To effectively decarbonize the Indian cement industry will require analyzing a variety of decarbonization levers across the entire value chain of the cement industry. These include the supply side, demand side, operational side, and logistics levers.

Table 46: Decarbonization opportunities across cement industry value chain

Decarbonization Opportunities in Value Chain Flow in Cement Manufacture		
Procurement	Raw Materials	• Sustainable raw material resources management for long-term • Alternative binding materials • Reserves of raw materials available for cement and risk for competing uses • Availability (tonne per year) of industrial byproducts as raw materials in circular economy
Production	Cement, Cementitious Materials	• Reduce CO_2 emissions through ○ Energy efficiency improvements ○ Alternative fuels and raw materials ○ Emerging technologies and innovation ○ Blended cements

		○ Composite cements ○ Clinker factor ○ Cement substitutes ○ WHRS ○ CCUS ○ Other emerging technologies
Logistics	Movement of Raw Materials, Fuels	• Partnerships and support for raw materials • Reduce CO_2 emissions ○ Geographic distribution of raw materials ○ Logistics and Transportation Mapping ○ CPP vs. Grid
End Use	Restore and Reuse, Circular Economy, Reduce cement demand	• Circular economy to promote recycle reuse and reduce industrial waste • Building partnerships for circular economy • Knowledge sharing • Reduce cement demand ○ Sustainable and innovative products ○ Efficiency in concrete production ○ Recarbonation of concrete ○ Design optimization ○ Extend useful life of concrete structure

Decarbonization opportunities include both quantitative and quantitative measures. For instance, on the qualitative side, building effective partnerships, knowledge sharing, change management, building motivation, incentives and policies support measures are necessary for ensuring that desired results occur. While quantitative and qualitative opportunities to decarbonize are like the two sides of the coin and function together, different decision frameworks are required for analyzing each of them. In this thesis, only quantitative opportunities were considered and evaluated to assess their decarbonization potential by using optimization. It also important to also conduct qualitative studies but such analyses and framework is outside the scope of this study.

4.1 Method for Analysis

The emissions reduction potential using optimization in the Indian cement industry was evaluated at the following scales:

- Individual Indian cement plant level
- Indian cement industry level

4.1.1 Individual Cement Plant Level Model

First, an individual cement plant was modeled and emissions from OPC, PPC, and PSC were obtained based on inputting respective Clinker Factors (CF: 0.95 for OPC, 0.65 for PPC, 0.4 for PSC). Next, the cement production process was optimized for achieving target emissions intensity using various plant architectural decision options and decarbonization levers such as varying kiln system, clinker factor, mix of alternative fuels, and types of fuels.

The plant level cement model included modeling a cement plant for calculating emissions and energy intensity of clinker and cement types. The optimization at plant level involved considering a set of variables such as grid factor, clinker factor, kiln system, % of moisture in fuels, and % of alternative fuels mix.

Alternative fuels are of varying energy densities, moisture levels, emissions factors, and availability. Methods included conducting optimization modeling to determine the optimal fuel mix, how much fuel to use, and its expected emissions outcome with the goal of lowering the emission intensity of cement. For the chosen variables, ranges of quantities of alternative fuels in the mix and other practical constraints were set.

To arrive at a solution, a built-in excel solver was used for optimizing the different variables and their constraints to achieve the target emission intensity of cement, i.e., a user-defined desired emissions intensity in tonne of CO_2 per tonne of cement value. If the parameters and constraints were satisfied and the solver identified a solution, the solution was saved as a scenario. If no solution existed, it involved readjusting parameters and rerunning the optimization solver to achieve the target emissions intensity. If the constraints could not be modified further, the target was adjusted to identify new solutions. The scenarios were results from optimizations that met specific parameters for that optimization and thus saved as scenarios across a range of emissions intensities targets and tabulated along with their values for the parameters. These values represent indicators for the scenarios. To achieve a particular emissions intensity target, the indicators under that scenario must be met.

Optimization modeling was used to assess the Analysis of Alternatives among form and function options in a cement plant such as number of stages of pre-heater kiln, kiln system efficiency, amount of fuel, etc., to evaluate what percent of alternate fuels mixes and fuel types at the plant level are suitable for lowering emissions.

Optimization of emissions intensity by fuel mix at plant level: For the given kiln system, the fuels mix optimization was conducted to understand the impact of a greater thermal substitution rate and its influence on emissions intensity. For kiln systems with a specific heat energy requirement, the goal was to identify opportunities to lower emissions through the increased share of alternative fuels. It is difficult to arrive at these answers without the help of optimization because of the several constraints that can quickly get computationally challenging. Here, the scenarios were prepared using the optimization solver to review what percentage of thermal substitution rate is feasible purely from the perspective of inputs and outputs and constraints and the relationship of emission and energy flows.

Optimization of emissions intensity by varying inputs at plant level: Model inputs at the plant level included grid factor, kiln system, types of clinkers produced, moisture content, and alternative fuels and raw materials (Table 47). Options for electricity grid factors include current emission intensity of electricity power generation, i.e., 0.725 kgCO_2/kWh, and other options possible based on India Energy Outlook for STEPS, SDS, IVC Scenarios (Table 48). Other inputs included the selection of proportions of alternate and conventional fuels (Table 49) factoring in their moisture content, energy density, and annual availability in tonnes per year. Inputs were allowed for different kiln systems having varying efficiency levels depending on the number of preheater kiln stages. Theoretically, the lowest possible specific heat consumption is around 1.8 GJ/tonne for a limestone-based clinker kiln system (Table 50). It is important to note that kiln efficiency system improvements that save the thermal energy consumption for the kiln will also lower the overall heat recovered from WHRS systems that rely on capturing this excess heat for power generation, so there are tradeoffs when considering WHRS. The WHRS was not considered a factor at the individual plant level due to its implementation costs, but can be integrated into the model in the future. Also, options were provided for clinker types that have their own emissions profile. These clinker types are made from calcination of various binding compounds, with each having its own composition and calcination emissions profile (Table 51). For instance, Belite clinker consists of Belite and Alite binding compounds with a specific composition or range of composition, and based on this composition, the net CO_2 emissions for these Clinker types are identified (Table 52).

Table 47: Cement plant scale model inputs and outputs

Inputs	Outputs
Grid Factor	Direct vs. indirect emissions intensity (Tonne of CO_2/tonne of cement)
Clinker Factor	
Kiln System	
Moisture content of raw materials	
Type of clinkers produced	
Alternative fuels used in kiln	

Table 48: Grid intensity indicators (potential scenarios)

Grid	Grid Intensity Factor ($kgCO_2/kWh$)	Source
2019 Grid 0.725	0.725	[63, p. 114]
STEPS 2030 Grid 0.537	0.537	[63, p. 114]
STEPS 2040 Grid 0.336	0.336	[63, p. 114]
SDS 2030 Grid 0.319	0.319	[63, p. 114]
SDS 2040 Grid 0.059	0.059	[63, p. 114]
IVC 2030 Grid 0.449	0.449	[63, p. 114]
IVC 2040 Grid 0.285	0.285	[63, p. 114]
Grid 0.68	0.680	Additional model input options
Grid 0.66	0.660	Additional model input options
Grid 0.61	0.610	Additional model input options
Grid 0.43	0.430	Additional model input options
Grid 0.29	0.290	Additional model input options
Grid 0.24	0.240	Additional model input options
Grid 0.18	0.180	Additional model input options
Grid 0.11	0.110	Additional model input options
Grid 0.08	0.080	Additional model input options
Grid 0.06	0.060	Additional model input options
Grid 0.05	0.050	Additional model input options
2000 Grid 0.817	0.817	[63, p. 114]

Table 49: List of alternative vs. conventional fuel used as inputs in plant level model

Category	Sub-Category	Fuel
Alternative fuels	Hazardous waste	Mixed HW Liquid
	Hazardous waste	Mixed HW Solid
	Hazardous waste	TDI Tar Waste
	Hazardous waste	Oil Sludge
	Hazardous waste	Spent Carbon
	Hazardous waste	Paint Sludge
	Hazardous waste	Spent Pot liner
	Hazardous waste	Spent solvent

	RDF from MSW	Raw MSW (100% yield of RDF)
	RDF from MSW	Acceptable RDF (10-15% yield of RDF)
	Used Tyres	Tyres
	Biomass	Rice husk
	Biomass	Rice straw
	Biomass	Coconut husk
	Biomass	Corn residue (corn cob, husk, straw)
	Biomass	Ground nut husk
	Biomass	Mustard straw
	Biomass	Sugar cane trash
	Plastic Waste	Wet plastic waste - raw waste
	Plastic Waste	Wet plastic waste - processed waste
Conventional fuels	Coal	Indian Coal
	Petcoke	Petcoke - Imported
	Petcoke	Petcoke - Indigenous
	Lignite	Lignite
	Diesel	Diesel

Table 50: Kiln systems with a range of heat consumption used in cement plant level model

Kiln Type	Specific Heat Consumption (GJ/Tonne of Clinker)
4 stage preheater	3.55
4 stage preheater + precalciner	3.14
5 stage preheater + precalciner	3.01
6 stage preheater + precalciner	2.93
Theoretical Minimum range (ECRA) Min	1.85
Theoretical Minimum Range (ECRA) Max	2.8
Theoretical Minimum (zero losses)	1.76
RTS - 2030 (Low Variability)	3.4
RTS - 2040 (Low Variability)	3.3
RTS - 2050 (Low Variability)	3.2
IEA Global Roadmap vision (2DS) - 2030 (Low Variability)	3.3
IEA Global Roadmap vision (2DS) - 2040 (Low Variability)	3.2
IEA Global Roadmap vision (2DS) - 2050 (Low Variability)	3.1

Table 51: Clinker compound options considered in cement plant level model

Clinker Compounds (Raw Materials)	Process CO_2 Emissions ($KgCO_2$/tonne of material)	Source
Compound: Alite (Ca_3SiO_5)	579	UNEP (2016); [29, p. 42]
Compound: Belite (Ca_2SiO_4)	512	UNEP (2016); [29, p. 42]
Compound: Tricalcium Aluminate ($Ca_3Al_2O_6$)	489	UNEP (2016); [29, p. 42]
Compound: Tetracalcium Alumino-ferrite ($C_4Al_2Fe_2O_{10}$)	362	UNEP (2016); [29, p. 42]

Compound: Lime from Limestone (CaO)	786	UNEP (2016); [29, p. 42]
Compound: Wollastonite ($CaSiO_3$)	379	UNEP (2016); [29, p. 42]
Compound: Ye'elimite ($Ca_4Al_6SO_{16}$) from calcium sulphate	216	UNEP (2016); [29, p. 42]
Compound: Periclase from magnesium carbonate (MgO)	1100	UNEP (2016); [29, p. 42]
Compound: Periclase from magnesium silicate rocks (MgO)	0	UNEP (2016); [29, p. 42]

Table 52: Clinker make-up by compounds and emissions considered in plant level model

Clinker	Composition	Process CO_2 emissions	Unit	Source
Clinker: OPC Clinker	Alite (Ca_3SiO_5): 67% Belite (Ca_2SiO_4): 6% Tricalcium Aluminate ($Ca_3Al_2O_6$): 15% Tetracalcium Alumino-ferrite ($C_4Al_2Fe_2O_{10}$): 12%	535.44	Kg CO_2/tonne of material	UNEP (2016); [29, p. 42]
Clinker: Belite Clinker	Clinker: Belite (40-90%) Clinker: Aelite (0-35%)	525.4	Kg CO_2/tonne of material	UNEP (2016); [29, p. 42]

Because Indian cement companies have suffered losses in recent years, the scenarios generated included decarbonization methods that can lower emissions intensity using levers that do not require a significant upfront investment. Currently, the cost to deploy such CCUS technologies and build CCUS infrastructure is high. Researchers globally are advocating for circular economy concept. Circular economy is least costly and expected to lower emissions by 33.6% in China. [64, p. 1] This is why circular economy and other low-cost decarbonization levers need to be streamlined and promoted for industry players to adopt decarbonization practices to achieve the 2DS and 1.5°C scenarios without having to depend on costlier technologies such as CCS or WHRS. For this reason, the performance metrics excluded adoption of CCS and WHRS since they incur higher upfront investment costs, but instead included clinker factor, blended cements, composite cements, alternative fuels thermal substitution rate (TSR%), and alternate binding materials to benefit from the circular economy and recycle, recover, reuse concept along with sustainable resources management of raw materials and fuels.

At the individual plant level, there are certain constraints to achieve a path to sustainable growth of the cement industry. For instance, it is hard to model and analyze the industry-wide mix of decarbonization levers that can be deployed. Therefore, in addition to the plant level (bottom-up) model, an industry level (top-down) decarbonization model using a macroeconomic view is considered.

4.1.2 Industry-level Model

After a plant-level bottom-up model was prepared to study decarbonization potential at the plant level, a further analysis was designed to assess the decarbonization potential at the Indian cement industry scale. At the plant level, we are unable to understand the complexities of a larger system nor its limitations and constraints in the bigger picture or take advantage of the decarbonization levers specific to the cement industry level. At the industry level, it is possible to explore more practical and achievable scenarios due to considering technology mixes. Various performance metrics and indicators are available based on guidance from IEA and WBCSD to ensure the Indian cement industry is on the path to the climate scenario of 2DS. For example, not all cement plants may incorporate waste heat recovery systems due to financial constraints. But at the industry level, it is possible to evaluate scenarios considering a fraction of plants that will incorporate waste heat recovery. Also, not all plants produce OPC clinker cement type or have access to the same industrial wastes or raw materials across regions. For instance, in 2018, 26% of total cement produced was OPC, 66% was PPC, and PSC was 7%, and other cement types were 1%, and based on this, the weighted average clinker factor is used for calculating emissions. Therefore, a cement industry scale model was prepared that comprised a few scenario mixes of decarbonization levers and mixes at the industry level to compare the outputs with the IEA defined performance metric indicators for climate change scenarios such as 2DS-High & Low Cement Demand (Table 53 & Table 54).

Optimization of emissions intensity by varying proportions of cement types: Evaluated scenarios comprised those where 2DS indicators were modified to include low-carbon cement types to assess the decarbonization potential of using low-carbon cement types like composite cements, geopolymer cements, LC^3 cements, CCSC, and Belite rich cements. Here, optimization modeling was conducted to achieve certain target emission intensities by varying proportions of low-carbon cement mixes (variables) and availability of raw materials in the country (constraints). If the optimization solver obtained a solution that fully met the constraints within the range of the set variables, this solution of mix proportions of cement typed was saved as a scenario. Using this approach, emissions intensity targets from current to 2DS levels were optimized to achieve solutions, which were saved as their respective scenario indicators. The overall goal was to bring the final target intensity to 0.35 tonne of CO_2 per tonne of cement in 2050 that is desired of a 2ºC. Further options were evaluated to consider possible net-zero scenario outcomes by 2040 that will allow for a global temperature rise to stabilize to 1.5ºC by 2100.

Optimization of cost intensity by varying cumulative emissions and a carbon tax: Here, optimization modeling was conducted by lowering the emissions intensities to much lower levels than those prescribed by the 2DS scenarios. The values used were based on alternate fuel mixes and alternate cement type scenarios that were optimized earlier. In the 2DS case, the emissions intensity indicator for 2050 is 0.35 tonne of CO_2/tonne of cement. This final optimization was done to assess the cost potential for early adoption of decarbonization levers to achieve lower emissions intensity early on and overall lower net emissions. Different emissions intensities are modeled and incorporated early on in the roadmap to 2050 to benefit from the net and cumulative CO_2 emissions reductions earlier than in the roadmap timeframes set by the IEA for decarbonizing the Indian cement industry in 2DS. The results help capture the CO_2 emissions cumulative savings that could diminish the need for extensive CCUS in future.

The IEA provided guidance for performance target indicators at the industry level; some of these are used while assessing plant-level emissions data (Table 53 and Table 54).

Table 53: Performance metrics for IEA 2ºC climate scenario for low-cement demand

PM#	Metrics	Description	Target Indicators
1	CO_2 emissions per tonne of clinker	The overall amount of CO_2 the system emits per tonne of clinker	Minimize emissions intensity, i.e., tonne of CO_2 emitted per tonne of clinker <0.743 tonne of CO_2/ tonne of clinker (2010) <0.742 tonne of CO_2/ tonne of clinker (2020) <0.718 tonne of CO_2/ tonne of clinker (2030) <0.621 tonne of CO_2/ tonne of clinker (2050)
2	CO_2 emissions per tonne of cement	The overall amount of CO_2 the system emits per tonne of cement	Minimize emissions intensity i.e., tonne of CO_2 emitted per tonne of cement < 0.55 tonne of CO_2/ tonne of cement (2010) < 0.52 tonne of CO_2/ tonne of cement (2020) < 0.46 tonne of CO_2/ tonne of cement (2030) < 0.36 tonne of CO_2/ tonne of cement (2050)
3	Energy use per tonne of clinker (GJ/t clinker)	The overall amount of energy used per ton of clinker	Minimize thermal energy intensity i.e., tonne of CO_2 emitted per tonne of clinker <3.033 GJ/ tonne of clinker (2010) <2.97 GJ/ tonne of clinker (2020)

			<2.90 GJ/ tonne of clinker (2030) <2.85 GJ/ tonne of clinker (2050)
4	Electricity use per tonne of cement (kWh/t cement)	The overall amount of electricity used per tonne of clinker	Minimize electrical energy intensity i.e., tonne of CO_2 emitted per tonne of clinker <80 kWh/ tonne of cement (2010) <76 kWh/ tonne of cement (2020) <73 kWh/ tonne of cement (2030) <71 kWh/ tonne of cement (2050)
5	Annual cement production (tonnes of Cement per year)	The total amount of cement production in a year (calendar or fiscal)	Lower Cement Demand Maximize utilization capacity of cement plants rather than adding more capacity <217 MTPA (2010) <416 MTPA (2020) <598 MTPA (2030) <780 MTPA (2050)
6	Clinker Factor for Portland Clinker, limestone-based (Average for industry mix)	Average clinker factor = [CF_{OPC} × Quantity of OPC $_{year}$ + CF_{PPC} × Quantity of PPC $_{year}$ + CF_{PSC} × Quantity of PSC_{year} + CF_{OTHER} × Quantity of $Other_{year}$]/ (Total Cement Quantity Produced per year)	Minimize the average clinker factor to lower the emissions from calcination process of limestone CFavg < 0.74 (2010) CFavg < 0.70 (2020) CFavg < 0.64 (2030) CFavg < 0.58 (2050)
7	Alternative fuels Used	The amount of alternative fuels used as a % of thermal energy consumption. This is also referred to as Thermal Substitution Rate (TSR)	Maximize use of alternative fuels in a circular economy concept TSR% > 0.6% (2010) TSR% > 5% (2020) TSR% > 19% (2030) TSR% > 25% (2050)
8	Per-Capita Consumption (kg/ capita)	Cement demand per person per year	Minimize cement demand extending life of buildings, reuse of concrete, reduce construction waste, recycle waste Per-Capita Cem. Consumption < 188 (2010) Per-Capita Cem. Consumption < 309 (2020) Per-Capita Cem. Consumption < 400 (2030) Per-Capita Cem. Consumption < 467 (2050)

- Metrics are based on recommendations for low-carbon technology roadmap for a Low-Demand Production in the Indian cement industry for a 2DS climate goal scenario

Table 54: Performance metrics for IEA 2ºC climate scenario for high-cement demand

PM#	Metrics	Description	Target
1	CO_2 emissions per tonne of clinker	The overall amount of CO_2 the system emits per tonne of clinker	Minimize emissions intensity i.e., tonne of CO_2 emitted per tonne of clinker <0.743 tonne of CO_2/ tonne of clinker (2010) <0.742 tonne of CO_2/ tonne of clinker (2020) <0.718 tonne of CO_2/ tonne of clinker (2030) <0.621 tonne of CO_2/ tonne of clinker (2050)
2	CO_2 emissions per tonne of cement	The overall amount of CO2 the system emits per tonne of cement	Minimize emissions intensity i.e., tonne of CO_2 emitted per tonne of cement < 0.55 tonne of CO_2/ tonne of cement (2010) < 0.52 tonne of CO_2/ tonne of cement (2020) < 0.46 tonne of CO_2/ tonne of cement (2030) < 0.36 tonne of CO_2/ tonne of cement (2050)
3	Energy use per tonne of clinker (GJ/t clinker)	The overall amount of energy used per ton of clinker	Minimize thermal energy intensity i.e., tonne of CO_2 emitted per tonne of clinker <3.033 GJ/ tonne of clinker (2010) <2.94 GJ/ tonne of clinker (2020) <2.89 GJ/ tonne of clinker (2030) <2.84 GJ/ tonne of clinker (2050)
4	Electricity use per tonne of cement (kWh/t cement)	The overall amount of electricity used per tonne of clinker	Minimize electrical energy intensity i.e., tonne of CO_2 emitted per tonne of clinker <80 kWh/ tonne of cement (2010) <75 kWh/ tonne of cement (2020) <72 kWh/ tonne of cement (2030) <70 kWh/ tonne of cement (2050)
5	Annual cement production (tonnes of Cement per year)	The total amount of cement production in a year (calendar or fiscal)	Lower Cement Demand Maximize utilization capacity of cement plants rather than adding more capacity <217 MTPA (2010) <492 MTPA (2020) <848 MTPA (2030) <1361 MTPA (2050)
6	Clinker Factor for Portland Clinker, limestone-based (Average for industry mix)	Average clinker factor = [CF_{OPC} × Quantity of OPC $_{year}$ + CF_{PPC} × Quantity of PPC $_{year}$ + CF_{PSC} × Quantity of PSC_{year} + CF_{OTHER} × Quantity of $Other_{year}$]/ (Total Cement Quantity Produced per year)	Minimize the average clinker factor to lower the emissions from calcination process of limestone CFavg < 0.74 (2010) CFavg < 0.70 (2020) CFavg < 0.64 (2030) CFavg < 0.58 (2050)
7	Alternative fuels Used	The amount of alternative fuels used as a % of thermal energy consumption.	Maximize use of alternative fuels in a circular economy concept TSR% > 0.6% (2010) TSR% > 5% (2020)

		This is also referred to as Thermal Substitution Rate (TSR)	TSR% > 19% (2030) TSR% > 25% (2050)
8	Per-Capita Consumption (kg/ capita)	Cement demand per person per year	Minimize cement demand extending life of buildings, reuse of concrete, reduce construction waste, recycle waste Per-Capita Cem. Consumption < 188 (2010) Per-Capita Cem. Consumption < 364 (2020) Per-Capita Cem. Consumption < 565 (2030) Per-Capita Cem. Consumption < 812 (2050)

- Metrics are based on recommendations for low-carbon technology roadmap for a High-Demand Production in the Indian cement industry for a 2DS climate goal scenario

Economic factors to assess cement related production and macro-economic conditions: The analysis method comprised macroeconomic factors and trends that influence the Indian cement industry. These include GDP, population, population growth rate, GDP growth rate, and per-capita consumption of cement. The model comprised of economic projections and scenarios as outlined in IEA India reports and at discrete annual intervals from 2010 to 2050. Various inputs were considered for preparing the macro-economic model for the cement industry. These include economic inputs, GDP growth rates, population growth rates, and assumptions from other models. (See Table 55, Table 56, Table 57, Table 58, Table 59, and Table 60)

Table 55: Economic inputs considered for industry level

Factor	Unit	Value	Source
India's per capita greenhouse gas (incl. land use) per capita (tCO2e/capita)	CAGR	+13.9%	Data for 2017. Sources: UN Department of Economic and Social Affairs Population Division, 2020; CAT 2019; Gütschow et al., 2019 [65, p. 1]
Cement - Installed Capacity for India (2020)	MTPA	545	CMA
Population - India	People	1,366.4 (2019) - 34% Urban 1,503.6 (2030) -37% to 40% Urban 1,639.2 (2050) – 53% Urban	World Bank, 2019; United Nations, 2018
Population Growth Rate - India	CAGR	1.4%	[26, p. 21]

India Households	Million households & population	Rural (2020) – 194.9 (pop: 890 mn) Urban (2020) – 113 (pop: 482 mn)	
No. of members per household - India	Decadal rate No. of persons per household	8.4% decline due to nuclearization 2011 – 4.94(Rural); 4.66 (Urban) 2021 – 4.22 (Rural); 4.22 (Urban)	[26, p. 21]

Table 56: Additional economic parameters

Parameters	Period	Value	Source
Growth rate of GDP per capita	2010-2050	6.8%	[66, p. 5]
2010 GDP per capita	2010	$2000	[66, p. 5]
Average annual rate of change of final energy per capita	2010-2050	2.4%	[66, p. 21]
2010 final energy per capita	2010	20 GJ	[66, p. 21]
Emissions trajectories for energy CO_2	2010	8-10 $GtCO_2$	[66, p. 5]
Emissions trajectories for energy CO_2	2050	5-7 $GtCO_2$	[66, p. 5]
Average annual GDP growth rate	2010-2050	7.2%	[66, p. 7]
Energy-related CO_2 emissions per capita	2010-2050	1-1.2 tCO_2/cap	[66, p. 7]
Energy-related CO_2 emissions per unit of GDP	2010-2050	1-0.09	[66, p. 7]

Table 57: GDP average growth assumptions based on direction of India's economy recovery

	2010-2019	STEPS			IVC	DRS	Source
		2019-2025	2025-2040	2019-2040	2019-2040	2019-2040	
India	6.6%	4.5%	5.7%	5.4%	6.0%	4.9%	[11, p. 63][49]
World	3.4%	2.7%	3.1%	3.0%	3.1%	2.6%	" "

Table 58: Sources of cement demand: housing, commercial, infrastructure and industry

Category	Cement Demand %	Source
Housing - Rural	35%	[26, p. 19]
Housing – Urban	30%	[26, p. 19]
Commercial & industrial – offices, malls, others	20%	[26, p. 19]
Infrastructure – roads, railways, bridges, dams, power plants, irrigation projects, others	15%	[26, p. 19]

[49] IEA analysis based on IMF (2020b); IMF (2020c); Oxford Economics (2020)

Table 59: Global population production growth rate

Global Population	Value	Source
Global Cement Production Growth Rate	12-23% by 2050 from 2018 CAGR: 0.2% until 2030	IEA
Global Population	9.7 Billion people	[67, p. 50] [50]
Global Economy	~ 150 trillion USD (2019) – 2020 ~ 310 trillion USD (2019) - 2050	[67, p. 50] [51]

Table 60: Input references for GDP [16, p. 466]

							2010 = 100	
		1	**2020**	**2030**	**2040**	**2050**	**2030**	**2050**
Population (model inputs)	**Million**	1201	1370	1523	1651	1751	127	138
GDP (model inputs)	**Trillion US$ 2010**	0.9	2.1	3.5	7.5	10.1	222	489
CO_2	**Scenario**	**Million Tonnes CO_2 (MT CO_2)**						
	BAU	1800	2893	4104	5170	5882	228	327
	NDC	1800	2889	3604	4317	4721	200	262
	2 °C	1800	2882	3230	3409	3163	179	176
	1.5 °C	1800	2866	3135	2823	2230	174	124
Energy		**Exa Joules (EJ)**						
	BAU	28.6	43.4	62.3	79.4	91.3	218	319
	NDC	28.6	43.1	58.4	72.1	79.6	204	278
	2 °C	28.6	43.3	59.2	75.3	85	207	297
	1.5 °C	28.6	43.4	59	73.1	76.5	206	267
CO_2/GDP		**MT CO_2/billion US$2010**						
	BAU	2000	1377	1173	689	582	59	29
	NDC	2000	1376	1030	576	467	51	23
	2 °C	2000	1372	923	455	313	46	16
	1.5 °C	2000	1365	896	376	221	45	11
CO_2/capita		**t CO_2/capita**						
	BAU	1.5	2.1	2.7	3.1	3.4	180	224
	NDC	1.5	2.1	2.4	2.6	2.7	158	180
	2 °C	1.5	2.1	2.1	2.1	1.8	142	121
	1.5 °C	1.5	2.1	2.1	1.7	1.3	137	85
CO_2/energy		**MT CO_2/EJ**						
	BAU	62.8	66.7	65.8	65.1	64.4	105	102

[50] Notes: GDP = gross domestic product in purchasing power parity; C & S America = Central and South America. Sources: IEA analysis based on UNDESA (2019); Oxford Economics (2020); IMF (2020a, 2020b)

[51] Notes: GDP = gross domestic product in purchasing power parity; C & S America = Central and South America. Sources: IEA analysis based on UNDESA (2019); Oxford Economics (2020); IMF (2020a, 2020b)

	NDC	62.8	67	61.7	59.9	59.3	98	94
	2 °C	62.8	66.6	54.6	45.3	37.2	87	59
	1.5 °C	62.8	66	53.2	38.6	29.1	85	46

The modeling framework comprised of utilizing some of the below formulae.

FORMULAE:

1. **Long term cement demand growth rate** = 1.2 × GDP Growth Rate

   Cement Demand = 1.09 × Industry Growth Rate

2. **Kaya Formula for calculating total CO_2 emissions from the economy:**

$$CO_2 = Pop \times \frac{GDP}{Pop} \times \frac{Energy}{GDP} \times \frac{CO_2}{Energy}$$

3. **Cement Industry CO_2 Emissions:**

$$CO_2 \text{ Cement} = Pop \times \frac{GDP}{Pop} \times \frac{cement\ consumption}{GDP} \times \frac{Energy\ consumption\ in\ cement\ manufacturing}{Tonnes\ of\ cement\ production} \times \frac{CO_2\ emissions}{Energy\ consumption\ in\ cement\ manufacturing}$$

$$CO_2 \text{ Cement} = (Pop) \times (\frac{GDP}{Pop}) \times (\frac{cement\ consumption}{GDP}) \times (Energy\ intensity\ of\ cement) \times (Emissions\ intensity\ of\ cement)$$

$$\text{Energy Intensity} = \frac{Energy\ consumption\ in\ cement\ manufacturing}{Tonnes\ of\ cement\ production}$$

$$\text{Emissions Intensity} = \frac{tonnes\ of\ CO_2\ emissions}{Energy\ consumption\ in\ cement\ manufacturing}$$

4. **Total emissions for each cement demand**:

   Total Industry CO_2 emissions = Cement Demand X Emission Intensity of cement

5. **Calculation of Cement Demand in India**:

   Cement Demand = A + B + C, where,

A = Demand from housing due to population growth + Urbanization + Nuclearization + Government schemes

B = Conversion from Semi-pucca to pucca houses

C = Demand from repairs, maintenance, expansion of existing stocks

6. **Cement Demand per rural house assumptions**:

- **Cement per house:** 25 kg of cement per sq. ft., i.e., 15,000 kg cement per house, or 15 Tonnes
- **Converting semi-pucca house to pucca:** 19 kgs per sq. ft., i.e. 10,800 kg cement per house, or 10.8 Tonnes of cement per house. [26, p. 21]

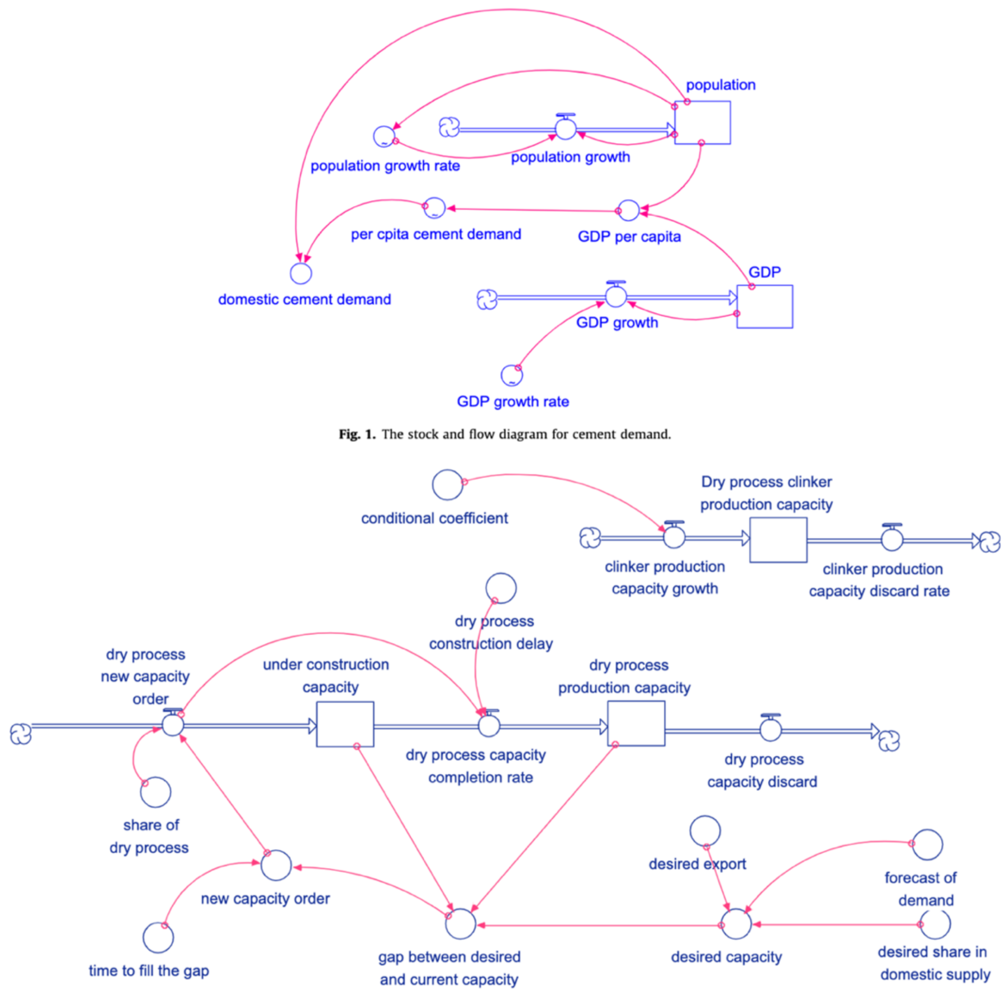

Figure 46: The stock and flow diagram for cement production capacity [68, p. 4]

Figure 46 shows an example stock and flow diagram for cement production and the influence of GDP and population growth, growth rates that can affect the overall cement industry, which was useful in guiding the macro-economic model.

India's GDP growth rate (2019-2040) = 5.4% annually

4.2 Constraints

Constraints and influences for low-carbon cements:

The model inputs included adding constraints for raw materials based on their availability. Each of the raw materials for low-carbon cement also has its own constraints such as energy and emissions intensity. There are also constraints in terms of ideal proportions needed at the industry level at any given time to ensure that there is a required cement supply by type for all types of cement applications, the analysis of which is not in the scope of this study. It is important to note the influence of a subsystem on the overall system. For instance, a tradeoff for using alternate green cements is the slightly reduced rate of recarbonation in those cements than conventional cement. Constraints also are present such as how soon the technology readiness level increases for these new cements and their current advancement from pilot tests, regulations, and incorporation in standards. Another constraint is whether or not they can use existing cement facilities to produce low-carbon cement. Other qualitative constraints include understanding the use cases of the innovative and new cement(s) application, presence of a guidance or reference material on properties, application and use, setting times, hardness, etc., and integrating them rapidly into design standards for use.

Constraints and influences for alternative fuels:

Because industrial wastes, municipal solid wastes, biomass, tyres, paints, and solvents, etc. are wastes that are finding use in the cement industry in a circular economy as alternative low-carbon kiln fuels, the availability of these materials as fuels is dependent on factors such as industrial production and waste generated from those respective industries. The usage of fuels is dependent on factors such as the ability of cement companies to efficiently adopt alternative fuels for coprocessing, and their handling and availability of storage on site, and timely supply of such fuels. For the analysis of alternatives, a fixed availability was chosen, which represented the tonne per year availability constraints for alternative fuels from literature (Table 61). For a more accurate representation, an integrative model with systems boundary extending to include other industries and activities of waste generation is helpful. The presence of competing industries in the circular economy could also pose a challenge. Therefore, it is helpful to know the other industry use cases and demands for waste. These factors were outside the scope of this thesis analysis but can be included in an extended system boundary in the future.

Table 61: Alternative fuel availability constraints

Alternative Fuel	Total availability (million tpy)	Percentage of total availability considered (%)	Availability for coprocessing (million tpy)	Source
Surplus Biomass	150	10	14.6	[69]
RDF from MSW	6.88	20	1.37	[69]
Used Tyres	0.83	50	0.4	[69]
Hazardous Waste	0.54	75	0.4	[69]
Industrial Plastic Waste	0.2	50	0.1	[69]

Constraints and influences for cement industry logistics:

The energy and emissions intensity contribution of cement freight varies based on distances traveled, modes of transport, % transported across each mode - rail, truck vs. ship, and capacities for each of these factors. It includes demand & production, and import & export dynamics. Each truck capacity has different fuel ratings for mileage and thus fuel consumed. Logistics also depend on freight demand at any given time. Other factors include the following:

- Coal demand, Quantity of coal transported, Distance to mine or stockpiles, Coal transport percentages via road, rail, ship
- Fuel economy and pricing, availability of low-cost high-efficiency fuels in future for trucks
- Alternative fuels and raw materials logistics – availability, distance to the cement plant, type, handling, storage on site
- Cement raw materials, i.e., Limestone or geopolymers or calcined clays, bauxite, shale, etc. and their distance from raw materials to processing plants, transport methods, storage on site
- Load factor, weight, and capacity constraints
- Direct to customer vs. Cement plant to bulk cement terminal (BCT) network distribution

- Multi-modal methods (Rail, Road, Ship) and % of cement and distances of each method
- Percent of cement transported by Rail, Road, and Ship
- Geographical location to ports, cities, etc.
- Bulk cement suppliers vs. bagged shipping of cement to project sites
- Industrialized concrete vs. preparation on site
- Transporting clinker vs. Transporting cement
- Limitations such as capital-intensive railway capacity expansion

A sample set of cement logistics from a typical plant are chosen as the base case (Table 62).

Table 62: Logistics assumptions for a cement plant

Raw Material	Source	Logistics	Distances	Storage on Site
Limestone	From adjacent captive limestone mines	Covered conveyor belt	0.05 km	12000 TPD
Bauxite	Nearby Districts	Truck/Rail	100 km	300 TPD
Iron Ore	Nearby Districts	Truck/Rail	130 km	150 TPD
Gypsum	Nearby Districts	Truck/Rail	1000 km	330 TPD
Fly Ash	Generation from CPP	Closed Conveyor Belt	0.05 km	900 TPD
Fly Ash	CPP purchase from thermal power plants nearby	Closed Tankers	200-300 km	900 TPD
Coal	Coal from nearby coal mine for clinker	Truck/Rail	375 km	300 TPD
Coal	Coal for CPP	Truck/Rail	250 km	650 TPD
Petcoke	Pet Coke for clinker from a nearby refinery	Rail	1200 km	660 TPD

Table 63: Freight transport by fuel projections (2010-2050)

Freight Transport	2010	2050	Source
Liquid FF	93%	68%	[66, p. 13]
Gas	7%	25%	[66, p. 13]
Electricity + Hydrogen	1%	9%	[66, p. 13]

Various nodes in cement manufacturing include integrated cement plant, clinker kiln, grinding unit, blending unit, waste fuels sourcing industry, power plant, steel plant, and limestone, bauxite and shale quarries and material flows across each of those nodes. There is also energy consumed at each node for procession or during the transport of these fuels and by mode of transport. Also, each of the materials transported and consumed during transportation have logistics and supply chain constraints, energy needs and emissions intensity, which can benefit from further analysis to lower emissions and cost intensity.

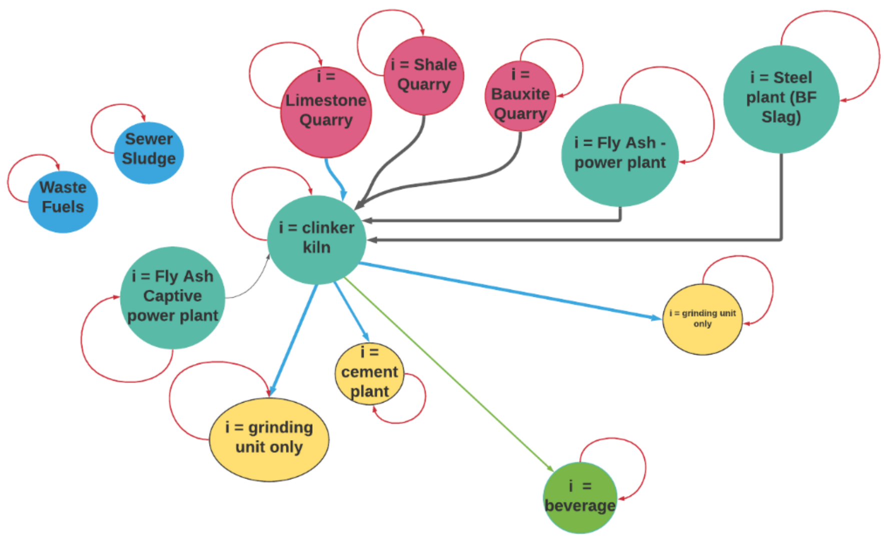

Figure 47: Various nodes in cement manufacturing and their processing loops and flows

Solving using optimization: The system boundary is critical in understanding the decarbonization pathways genuinely available. If we consider including other alternative binders, we must bring them within the system boundary and evaluate the constraints present in the wider boundary. For instance, if we consider alternative binders for cement production, such as those listed in Table 37, it is essential to identify the constraints for those cements. It will require us to expand the system boundary to understand the constraints of integrating those novel binders into the current system and to be able to use them effectively for decarbonizing the cement industry. An optimization model is helpful when many cement types are present with their own CO_2 emissions intensity profile and ranges of potential raw material reserves, applicability, etc. Table 64 shows an optimization setup that was prepared to evaluate the CO_2 emission intensity reduction potential through the use of green cements in India. The total % mix was considered 100%, and in this scenario, the geopolymers were set to > 10% and < 40%, and LC^3 was also set to increase to a range of >10% of total cement mix to <40% of the total cement mix. For this scenario, we considered achieving a target value of emission intensity (for instance, the 0.35 tonne of CO_2 per tonne of cement for the year 2050 lever in the IEA 2DS low-cement demand scenario). We can set the optimization model to achieve this target solution based on the constraints we set for the system. If all the conditions and constraints of the system are satisfied and there lies a solution, the optimization solver presents that solution. If a solution does not exist, we run against a minimum rather than a target value and identify the decarbonization potential. The optimization scenarios were carried out using the built-in Solver function in Microsoft Excel where scenarios comprised of variables and constraints and were optimized for a target result (Figure 48). Where a solution was found, it was documented as a decarbonization scenario and summarized to document results. At this stage, the scenarios were descoped to include a few optimization scenarios for limiting it to evaluating decarbonization potential of alternative fuels and alternative cement binders.

Table 64: Optimization constraints for alternate binding materials in cement industry level

Factor	Example Value	Constraint
% Mix	100.0	100
EF tonne of CO_2/ T Cement	0.37	0.37
OPC % Mix	20.4	≥ 20
PPC % Mix	20.2	≤ 64
PPC % Mix	20.2	≥ 20
PSC % Mix	10.0	≤ 10
Belite Rich Portland Cement % Mix	0.3	≤ 3
BYF/CSA % Mix	0.0	0
LC^3 % Mix	10.2	≤ 40
LC^3 % Mix	10.2	≥ 10
Composite Cements % Mix	0.1	≤ 10
Geo-polymer Concrete % Mix	38.6	≤ 40
Geo-polymer Concrete % Mix	38.6	≥ 10
MOMS# % Mix	0.0	0

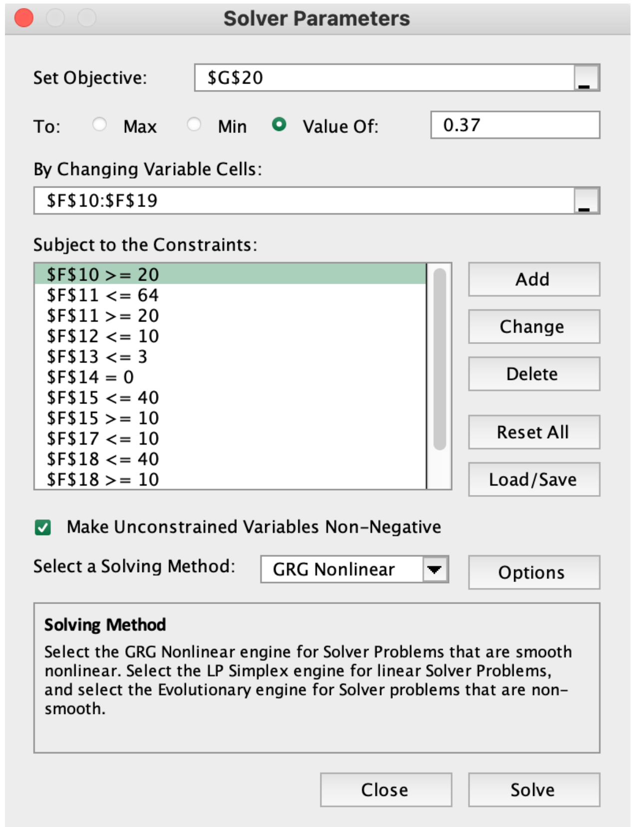

Figure 48: Excel solver optimization setup variable and constraints for an example scenario

Climate concerns:

Without effective decarbonization, cumulative pollution levels will continue to rise, resulting in additional problems. For instance, more than a million people die due to health consequences arising from outdoor air pollution due to stroke, heart disease, lung cancer, and chronic respiratory diseases in India. There is an attributable death rate and average annual monetary losses due to air pollution (Table 65).

Table 65: Pollution related factors that result in deaths and annual losses

Climate-related factors	Value	Source
Death rate attributed to air pollution – India	1.84 per 1000 people	[65, p. 2]; WHO, 2018
Death rate attributed to air pollution – G20 nations	0.1-1.1 per 1000 people	[65, p. 2]; WHO, 2018
Annual weather-related fatalities	0.25 per 100,000 people	[65, p. 3] Germanwatch, 2019
Annual average losses (USD million PPP)	14,009	[65, p. 3] Germanwatch, 2019

There are climate influences present that affect the quality of life for each of the 1.5ºC, 2ºC, and 3ºC (i.e., 1.5 DS, 2DS, and 3DS) rise in global temperatures. Each of the 1.5DS, 2DS, and 3DS scenarios can impact the world we live in, in various ways. In Table 66, a score was provided for each factor to assign a value with low – 1 to high risk – 5, and the scores can help understand the impacts, many irreversible. This awareness is essential for all industry players and stakeholders to work towards decarbonizing the sector.

Climate Influences:

Table 66: Assigning scores to understand 1.5ºC, 2ºC, 3ºC climate change impacts [65, p. 3]

Climate	Impact	1.5 ºC	2 ºC	3 ºC	Total Score
Water	% of area with increase in water scarcity	1	2	3	6
Water	% of time in drought conditions	1	1	1	3
Heat and Health	Heatwave frequency	2	3	5	10
Heat and Health	Days above 35 ºC	5	5	5	15
Agriculture - Maize	Reduction in crop duration	1	1	2	4
Agriculture - Maize	Hot spell frequency	3	3	4	10
Agriculture - Maize	Reduction in rainfall	5	5	5	15
Agriculture - Rice	Reduction in crop duration	1	3	4	8
Agriculture - Rice	Hot spell frequency	5	5	5	15
Agriculture - Rice	Reduction in rainfall	1	1	2	4
Agriculture - Wheat	Reduction in crop duration	1	1	2	4
Agriculture - Wheat	Hot spell frequency	5	5	5	15
Agriculture - Wheat	Reduction in rainfall	1	1	2	4
Total score		32	36	45	**113**

Individual Score: Very Low – 1; Low – 2; Medium – 3; High – 4; Very High – 5

Total Score: Low risk: 39 -78; Moderate risk: 79-117; High risk: 118-130; Very High: >130

1.5 ºC, 2 ºC and 3 ºC climate scores: Low risk: 13-26; Medium risk: 14-29; High risk: >29

The scenarios prepared, i.e., RTS, IEA 1.5, 2DS and 6DS (See Table 67, Table 68, Table 69) and net-zero (Table 70) will help to understand what not meeting climate goal indicators would mean when coupled with the frightful reality of climate impacts hinted in Table 66.

Table 67: IEA – RTS indicators in global cement industry

	Key Scenario Indicators	Actual	Actual	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
		Global - 2014	India (2014)	RTS - Global	RTS - Global	RTS - Global	RTS - Global	RTS - Global	RTS - Global
Factors	Year	2014	2014	2030	2040	2050	2030	2040	2050
Economic	Production (Mt)	4171	217	4250	4429	4682	4250	4429	4682
Technology	Clinker-to-cement Ratio	0.65	0.74	0.66	0.67	0.66	0.64	0.63	0.6
Technology	Thermal Intensity of clinker production (kcal/kg clinker)	837	725	813	789	765	789	765	741
Technology	Electric Intensity of cement production (kWh/t cement)	91	80	89	86	82	87	83	79
Technology	Share of Alternate Fuel Use (%)	5.6	0.6	10.9	14.4	17.5	17.5	25.1	30
Technology	CO_2 Captured (Mt CO_2/ yr)	0	0	7	65	83	14	173	552
Economic	Per-Capita Consumption (kg/capita)		188						
Economic	Population								
	Energy Use (Mtoe)								
	Source			1	1,2	1,2	1,2	1,2	1,2

- Sources: 1 - [51]; 2 - [19, p. 15], 3 - [53, p. 4], 4 - [52, p. 10]

Table 68: IEA 2ºC indicators for low vs. high demand projections for Indian cement industry

	Key Scenario Indicators	Actual	Actual	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
		Global - 2014	India (2014)	2DS - Low Demand - India	2DS - Low Demand - India	2DS - Low Demand - India	2DS - high demand - India	2DS - high demand - India	2DS - high demand - India
Factors	Year	2014	2014	2020	2030	2050	2020	2030	2050
Economic	Production (Mt)	4171	217	416	598	780	492	848	1361
Technology	Clinker-to-cement Ratio	0.65	0.74	0.7	0.64	0.58	0.7	0.64	0.58
Technology	Thermal Intensity of clinker production (kcal/kg clinker)	837	725	709	694	680	703	690	678
Technology	Electric Intensity of cement production (kWh/t cement)	91	80	76	73	71	75	72	70
Technology	Share of Alternate Fuel Use (%)	5.6	0.6	5	19	25	5	19	25
Technology	CO_2 Captured (Mt CO_2/ yr)	0	0	0	0	86	0	0	171
Economic	Per-Capita Consumption (kg/capita)		188	309	400	467	364	565	812
Economic	Population								
	Energy Use (Mtoe)								
	Source			1,2	1,2	1,2	1,2	1,2	1,2

- Sources: 1 - [51]; 2 - [19, p. 15], 3 - [53, p. 4], 4 - [52, p. 10]

Table 69: IEA 1.5ºC indicators for Indian cement industry for low vs. high demand

	Key Scenario Indicators	Actual	Actual	Scenario 13	Scenario 14	Scenario 15	Scenario 16	Scenario 17	Scenario 18	Scenario 19	Scenario 20
		Global - 2014	India (2014)	1.5DS - Low Demand - India	1.5DS - Low Demand - India	1.5DS - High Demand - India	1.5DS - High Demand - India	Blue Low Demand - India	Blue Low Demand - India	Blue High Demand - India	Blue High Demand - India
Factors	Year	2014	2014	2030	2050	2030	2050	2030	2050	2030	2050
Economic	Production (Mt)	4171	217	416	598	780	492				
Technology	Clinker-to-cement Ratio	0.65	0.74					0.73	0.71	0.72	0.72
Technology	Thermal Intensity of clinker production (kcal/kg clinker)	837	725								
Technology	Electric Intensity of cement production (kWh/t cement)	91	80								
Technology	Share of Alternate Fuel Use (%)	5.6	0.6					23%	33%	27%	35%
Technology	CO_2 Captured (Mt CO_2/ yr)	0	0					23.7	99.8	28.8	173.1
Economic	Per-Capita Consumption (kg/capita)		188	309	400	467	364				
Economic	Population										
	Energy Use (Mtoe)							29.9	47.4	33.6	60.1
	Source			4	4	4	4	3	3	3	3

- Sources: 1 - [51]; 2 - [19, p. 15], 3 - [53, p. 4], 4 - [52, p. 10]

Table 70: Global path to net-zero in cement industry for 1.5ºC [52, p. 10]

	Type of Lever	Description	% of savings	Emissions Savings	Unit
1	CCUS	Capture at cement plants	36%	1370	$MTCO_2$
2	Efficiency in design and construction	Design optimization, construction site efficiencies, re-use, and	22%	840	$MTCO_2$

		extension of the useful life of buildings			
3	Concrete efficiency	Optimized mix design; Optimization of constituents in concrete production, industrialize manufacturing, quality control	11%	430	$MTCO_2$
4	Clinker production efficiency	Alternative fuels, thermal efficiency, decarbonated raw materials and hydrogen fuel	11%	410	$MTCO_2$
5	Cement and Clinker Substitutes	Portland clinker cement substitutes, i.e., clinker binder ratio; Alternatives to Portland clinker cements	9%	350	$MTCO_2$
6	Recarbonization	Natural uptake of CO_2 in concrete as a carbon sink	6%	240	$MTCO_2$
7	Decarbonization of Electricity	Lower electricity emission intensity at cement plants and concrete production	5%	190	$MTCO_2$
			100%	**3830**	$MTCO_2$

The macro-economic model was used to understand the climate-based scenarios as well as the dynamics of the GDP and population on cement demand. (Figure 49)

Scenario - Climate + Economy recovery	**1.5DS STEPS**
Population	**Low Growth**
GDP Scenario	GDP 1.5DS STEPS
Energy Scenario	ENERGY 1.5DS STEPS
CO_2 Scenario	CO2 1.5DS STEPS

LEGEND

ACTION	CELL COLOR	COMMENT
Do not edit		These cells do not require user input
User Input		These cells require user inputs, either from drop-down lists, or require manual entry where there is no dropdown
Output value		These are output cells, such as emissions intensity - direct vs. indirect emissions
Referenced value		

Category	Unit	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Population Low Growth	CAGR %	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
Population Low Growth	Million	1201	1213	1225	1237	1250	1262	1275	1288	1301	1314	1327	1340	1353	1367	1381	1394
GDP 1.5DS STEPS	CAGR %	6.6%	6.6%	6.6%	6.6%	6.6%	6.6%	6.6%	6.6%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	4.5%	5.7%
Cement Demand Growth Rate (=1.2 X GDP) high	CAGR %	8%	8%	8%	8%	8%	8%	8%	8%	5%	5%	5%	5%	5%	5%	5%	7%
Cement Demand Growth Rate (=0.7 X GDP) low	CAGR %	5%	5%	5%	5%	5%	5%	5%	5%	3%	3%	3%	3%	3%	3%	3%	4%
GDP 1.5DS STEPS	Trillion US$ 2010	1.71	1.82	1.94	2.07	2.21	2.35	2.51	2.67	2.85	2.98	3.11	3.25	3.4	3.55	3.71	3.88
GDP/ POP	Trillion US$/ Million people	0.0014	0.0015	0.0016	0.0017	0.0018	0.0019	0.0020	0.0021	0.0022	0.0023	0.0023	0.0024	0.0025	0.0026	0.0027	0.0028
ENERGY 1.5DS STEPS	CAGR %	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	0.62%	0.62%	0.62%	0.62%	0.62%	0.62%
ENERGY 1.5DS STEPS	Exa Joules (EJ)	28.6	29.6	30.6	31.7	32.8	33.9	35.1	36.3	37.6	38.9	40.3	40.5	40.8	41.0	41.3	41.5
Energy/ GDP in Scenario: 1.5DS STEPS	Exa Joules (EJ)/ Trillion US$	16.7	16.3	15.8	15.3	14.9	14.4	14.0	13.6	13.2	13.1	12.9	12.5	12.0	11.6	11.1	10.7
CO2 1.5DS STEPS	CAGR %	3.72%	3.72%	3.72%	3.72%	3.72%	3.72%	3.72%	3.72%	3.72%	3.72%	-0.37%	-0.37%	-0.37%	-0.37%	-0.37%	-0.37%
CO2 1.5DS STEPS	GT CO_2	1.80	1.87	1.94	2.01	2.08	2.16	2.24	2.32	2.41	2.50	2.59	2.58	2.57	2.56	2.55	2.55
CO2/ENERGY in Scenario: 1.5DS STEPS	MT CO_2/ EJ	62.9	63.1	63.2	63.4	63.5	63.7	63.8	64.0	64.1	64.2	64.4	63.8	63.1	62.5	61.9	61.3
Cumulative Emissions for Scenario 1.5DS STEPS	GT CO_2	**1.80**	**3.67**	**5.60**	**7.61**	**9.69**	**11.85**	**14.10**	**16.42**	**18.83**	**21.33**	**23.92**	**26.51**	**29.08**	**31.64**	**34.20**	**36.74**
Cement (high demand)	MTPA	206.6	216	230.49	248.23	255.83	270.04	283.46	279.81	297.56	337.32	247.43	294	310	327	344	363
Cement (low demand)	MTPA	206.6	216	230.49	248.23	255.83	270.04	283.46	279.81	297.56	337.32	247.43	294	303	313	323	333
Per-Capita Cement Consumption (High Cement	Tonne per year/Person	0.172	0.178	0.188	0.201	0.205	0.214	0.222	0.217	0.229	0.257	0.187	0.219	0.229	0.239	0.249	0.260
Per-Capita Cement Consumption (High Cement	Tonne per year/Person	0.172	0.178	0.188	0.201	0.205	0.214	0.222	0.217	0.229	0.257	0.187	0.219	0.224	0.229	0.234	0.239
Cement Growth Rate - another estimate	CAGR %																

2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037
1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
1394	1408	1422	1437	1451	1465	1480	1495	1510	1525	1540	1556	1571
5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%
7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
3.88	4.1	4.33	4.58	4.84	5.12	5.41	5.71	6.04	6.38	6.75	7.13	7.54
0.0028	0.0029	0.0030	0.0032	0.0033	0.0035	0.0037	0.0038	0.0040	0.0042	0.0044	0.0046	0.0048
0.62%	0.62%	0.62%	0.62%	0.62%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%
41.5	41.8	42.0	42.3	42.6	42.8	43.4	44.1	44.7	45.4	46.0	46.7	47.3
10.7	10.2	9.7	9.2	8.8	8.4	8.0	7.7	7.4	7.1	6.8	6.5	6.3
-0.37%	-0.37%	-0.37%	-0.37%	-0.37%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%
2.55	2.54	2.53	2.52	2.51	2.50	2.43	2.36	2.29	2.23	2.16	2.10	2.04
61.3	60.7	60.1	59.5	58.9	58.3	55.9	53.5	51.3	49.1	47.0	45.0	43.1
36.74	**39.28**	**41.81**	**44.32**	**46.83**	**49.33**	**51.76**	**54.12**	**56.41**	**58.64**	**60.80**	**62.90**	**64.94**
363	388	414	442	473	505	540	577	616	658	703	751	803
333	346	360	374	389	405	421	438	455	473	492	512	532
0.260	0.275	0.291	0.308	0.326	0.345	0.365	0.386	0.408	0.432	0.457	0.483	0.511
0.239	0.246	0.253	0.261	0.268	0.276	0.284	0.293	0.301	0.310	0.320	0.329	0.339

2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
1587	1603	1619	1635	1651	1668	1684	1701	1718	1736	1753	1770	1788
5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	5.7%	6.0%	5.7%
7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
7.97	8.42	8.9	9.41	9.95	10.52	11.11	11.75	12.42	13.13	13.87	14.66	15.54
0.0050	0.0053	0.0055	0.0058	0.0060	0.0063	0.0066	0.0069	0.0072	0.0076	0.0079	0.0083	0.0087
1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%	1.44%
48.0	48.7	49.4	50.1	50.8	51.6	52.3	53.1	53.8	54.6	55.4	56.2	57.0
6.0	5.8	5.5	5.3	5.1	4.9	4.7	4.5	4.3	4.2	4.0	3.8	3.7
-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%	-2.84%
1.98	1.93	1.87	1.82	1.77	1.72	1.67	1.62	1.58	1.53	1.49	1.45	1.41
41.3	39.6	37.9	36.3	34.8	33.3	31.9	30.6	29.3	28.1	26.9	25.7	24.7
66.93	**68.86**	**70.73**	**72.55**	**74.32**	**76.04**	**77.71**	**79.33**	**80.91**	**82.44**	**83.93**	**85.38**	**86.78**
858	916	979	1046	1117	1194	1275	1363	1456	1555	1662	1776	1903
553	576	599	622	647	673	700	728	757	787	819	851	887
0.540	0.572	0.605	0.640	0.677	0.716	0.757	0.801	0.847	0.896	0.948	1.003	1.064
0.349	0.359	0.370	0.381	0.392	0.404	0.416	0.428	0.440	0.454	0.467	0.481	0.496

Figure 49: Macro-economic model for India

Table 71: Per-capita cement consumption projections

Sector	2019	2030	Source
Per-Capita cement consumption	235	400-565 kg	[19, p. 15]
Per-Capita steel consumption*	74	160 kg	[12, p. 16]; National Steel Policy (NSP)

The National Steel Policy (NSP) launched in 2017 aims at achieving 100% indigenous fulfillment of the demand for high-grade automotive steel, electrical steel, special steels and alloys. The cement industry uses nearly all of its granulated slag and is the largest consumer of fly ash. There is a constraint on the amount of slag or fly ash available now and in the future. Due to this, the production of PSC and composite cements has limitations in instances of significant demand and the future growth of the cement industry. Using built-in Excel Solver tool, alternative clinkers such as calcined clay and other low-carbon cements were assessed to solve this as an optimization problem.

After running a few optimizations scenarios for alternate cements and alternative fuels, the final step involved calculating total annual CO_2 emissions for select scenarios and further calculating cumulative CO_2 emissions from 2020 to 2050. The idea was to understand benefits of early adoption of green cements to meet carbon targets and enable the smaller stakeholders to survive the business impacts of climate change.

The non-availability of industrial byproducts in certain regions is a constraint for India as these byproducts are located only in specific regions, and transportation is expensive and emission intensive. To limit the broad scope of the research, the logistics optimization was considered to be included as part of future study and some optimizations discussed in the methods were descoped to limit to the possibility of the time-frame for this thesis study. The method can still be applied to conduct more optimizations and obtain results. Although it is not within the limited scope of this thesis to consider all possible extended system boundaries, it is the hope that this research can be integrated with the efforts of other researchers to enlarge the scope and identify the decarbonization pathways for the Indian cement industry.

5 Results

In a business-as-usual situation in India, high cement production over the next few decades will result in huge amounts of CO_2 emissions. With ever-increasing capital and operational costs due to escalating land costs, rising raw materials prices, limited availability of cement grade limestone and high-grade fuel, and rising transport and fuel expenses, it will significantly impair the Indian cement industry from being able to allocate funds towards green investments. Decarbonization levers such as WHRS, Carbon Capture systems, or other novel technologies like concentrated solar as kiln fuel require upfront investments.

When a carbon tax is imposed in the future, it will hurt many traditional Indian cement companies that were unable to prioritize decarbonization efforts due to lack of funds. Moreover, there aren't any policies in place to provide favorable economics or incentives for decarbonizing the Indian industry. Given that many traditional and small players may not even be in a position to adopt CCS when it becomes a mature technology, the industry needs to look at alternative methods of decarbonization. This is where optimization can be beneficial. Optimization, as defined in the Oxford dictionary refers to the action of making the best or most effective use of a situation or resource. The goal was to identify through optimization, three key areas to lower emission intensity and strategize the decarbonization transition of Indian cement industry. The results emphasized on the following optimizations:

- **Optimization of plant level cement model** such as grid factor, clinker factor, kiln system, % of moisture in fuels, % of alternative fuels mix, and overall kiln energy thermal substitution rate for lowering emission intensity of cement, i.e., tonne of CO_2 per tonne of cement.

- **Optimization of cement mix in the industry**, i.e., changing percentages of share of cement production by type and factoring in the individual energy and emissions intensity of each of the cement types and the availability of such cements in India for lowering emission intensity of cement, i.e., tonne of CO_2 per tonne of cement.

- **Optimization of industry wide decarbonization timeframes** to achieve climate goals and using carbon tax (low, mid and high level) as a cost reference.

Optimization of plant level model:

Figure 50 shows the tool prepared to conduct the plant level optimizations that factor in various model inputs and outputs. The results in

Table 74 show the summaries of scenario results of analysis of alternatives to achieve decarbonization at the plant level. Optimization was conducted for assessing analysis of alternative fuel types with varying moisture and energy and emissions factors and scenarios were also run against various grid factors, emissions factors and clinker factor. It was found that grid factor had least influence on the decarbonization pathway, however, the type and mix of alternative fuels and the clinker factor had a bigger influence. In the future, this modeling approach can be further developed to include a higher level of decomposition of the cement plant with more comprehensive levers to incorporate costs and complexity for handling, processing, and storage of raw materials and fuels that might affect the emissions or cost intensities.

LEGEND

ACTION	CELL CC	COMMENT
Do not edit		These cells do not require user input
User Input		These cells require user inputs, either from drop-down lists, or require manual entry where there is no dropdown
Output value		These are output cells, such as emissions intensity - direct vs. indirect emissions
Referenced value		

CEMENT PLANT MODEL

Plant Location State	*2019 Grid 0.725*			
Grid Intensity Factor	0.725	Kg CO_2/kWh		
1kWh	13.4	MJ/kWh		
Clinker Factor	*0.71*	Clinker % in Cement		
Kiln System	*5 stage preheater + precalciner*			
Raw Material Moisture	3%			
Clinker: OPC Clinker	*100%*			
Clinker: Belite Clinker	*0%*			
Compound: Lime from Limestone (CaO)	*0%*			
Compound: Wollastonite (CaSiO3)	*0%*			
	100%			
Heat required for clinker (GJ/tonne)	3.01	GJ/tonne of clinker		
Energy required for Clinker	3010	MJ/tonne of clinker		
Select Kiln Fuels	**Contributon of fuel (%)**	**Calorific Value of Fuel (MJ/tonne of fuel)**	**Quantity of Fuels (tonnes of fuel/tonne of clinker)**	**Moisture Content of Fuels (%)**
Paint Sludge	*50%*	14644	0.1028	10.0
Petcoke - Imported	*0%*	33330	0.0000	0.0
Acceptable RDF (10-15% yield of RDF)	*0%*	10460	0.0000	20.0
Tyres	*0%*	27501	0.0000	1.0
Oil Sludge	*39%*	20920	0.0555	0.1
Rice husk	*0%*	13389	0.0000	10.0
Tyres	*0%*	27501	0.0000	1.0
Spent solvent	*11%*	20920	0.0164	10.0
Wet plastic waste - processed waste	*0%*	14644	0.0000	20.0
Paint Sludge	*0%*	14644	0.0000	10.0
Total Fuel %	100%			
Average moisture content in kiln fuels %	7%			
Total Direct Emmisions in Clinker	793.97	Kg CO_2/ T Clinker		
Total Indirect Emmisions in Clinker	47.89	Kg CO_2/ T Clinker		
Total Direct Emmisions in Cement	563.72	Kg CO_2/ T Cement		
Total Indirect Emmisions in Cement	57.82	Kg CO_2/ T Cement		
Total EI	621.54	Kg CO2/ T Cement		
Total EI	0.6215	T CO2/T Cem		

CLINKER MANUFACTURING

Up Stream

Manufacturing Stages	Energy Required (MJ/tonne of Clinker)	Fuel Type	Material needed (t of fuel)	Fuel EF (kg of CO_2/t of fuel)	EI (Kg of CO_2/T Clinker)
1. limestone extraction and transportation	89.89	*Diesel*	0.0021	6900	14.53
2. limestone crushing, stacking and reclaiming	15.00	2019 Grid 0.725		0.725	0.81
3. raw meal preparation	342.00	2019 Grid 0.725		0.725	18.50
3b. Raw meal moisture: 3%	210.00	*Indian Coal*	0.0082	2270	18.61
4. fuel Preparation	88.00	2019 Grid 0.725		0.725	4.76
5a. clinkerization Fuel 1: Paint Sludge	1,505.00	Paint Sludge	0.1028	981	100.82
5a. clinkerization Fuel 2: Petcoke - Imported	-	Petcoke - Imported	-	3060	0.00
5a. clinkerization Fuel 3: Acceptable RDF (10-15% yield of RDF)	-	Acceptable RDF (10-15% yield of RDF)	-	1000	0.00
5a. clinkerization Fuel 4: Tyres	-	Tyres	-	2237.5	0.00
5a. clinkerization Fuel 5: Oil Sludge	1,161.44	Oil Sludge	0.0555	1000	55.52
5a. clinkerization Fuel 6: Rice husk	-	Rice husk	-	1000	0.00
5a. clinkerization Fuel 7: Tyres	-	Tyres	-	2237.5	0.00
5a. clinkerization Fuel 8: Spent solvent	343.56	Spent solvent	0.0164	1000	16.42
5a. clinkerization Fuel 9: Wet plastic waste - processed waste	-	Wet plastic waste - processed waste	-	1000	0.00
5a. clinkerization Fuel 10: Paint Sludge	-	Paint Sludge	-	981	0.00
5a. Additional energy for moisture content of fuels: 6.9%	430.00	*Indian Coal*	0.01678466	2270	38.10
5b. Calcination Reaction - Clinker: OPC Clinker			1.0000	535.44	535.44
5b. Calcination Reaction - Clinker: Belite Clinker			-	0	
5b. Calcination Reaction - Compound: Lime from Limestone (CaO)			-	0	
5b. Calcination Reaction - Compound: Wollastonite (CaSiO3)			-	0	
5b. clinkerization, cooling and storing	420.38	2019 Grid 0.725		0.725	22.74
5c. clinkerization, cooling and storing	19.79	2019 Grid 0.725		0.725	1.07
6. Others	36.97	*Diesel*	0.0021	6900	14.53

Clinker manufacturing Direct process energy and emissions	3,010.00	Calcination only	535.44
Clinker manufacturing Direct Energy and Emissions	10,678.58		793.97
Clinker manufacturing Indirect Energy and Emissions	885.17	2019 Grid 0.725	47.89

CEMENT MAKING

Down Stream

Manufacturing Stages	Energy Required (MJ/T of Clinker)	Fuel Type	Fuel EF(T of CO_2/MJ)	EI (Kg of CO2/T Cement)
Cement Direct Energy and Emissions	**2,137.10**	**fraction of calcination only**		**380.16**
Cement Direct Energy and Emissions	**7,581.79**	**fraction of direct**		**563.7222193**
Cement Indirect Energy and Emissions	**628.47**	**fraction of indirect**		**34.00**
7. grinding of cement	384.05	2019 Grid 0.725	0.725	20.78
8. packing of cement	9.63	2019 Grid 0.725	0.725	0.52
9. services	46.57	2019 Grid 0.725	0.725	2.52

Cement manufacturing Direct process energy and emissions	2,137.10	cement	380.16
Cement manufacturing Direct Energy and Emissions	7,581.79	cement	563.72
Cement manufacturing Indirect Energy and Emissions	1,068.71	cement	57.82

Figure 50: Plant level model prepared for optimization of emissions intensity with variables such as grid factor, mix of fuels, Kiln System, TSR%, fuel energy density, moisture content

The scenarios were set up as noted in (Table 72). First, all else constant, Grid Factor was modified. Other scenarios comprised varying raw material moisture content, alternative fuel mixes, kiln efficiency, and overall cement mix variations, and a combination of some of these factors.

Table 72: Scenarios setup for plant level

	Unit	Base Scenario	Alt scenario 1	Alt Scenario 2	Alt Scenario 3	Alt Scenario 4	Alt Scenario 5
Grid Intensity Factor	**kg CO2/kWh**	0.725	Varying grid factor (all else constant)	Varying only clinker factor (all else constant)	Varying of raw material moisture content (all else constant)	Varying of alternative fuel mix (all else constant)	Varying of Grid intensity, Clinker factor, and Moisture content
Kiln System		4 stage pre-heater					
Raw Material Moisture	**%**	5%					
Clinker Factor	**%**	75%					
Clinker - portland clinker	**%**	100%					
Conventional fuel mix	**%**	35% Indian coal, 65% Petcoke, 5% RDF					
Alternative fuel mix	**%**	5%					
Average Moisture Content in kiln fuels		1%					

Grid Intensity Results: The scenario assumptions for grid intensity ratio included various scenarios of STEPS, SDS and IVC over the next few decades of switching to net-zero energy and renewable power. When only grid factor of electricity in a cement plant was analyzed across a range of scenarios, the model results were listed in Table 73. Since majority of the emissions in a cement plant are direct emissions, improving the grid intensity only lowered them from present case by 35.5 kg CO_2 per tonne of cement, i.e., 0.035 t CO_2/ t of cement.

Table 73: Results from electricity grid emissions intensity improvements

Grid Intensity Scenario	Total Direct Emissions in Cement ($kgCO_2$/ t of cement)	Total Indirect Emissions in Cement ($kgCO_2$/ t of cement)
2019 Grid 277.3	277.3	38.19
STEPS 2030 Grid 277.3	277.3	28.28
STEPS 2040 Grid 277.3	277.3	17.7
SDS 2030 Grid 277.3	277.3	16.8
SDS 2040 Grid 277.3	277.3	3.11
IVC 2030 Grid 277.3	277.3	23.65
IVC 2040 Grid 277.3	277.3	15.01
Grid 277.3	277.3	35.82
Grid 277.3	277.3	34.76
Grid 277.3	277.3	32.13
Grid 277.3	277.3	22.65
Grid 277.3	277.3	15.27
Grid 277.3	277.3	12.64
Grid 277.3	277.3	9.48
Grid 277.3	277.3	5.79
Grid 277.3	277.3	4.21
Grid 277.3	277.3	3.16
Grid 277.3	277.3	2.63

Analysis of Alternatives (AOA): Instead of evaluating once scenario at a time, the optimization modeling was used to conduct a scenario analysis (Table 74) and results were summarized. The scenarios considered 0% of petcoke in the conventional fuels mix. This constraint was used because India is looking to utilize domestic fuels instead of imported petcoke. For the scope of the study, a few alternative fuels were selected for the analysis of alternatives. Various ranges of thermal substitution rates were considered across each of the scenarios to conduct a parametric analysis. The moisture of these raw materials was factored in the calculations. The scenario results found that none of these low carbon alternative fuel substitutions even when combined with improved kiln efficiencies were able to achieve 0.35 t CO_2/ t cement needed for a 2DS scenario. Although in this calculation, the emissions from alternative fuels are included, in reality, the industry does not account the emissions from alternative fuels as these would have been incinerated or have been accounted as emissions elsewhere and would have otherwise been replaced by convectional coal in a cement plant. Even if we discount these emissions as per the scope, it still will leave us with considerable process emissions resulting from the very process of calcination of limestone-based raw materials. This is why the scenarios of cement types and the industry level cement mix were investigated to assess their emissions reduction opportunities.

Table 74: Optimization results of Analysis of Alternatives (AOA) in a cement plant

Scenario Summary	Current Values:	0 petcoke, 0.725 GF, CF - 0.64, 7% kiln fuel moisture, 6 stage preheater + precalciner	Grid - 0.725, CF 0.64, 60% Indian Coal, 0 petcoke, 40% TSR, 7% Moisture, 6 stage preheater + precalciner	Fully renewable grid, CF-0.64, 6 stage preheater + precalciner	0.05 low grid, 0.64 CF, 6-stage preheater + precalciner, 42% Indian coal, 58% TSR	Grid 0.725, CF 0.64, 5% moisture of fuels, 42% Indian Coal, 6 stage pre-heater + precalciner	GF- 0.725, CF - 0.718, 42% Indian coal, 68% TSR, 6 stage preheater + precalciner	GF - 0.725, CF - 0.718, Fuel Moisture 2%, TSR - 50%, 5 stage pre-heater + precalciner
Changing Cells:								
Clinker Factor	0.718	0.64	0.64	0.64	0.64	0.64	0.718	0.718
Indian Coal	50%	60%	60%	60%	42%	42%	42%	50%
Petcoke - Imported	0%	0%	0%	0%	0%	0%	0%	0%
Acceptable RDF (10-15% yield of RDF)	0%	5%	5%	5%	0%	0%	0%	0%
Tyres	0%	3%	3%	3%	0%	0%	0%	0%
Oil Sludge	39%	8%	8%	8%	31%	31%	31%	39%
Rice husk	0%	4%	4%	4%	3%	3%	3%	0%
Tyres	0%	3%	3%	3%	0%	0%	0%	0%
Spent solvent	11%	8%	8%	8%	13%	13%	13%	11%
Wet plastic waste - processed waste	0%	5%	5%	5%	5%	5%	5%	0%
Paint Sludge	0%	5%	5%	5%	6%	6%	6%	0%
Result Cells:								
Emission Intensity (T CO2/ T Cement)	0.6332	0.6053	0.6053	0.6053	0.5745	0.5745	0.6416	0.6332

Notes: Current Values column represents values of changing cells at time Scenario Summary Report was created. Changing cells for each scenario are highlighted in gray.

India's cement production per year	MTPA	320	457	584	711
Clinker Emission Intensity	tonnes of CO_2/tonne of clinker	0.742	0.718	0.718	0.621
Cement Emission Intensity	tonnes of CO_2/tonne of cement	0.52	0.46	0.46	0.36
Total Emissions from Cement Industry	tonnes of CO_2 per year	166	210	269	256
Cumulative Emissions from Cement Industry	tonnes of CO_2 per year	974	3028	5453	8390

Optimization of Cement Mix in the Industry: Optimization of cement mix in the industry, i.e., changing percentages of share of cement production by type and factoring in the individual energy and emissions intensity of each of the cement types and the availability of such cements in India for lowering emission intensity of cement, i.e., tonne of CO_2 per tonne of cement.

First, scenarios were run without constraints. When constraints were added, the results from optimization did not achieve a emission intensity of ≤ 0.35 t CO_2/ t of cement because the system problem was over-constrained. Since MOMS is not available in India, the optimization input it as a constraint and the optimizations were rerun and solutions obtained included 0.48 and 0.37 emissions intensities under different scenario constraints and mixes. The optimization identified a solution for a low OPC, PPC and PSC, but high Geo-polymer scenario (OPC: 21%, PPC: 20%, PSC: 10%, Geo: 39%) achieving an emission intensity of 0.37. Another scenario with a high PPC, low OPC, and low Geo-polymer (OPC: 20%, PPC: 64%, Geo: 16%) achieved an emission intensity of 0.48 tonne of CO_2 per tonne of cement.

Table 75: Scenario mixes of cement types and optimization solutions

		Scenario Mixes Outputs in Optimizaation								
	Current Values	OPC: 10%, PPC: 37%, PSC: 10%, Geo: 10%, MOMS*:10%	OPC: 75%, PPC: 25%,	OPC 29%, PPC 71%	OPC 10%, PPC 87%, MOMS*: 1.4%	OPC: 10%, PPC: 76%, Geo: 2%, MOMS*: 10%	OPC 10%, PPC 64%, PSC: 2% Geo: 9%, MOMS*: 15%	OPC: 19%, PPC: 41%, PSC: 10%, Geo: 10%, MOMS*: 10%	OPC: 20%, PPC: 64%; Geo: 16%	OPC: 21%, PPC: 20%; PSC: 10% Geo: 39%
Changing Cells:										
OPC	20.4	10.0	75.0	29.1	10.0	10.0	10.0	19.1	20.0	20.7
PPC	20.2	34.7	25.0	70.4	87.1	76.2	63.6	40.9	64.0	20.4
PSC	10.0	10.0	0.0	0.1	0.4	0.9	2.0	10.0	0.0	10.0
Belite Rich Portlar	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BYF/CSA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LC3	10.2	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.1
CCSC	0.2	5.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Composite Cements	0.1	10.0	0.0	0.1	0.2	0.3	0.4	10.0	0.0	0.0
Geo-polymer Concrete	38.6	10.0	0.0	0.1	0.7	2.2	9.0	10.0	16.0	38.7
MOMS#	0.0	15.0	0.0	0.1	1.4	10.3	15.0	10.0	0.0	0.0
EI Target ($T\ CO_2$/ T cement)	**0.37**	**0.36**	**0.65**	**0.55**	**0.50**	**0.45**	**0.40**	**0.40**	**0.48**	**0.37**

(red)	High Risk - Raw Material Unavailable in India
(orange)	Medium Risk in future when coal plants are ceased from production
(light yellow)	Moderate risk - Slag availability depends on I&S growth
(green)	Widely Available - Geopolymers and LC3, verify potential for others

* Not feasible due to MOMS not available in India

Based on scenarios analyzed, the lowest for just the cement type was 0.37 t CO_2/ t cement. Now, when this scenario is combined with reduction potential of grid emission intensity that we found earlier, which was 0.035 from the current grid intensity to best case scenario, the net emissions were

$$= 0.37 \text{ t } CO_2\text{/ t cement} – 0.035 \text{ t } CO_2\text{/ t cement} = 0.335 \text{ t } CO_2\text{/ t cement}$$

This is reflective of achieving a 2DS climate scenario. While the grid emissions factors are not going to suddenly improve to the best-case scenario, it is recommended that when a cement mix scenario is implemented along with a few other improvement factors, there is potential for meeting the decarbonization goals. The cement type mix was the most important emissions reduction opportunity from the results analysis of alternatives as it has the ability to reach close to the emissions reductions. Research has indicated that raw materials for geopolymer cements are widely available. Thus, further R&D should be allocated towards bringing these cements, especially the geopolymers into market.

6 Conclusions and Future Work

6.1.1 Discussion

Most cement manufactured in India is made out of Portland clinker, which is derived from the calcination of limestone ($CaCO_3$). The very process of calcination of limestone at high-temperature high-heat releases large amounts of CO_2 emissions (nearly two-thirds of direct emissions), making it a very hard-to-abate sector. To decarbonize the cement sector, IEA has suggested the incorporation of several decarbonization levers such as Waste Heat Recovery System and Carbon Capture which require high upfront capital investment. Unlike in China, where cement is state-owned and access to capital is easy, the same is not true for India, where 99% of companies are privately-owned and have to develop their own capital to invest in these decarbonization technologies. Major cement companies from around the globe with excess and low-cost capital are seizing this opportunity and already started entering the Indian cement industry through Foreign Direct Investment, as they are aware that India is next in line for the world's next cement boom.

The lack of access to capital for many Indian cement companies leaves them at risk of being bought out by other larger international companies or being shut down in the future due to environmental hazards. The future also presents an impending carbon tax and climate concerns that will make it more dismal to many traditional industry players. These cement industry stakeholders need to be presented with sustainable ways to produce cement and clinkers without being burdened by expensive technologies. Thus, the goal to decarbonize the cement industry must be a unified one met with collaboration of academia, industry, government, where all stakeholders need to come together to unify and share research, processes, methods and technologies, materials knowledge, and so forth with all players. Additionally, the research efforts must include alternative pathways than those currently described in the 2DS scenarios so that such players can decarbonize their production without high upfront investment costs or without being subject to a carbon tax in the future.

To mitigate climate change, this thesis proposes directing government funding towards improving the technology readiness levels (TRL) of low-investment costs, low-to-medium TRL non-high grade limestone materials, and incorporating them into standards. It also emphasizes expanding the system boundary to have a well-integrated space for arriving at decarbonization solutions in the circular economy. End users should receive as much guidance about the application, safety, processing, and use and integration with existing facilities and the raw materials' entire lifecycle. The government should present grants to universities to conduct such research to bring these materials into production. The industry must have a process for establishing alternative raw materials quickly so as to bring alternative materials to use quickly. Also, there should be a central continually updated database system for the industry to benefit from a real-time status update on production, physical and chemical properties, supply, demand, and availability of materials in a circular economy. Other levers comprise demand-side reduction of cement and concrete, such as adding additives and improving techniques to increase the longevity of the building and optimizing concrete production, as noted in Section 3.20. To prevent price-jacking of waste materials in circular economy, it will help to have policies and regulations for specifying and regulating pricing, and mandating diverting waste materials and industrial by-products for use as alternative fuels and alternative raw materials to facilitate a level-playing field of sourcing opportunities for all cement industry players, large or small.

Lastly, the cement industry policymakers should arrive at a consensus of the arriving at a system boundary in consultation with a wide range of experts and stakeholders. The scale and scope clarity are essential components of engineering systems design as the behavior of the system changes at different scales and scopes. It influences relationships of elements within the system, i.e., intrasystem, as well as contextual interfaces that are the external interfaces of the system within its context [70, p. 50]. The decarbonizing of the cement industry is a complex task, especially in a circular economy concept when there is an interplay of numerous factors and requires an understanding of scale and scope. We don't want solutions that suggest locating a cement plant near a railway station or a port for cost-effective transport. Instead, we want to expand the system boundary to be scoped and scaled appropriately for leading industry-wide decarbonization. Some alternative raw materials with a higher volume-to-weight or higher moisture content are more advantageous to have kilns located next to mines to lower transportation costs. Some raw materials are too heavy for long-distance transport. While designing these systems, are we considering the contextual interfaces, such as alternative raw materials or alternative fuels in a circular economy needed for our system to function, the spatial location of those raw materials, and their logistics problems? It is easy to say to locate plants near ports or rail for logistics optimization to end-users or low-cost shipping to end-users when only thinking in the context of conventional limestone-based clinker manufacturing. When processes change, the assumptions we make now may not be loyal to our needs in the future.

Further, in designing systems, it is essential to consider the social systems in addition to these technical and operational considerations. How broad the system boundary extends should be evaluated based on the extent of the scope and its impacts and risks. Will the boundary for decarbonization problem expand to only include adjacent boundaries across the value chain, i.e., transportation and logistics, or, will it also consider an even wider boundary for new issues that may arise, such as safety of logistics drivers and operators, what kind of training will they require if the system transitions to bulk cement operators and over long distances, or, what other competing use cases are present or may arise for alternative raw materials and fuels in a circular economy for meeting needs of cement industry in an ever-evolving landscape of materials, processes, and technologies. Circular economy will need a partially designed and partially evolved system to maintain flexibility that are suitable for a large-scale socio-technical system. [70, p. 141]

6.1.2 Future Work

The transportation costs in cement manufacturing have sky-rocketed in the past few years. There is huge need for identifying the optimization gap for emissions and cost intensity. The need for transportation optimization has been emphasized in the recent CMA report. [50, p. 10] Typically, plants are located near limestone mines. The use of alternate raw materials in a circular economy might change the desired spatial layout. While one of the goals in this CMA report has listed logistical optimization to locate cement plants near modes of transport like rail and ports, this requires further analysis of extending system boundary to consider other non-limestone based raw materials that have other needs, and other social and safety factors.

As an extension of the study, future work will include logistics of commodity flows and modes of transport for identifying emission intensity optimization gap based on analysis of spatial flows of commodities such as movement of raw materials, consumption of freight fuels, availability of raw materials, and supply and demand needs. Optimization can also be used to determine which architectures of cement distribution are more economical and present low risk in a circular economy. For example, Option 1 comprises a network of integrated cement plants (i.e., clinker & cement manufacturing facility at the same site) located near limestone mines. The finished product produced in these integrated plants is transported to networks of end users, or Option 2. Option 2 produces clinker in few clinker plants near mines, and transports clinker (instead of finished cement) to a network of clinker grinding and cement-blending units conveniently located near major consumption hubs, and dispatches the blended cements to the nearby end user.

Bulk vs. bagged shipping can also be explored in addition to industrialized concrete manufacturing for bulk use and feasibility of sourcing and adding additives. The optimization method will involve using a Generalized Multi-Commodity Network Flow (GMCNF) analysis approach to identify the optimization gap. Below are some of the logistical modes that can be used to further explore this concept.

Table 76: Transport modes, capacity, fuel & mileage

Mode	**Distance**	**Capacity (Tonnes)**	**Fuel**	**Mileage**
Trolley, Truck	Very short Distance	1 – 2	Diesel	8-10 km/litre
Trolley, Truck	Short Distance	6 – 10	Diesel	6-7 km/litre
Trolley, Truck – finished product	Long Distance – Low Load	15 - 25	Diesel	5 km/litre
Trolley, Truck – coal, clinker from one plant to grinding unit	Long Distance – High Load	35 - 40	Diesel	4-5 km/litre for 40 tonnes; or 0.005 litre/km/ton
Rail (60 containers/boogie) Bulk materials or packed cement	Long Distance	50 per container	Diesel	10 litre/km for 3000 tonnes or, 0.0033litre/km/ton

Note: Factors for truck size - Material density; current modes, ability for expansion
Note: 1 goods train – 60 containers × 50 tonnes per container = 3000 tonnes which is raw material for 1 MTPA of finished output

Table 77: Daily production capacity (Tonnes Per Day i.e., TPD) per plant type

Plant Type	**TPD per lines i.e., kiln**	**Year of setup**
Older plants - no vertical roller mill (vrm), only ball-mill grinders	1000	<1995
Mid plants - mix of vrm, ball mill and smaller hydraulic roller press (hrp)	3500	1995-2003
Modern plants - vrm, hrp	5000-8000	2003-2015
Ultra-Modern plants	10,000 – 12,000	>2015

Note: A plant may have more than 1 kiln

Further, as various policies affect different industries, an integrated view of different industries at the systems level is needed to put into perspective the relationships between different industries and policies made across industries. It is beneficial to incorporate policies that benefit multiple industries in the path to decarbonization.

6.1.3 Key Takeaways

There are numerous risks that are present in the Indian cement industry, such as the limited availability of high-quality limestone for cement production, energy security concerns, and emissions resulting from conventional cement manufacturing, which if not managed right away will present serious climate change concerns such as high-heat and hot spells. These will in turn have cascading effects such as food and water insecurity resulting from reduced crop durations in a nation that is already growing its population with rising needs for food and water. This makes it a governance issue which will also have global impacts.

Decarbonization of Indian cement industry is crucial for the nation to meet its climate goals due to its large share of emissions and projections for future cement demand. Effectively staying on track to lower cement industry emissions will require policy interventions, changes to existing technology, incorporating technology innovations, process emissions optimizations, improved environmental performance and resource management, and optimization of logistics and operations.

Without a robust energy security and emissions reductions strategy in place, India will face a huge crisis in the future if a high carbon price is employed. If there is a high carbon price, it will lower India’s share of production of cement, thereby affecting the Indian economy. Moreover, it will hurt many traditional Indian cement players who simply do not have access to capital for green investments like CCUS or WHRS. Since many traditional players are at risk of being bought out by other foreign cement companies investing in India at a rapid rate to capitalize from the upcoming cement boom, especially when there is a carbon tax, it should present sufficient motivation for the industry and government to support policies and funds to explore low-cost green cement options, lower material supply risks and to bring a greater share of alternate green cements to the market within the next five years. These traditional players must be provided with options to produce cement at reduced emissions without incurring major upfront investments. With some support and aid in terms of R&D, bringing these low-cost technologies to be ready for adoption as well as streamlining the process of alternate cements for all industry players, and incorporating their use cases into construction standards is crucial for enabling a path to decarbonization.

Strategies implemented on a larger scale have been found to improve sustainability and avoid exploitation of resources, such as of natural resources in places where there is more high-quality fuel and concentration of raw materials which leads to over-exploitation, and thus pose environmental degradation issues. This also results in overbidding of such high-quality resources and paying premiums greater than 125% of the typical costs of raw materials. This mismanaged and disproportionate allocation of funds is not sustainable for India’s decarbonization. The path to decarbonization is not an easy task. While lofty goals are often committed to, there exists a rhetoric gap and these targets are often not met. Considering some of these key concerns and gaps and evaluating as a system is critical to address climate change.

The climate change will impact the nation greatly and will have effects globally. A carbon tax is an added expense in addition to the already rising costs of land and freight transportation. While carbon tax is viewed as motivator for shift to green economy, when such taxes are imposed, it will hurt many traditional players who will risk shut downs or being acquired by foreign investors with access to low-cost capital to switch to green investments. Added to it, all the additional costs will be expected to be borne by the end user. This is why lowering emissions using low-cost technology and optimization to achieve it is crucial. The traditional cement industry stakeholders need to be presented with sustainable ways to produce cement and clinkers without being burdened by expensive technologies or major retrofits to existing plants. The green cement production will enable a low-cost transition towards decarbonization of the Indian cement industry. The challenge lies in funding research to increase technology readiness level (TRL) to bring to market quickly, and incorporate into design and construction standards. Circular economy is the cheapest way to lower emissions, but has its challenges. Solving the decarbonization problem in the cement industry will require expanding system boundary so as to include transportation and logistics, and diverting funds towards R&D for innovative cements and alternative raw materials.

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