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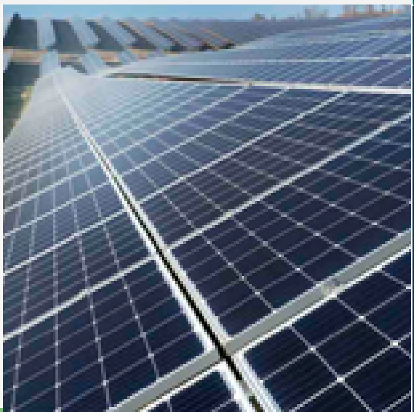
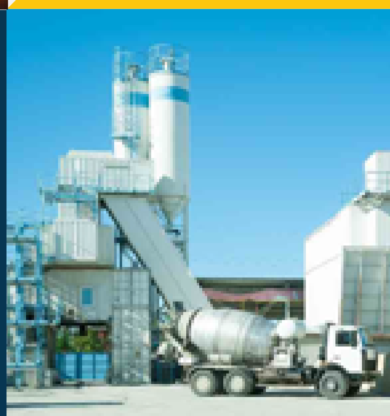
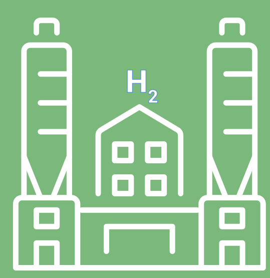
Green ways for a good earth!

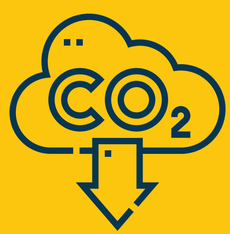
Exploring
Deep Electrification Pathways to Abate Emissions from Cement Manufacturing in India

April 2024









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About Vasudha Foundation

Vasudha Foundation is a non-profit organisation set up in 2010. We believe in the conservation of Vasudha, which in Sanskrit means the Earth, the giver of wealth, with the objective of promoting sustainable consumption of its bounties. Our mission is to promote environment-friendly, socially just and sustainable models of energy by focusing on renewable energy and energy-efficient technologies as well as sustainable lifestyle solutions. Through an innovative approach and data- driven analysis, creation of data repositories with cross-sectoral analysis, along with outreach to ensure resource conservation, we aim to help create a sustainable and inclusive future for India and Mother Earth.

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This report is based on the best available information in the public domain. Every attempt has been made to ensure the correctness of data. However, Vasudha Foundation does not guarantee the accuracy of the data or accept responsibility for the consequences of using the same.

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Executive Summary

The cement industry in India plays a pivotal role in economic growth and development, generating substantial revenues for both Central and State governments and offering numerous employment opportunities. Cement's importance lies in its fundamental role in construction and public infrastructure development. Despite India's per capita consumption of cement being lower than the global average, the sector is poised for significant growth due to government initiatives focusing on housing schemes, infrastructure development, and smart cities.

Globally, India ranks as the second-largest producer of cement after China, with an annual production capacity of 600 million tonnes in 2022-23. However, cement production is an emission-intensive process, making decarbonisation a pressing concern. The industry has made strides in energy efficiency through interventions like the Perform, Achieve, Trade (PAT) scheme, surpassing global efficiency standards.

This report primarily focuses on decarbonisation pathways within cement manufacturing, which constitutes about 95% of emissions. The main contributors to emissions include raw material processing, heat generation, and electricity production. The report focuses on green hydrogen integration, plasma generators powered by renewable electricity, and biomethane production.

Key findings reveal substantial potential for emissions reduction through these aforementioned technologies. For instance, the conventional method typically requires 842.61 kWh of energy per tonne of clinker, resulting in emissions of 286.9 kgCO_2 per tonne of clinker. In contrast, the adoption of green hydrogen presents a cleaner alternative. While the energy requirement per tonne of clinker increases to 1389.3 kWh, emissions drop to zero, signifying a remarkable shift towards sustainability. Similarly, the utilisation of plasma generators, particularly when powered by 100% renewable electricity, demonstrates substantial emissions reduction potential. With an energy requirement comparable to conventional methods (850.68 kWh per tonne of clinker), emissions are completely eliminated. Another noteworthy alternative is biomethane production coupled with 100 percent renewable electricity. This approach boasts an impressively low energy requirement of 76.81 kWh per tonne of clinker and effectively eliminates emissions from the upgrading process.

Moreover, the report examines case studies of emerging technology providers, including pathways for direct or indirect electrification of energy requirements. Finally, there are recommendations for expediting the adoption of these technologies in the Indian cement sector. It emphasises the importance of policy and financial support alongside collaborative efforts between industry stakeholders and policymakers to facilitate the transition towards a decarbonised cement sector. Focused initiatives aimed at scaling up emerging technologies and creating an enabling environment for innovation will be critical in achieving sustainable and low-carbon cement production in India.

1

Introduction

The Cement industry is regarded as one of the vital sectors for economic growth and development. Apart from generating substantial revenues for Central and State governments, the industry also generates a large number of employment opportunities. Cement as a material, is fundamental to construction and public infrastructure development. Concomitantly, the per capita consumption of cement is indicative of a country's economic growth and is viewed synonymously with the pace of infrastructure development. While India's per capita consumption of cement (200-260 kg) is lower than the global average of 540 kg[1], the sector is poised to see an increase in demand in the coming years. This is attributed to major government initiatives surrounding housing schemes, dedicated freight corridors, ultra-mega power projects, and infrastructure for smart cities.

Globally, India stands as the second-largest producer of Cement, after China. In 2022-23, the annual cement production capacity stood at 600 million tonnes, while the actual production was around 391 million tonnes[2]. Cement production is an emission-intensive process, and the requirement of high temperatures as part of its processes, categorises it among the hard-to-abate sectors from a decarbonisation standpoint. Several energy efficiency interventions in the Indian cement sector under the Perform, Achieve, Trade (PAT) scheme have aided in reducing the specific energy consumption in cement production and thereby the emissions. The Indian cement industry supersedes global efficiency standards as shown in Figure 1.

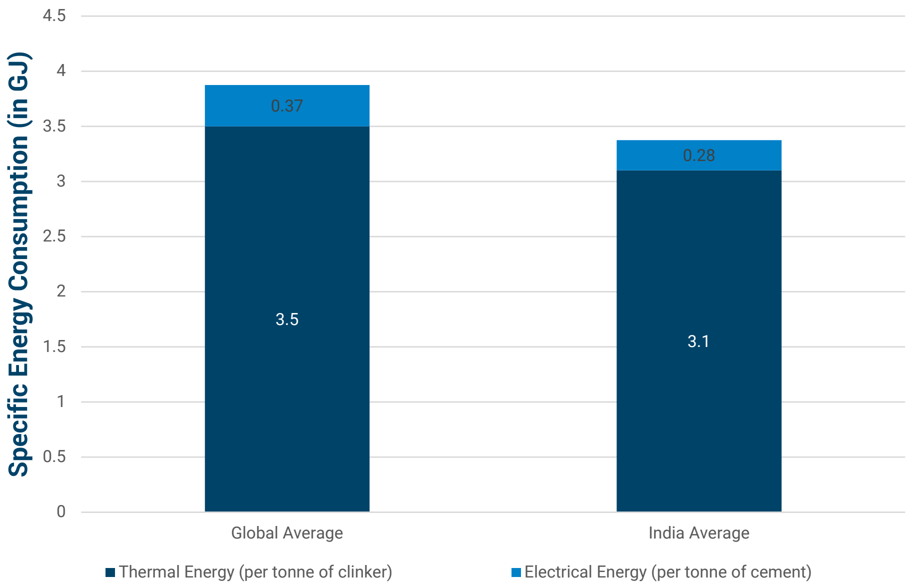

Figure 1: Specific Energy Consumption of Cement Production[3]

Cement production in India resulted in 117.28 million tonnes of carbon dioxide equivalent emissions ($MTCO_2e$) which constituted around 4 percent of the total economy-wide emissions in 2018[4]. Further, within the emissions attributed to the Industrial Processes and Product Uses (IPPU) sector in the country which encompasses the chemical, metal, and mineral industries, cement production contributed to 56.74 percent[4] of the total emissions. This underscores the importance of complementing ongoing energy efficiency efforts in the cement sector with additional strategies to bolster the decarbonisation narrative.

1.1 Scope of Study

The cement value chain as shown in Figure 2, constitutes five major stages beginning with extraction and processing of raw materials, manufacturing of cement, distribution of cement, end-use stage, and the end-of-life stage where the processing of waste from the end-use applications is dealt with.

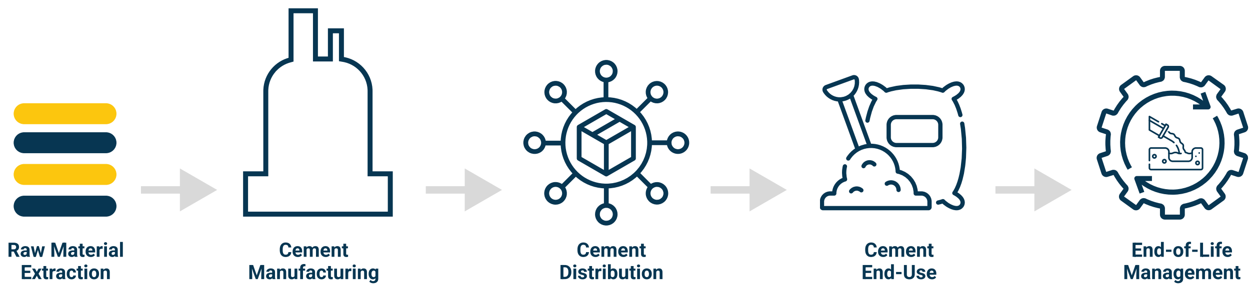

Figure 2: Cement Sector Value Chain

The cement manufacturing stage constitutes the largest share of emissions of ~95 percent[5], and thus posits as the focus of this study. The main contributors to emissions during cement manufacturing include the processing of raw materials, the generation of heat for various processes, and electricity production. On average, 60 percent of the emissions are attributed to clinker production, while the emissions from the fuels consumed in the kilns and electricity consumed account for 35 percent[5]. The remainder of the emissions (5 percent)[5] are from transport activities within the manufacturing plant. In this report, we look into the various pathways to directly or indirectly electrify the energy requirements in cement manufacturing.

2

Overview of the Cement Sector

India's cement industry ranked second globally after China, is a core component of India's economy, poised to hit 550-600 million tonnes in demand by 2025[1]. The industry's manufacturing hubs are strategically located near the main raw material- limestone quarries, with 98 percent[6] of total production capacity held by the private sector.

2.1 Global Cement Scenario

The world production capacity of cement stood at 4128 million metric tonnes (MMT)[7], in 2022. More than half of the cement production capacity is in China which leads with a global share of 50.87 percent as shown in Figure 3. India has the second-largest cement production capacity share at 8.97 percent. The remaining production capacity of 40.16 percent is attributed to the rest of the world. This includes some of the top 10 economies of the world (2024) such as the United States of America, Japan, and Brazil,[8] and other major economies such as Germany, the United Kingdom, France, Italy, and Canada[7].

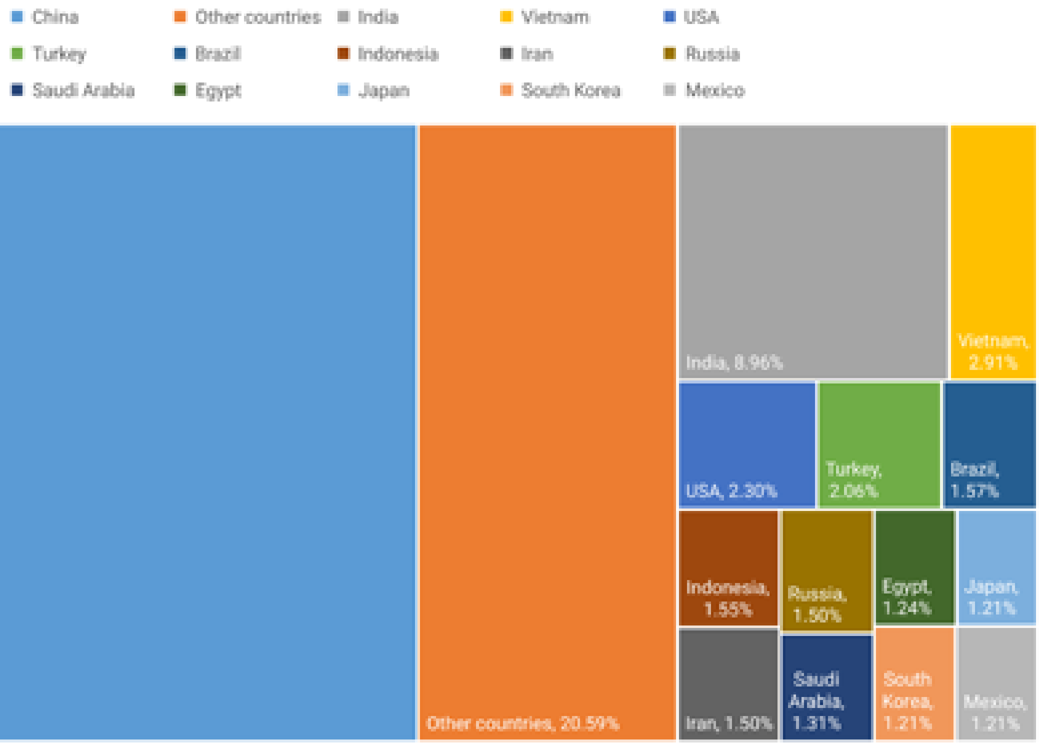

Figure 3: Global Share of Cement Production Capacity

Energy Demand for Cement Production: Thermal energy requirement for clinker production stands at about 3.6 GJ/tonne, as of 2022[9]. The corresponding electricity requirement stood at 100 kWh/tonne[8] of cement produced. As per IEA's Net Zero scenario analysis, the average thermal energy and electricity requirement must fall below 3.4 GJ/tonne of clinker and 90kWh/tonne of cement respectively[8]. This excludes the additional electricity required to support emission reduction technologies such as carbon capture systems which require ~5kWh/tonne[8] of cement. Concerning source of thermal energy, fossil fuels lead with a 90 percent[9] share, supported by bioenergy, renewable, and non-renewable waste.

Emission Scenario: As of 2022, the average emissions intensity of cement stood at 0.58 tCO_2/tonne[8]. In order to align with the Net Zero Scenario target, set by the IEA, emissions must be reduced at an annual rate of 3 percent. Energy efficiency improvements coupled with the adoption of low-carbon fuels, and integration of clean energy sources for the production processes will be key to realising this target.

Global Standard for Low-Carbon Cement: Table1 showcases the emissions intensity target set by various international standards. We observe that the International Energy Agency's (IEA's) Industrial Deep Decarbonisation Initiative (IDDI) has set the lowest permissible emission intensity level for classification as low-carbon/near-zero cement. Further, the definitions of these standards vary in comprehensiveness given that IEA's definition is the only standard to consider the clinker-cement ratio used.

Table 1: Global Standards of Emission Intensity Limits for Low-Carbon Cement[10]

Standard/ Initiative	Emission intensity limit (tonne of CO_2e/tonne of cement)
Climate Bonds Initiative	0.437-0.58
IEA-IDDI	0.04-0.125
First Movers Coalition	0.186
U.S. General Services Administration IRA Requirement	0.751
New York (USA) Buy Clean	0.411
Colorado (USA) Buy Clean	1.112

2.2 Cement Sector in India

Types of Cement

Cement types fall into two main categories: Hydraulic and Non-Hydraulic, depending on how they set and harden. Hydraulic cement, the most prevalent, hardens when water is added through the hydration of clinker minerals. The widely used hydraulic cement in India is Portland cement. The Bureau of Indian Standards (BIS) has outlined 14 types of cement and clinker specifications as highlighted in Table 2 below.

Table 2: Types of Cement as per BIS[11]

Sr. No.	Type of Cement	IS Code No.
1	Ordinary Portland Cement (OPC) (OPC33, 43, 43S, 53 & 53S)	IS 269:2015
2	Portland Pozzolana Cement (PPC)	IS:1489-2015 (Part-I): Fly ash
3	Portland Pozzolana Cement (PPC)	IS:1489-2015 (Part-II): Calcined Clay
4	Portland Slag Cement (PSC)	IS:455-2015
5	Composite Cement	IS:16415-2015
6	White Portland Cement	IS: 8042-2015
7	Sulphate Resisting Portland Cement	IS:12330-1988
8	Super Sulphated Cement	IS:6909-1990
9	Low Heat Portland Cement	IS:12600-1989
10	Hydrophobic Portland Cement	IS:8043-1991
11	Rapid Hardening Portland Cement	IS:8041-1990
12	Masonry Cement	IS:3466-1988
13	Oil Well Cement	IS:8229-1986
14	High Alumina Cement	IS:6452-1989

In India, the most common cement types are Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), and Portland Slag Cement (PSC). Recently, in February 2023, BIS introduced standards for a new type called Composite Cement (CC), made from limestone, fly ash, slag, and gypsum[12]. Table 3 provides details for the common variants.

Table 3: Description of Common Cement Variants in India

Name	Raw materials used	BIS certification	Uses
Ordinary Portland Cement (OPC)	Limestone	IS 269:2015	1) 33 grade OPC- masonry and plastering 2) 43 grade OPC- high grade concrete
			3) 53 grade OPC- specialised construction
Pozzolana Portland Cement (PPC)	Fly Ash	IS: 1489 (I)-2015	General construction, especially marine and hydraulic
Portland Slag Cement (PSC)	Slag (from steel)	IS 455:2015	General construction, also used for marine construction
Composite Cement (CC)	Limestone, fly ash, slag and gypsum.	IS 16415:2015	General construction

Capacity and Production of Cement

With a cement production capacity exceeding 600 million tonnes per annum[13], India ranks as the second-largest cement producer worldwide, contributing to around 9 percent of the global installed capacity[14]. The production of cement since 2007-08 is detailed in Table 4 below:

Table 4: Cement Installed Capacity, Production and Utilization[13, 15, 16]

Year	Installed Capacity (million tonnes/yr)	Production (million tonnes/yr)	Capacity Utilisation (%)
2007-08	209.20	174.31	83.32
2008-09	232.54	187.60	80.67
2009-10	294.32	217.44	73.88
2010-11	323.20	228.30	70.64
2011-12	336.10	246.70	73.40
2012-13	350.00	248.23	70.92
2013-14	360.00	255.60	71.00
2014-15	378.00	270.00	71.40
2015-16	420.00	283.45	67.40
2016-17	445.00	280.00	63.00
2017-18	509.00	297.50	58.44
2018-19	537.21	337.32	62.77
2019-20	537.21	334.37	62.21
2020-21	537.00	299.94	55.85
2021-22	537.00	360.19	67.07
2022-23	600.00	391.00	65.17

Over the last 16 years, the capacity utilisation of India's cement industry has declined from 83 percent to 65 percent, signalling an idle capacity of over 209 million tonnes. The sector consists of approximately 150 large integrated cement plants, 116 grinding units, 62 mini cement plants, and 5 clinkerisation units[1].

Regionally, Rajasthan and Andhra Pradesh have the highest installed capacities. These are followed by states like Karnataka, Madhya Pradesh, Tamil Nadu, Maharashtra, and Gujarat. Together these seven states contribute to over 63% of the overall installed capacity. Table 5 depicts the state and UT-wise installed cement capacities along with the number of plants installed. Figure 4 depicts the same information on a map.

Table 5: State and UT-wise Installed Cement Capacity[17, 18]

State/UT	Capacity (MTPA)	No. of Plants
Rajasthan	72.9	42
Andhra Pradesh	65.26	38
Karnataka	47.23	30
Madhya Pradesh	41.39	23
Tamil Nadu	40.85	33
Maharashtra	39.48	21
Gujarat	39.04	27
Telangana	29.77	22
Uttar Pradesh	27.52	28
Chhattisgarh	27.39	15
West Bengal	25.82	21
Odisha	17.48	17
Jharkhand	13.43	8
Himachal Pradesh	12.85	9
Bihar	10.6	7
Meghalaya	8.98	9
Haryana	7.6	7
Assam	6.98	11
Punjab	6.35	7
Uttarakhand	3.9	3
Jammu and Kashmir	0.86	11
Kerala	0.86	3

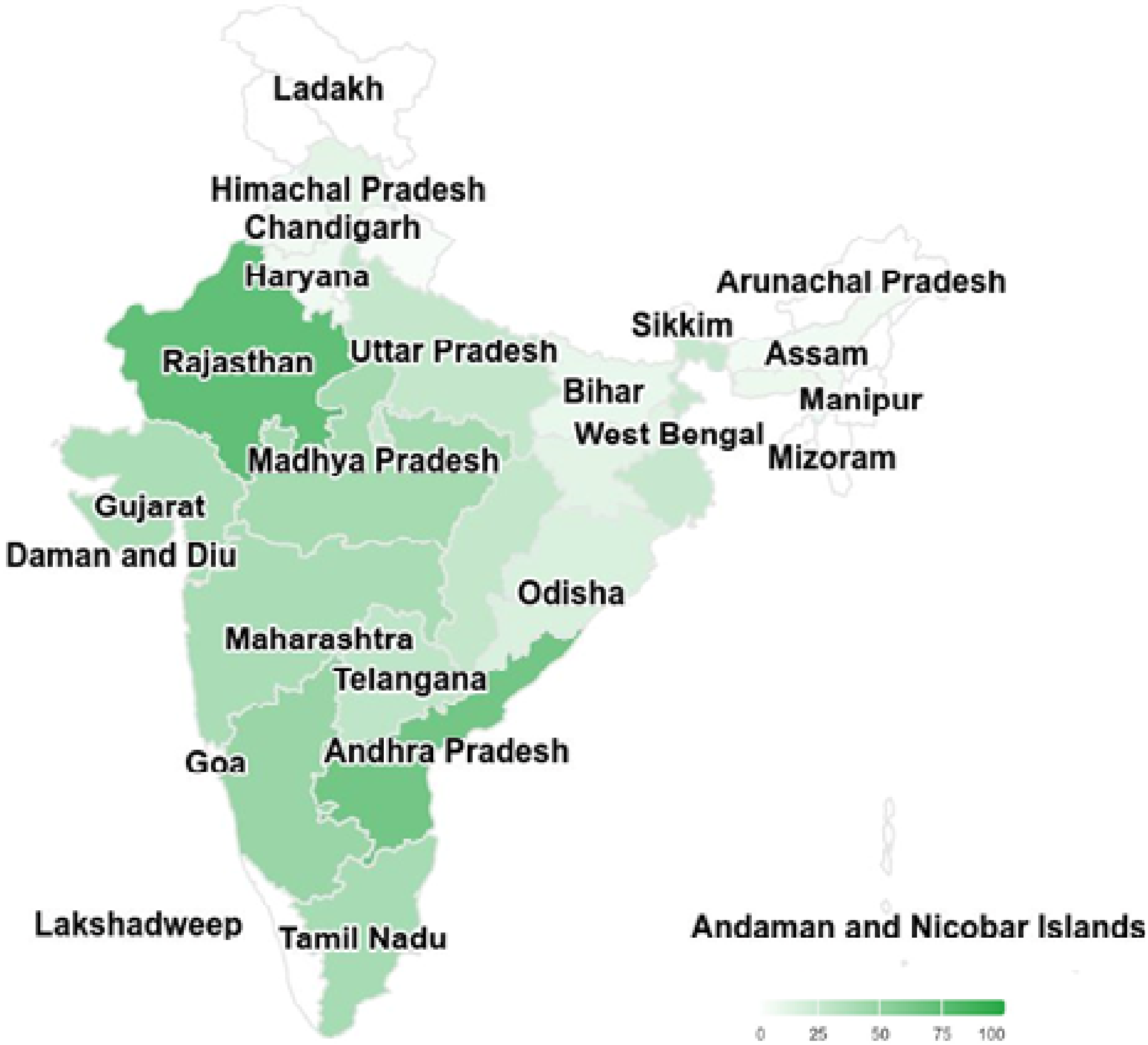

Figure 4: State-wise Installed Cement Capacity

Power Consumption: On average, India's cement sector consumed about 725 kcal/kg (~842.61 kWh/tonne)[2] equivalent of thermal energy for the production of clinker, and about 80 kWh[2] of electrical energy to produce one tonne of cement.

Emission Intensity: As of 2018-19, cement sector in India resulted in 117.28 million tonnes of CO2eq to produce 337.32 million tonnes of cement correspondingly.[4] This ranslates to an emission intensity of 0.348 tonnes of CO_2eq/tonne of cement. Figure 5 shows the emission intensities over the years 2010-11 to 2018-19. We observe a declining trend in emission intensity despite an increment in cement production which can be attributed to the energy efficiency measures employed by the cement sector in India.

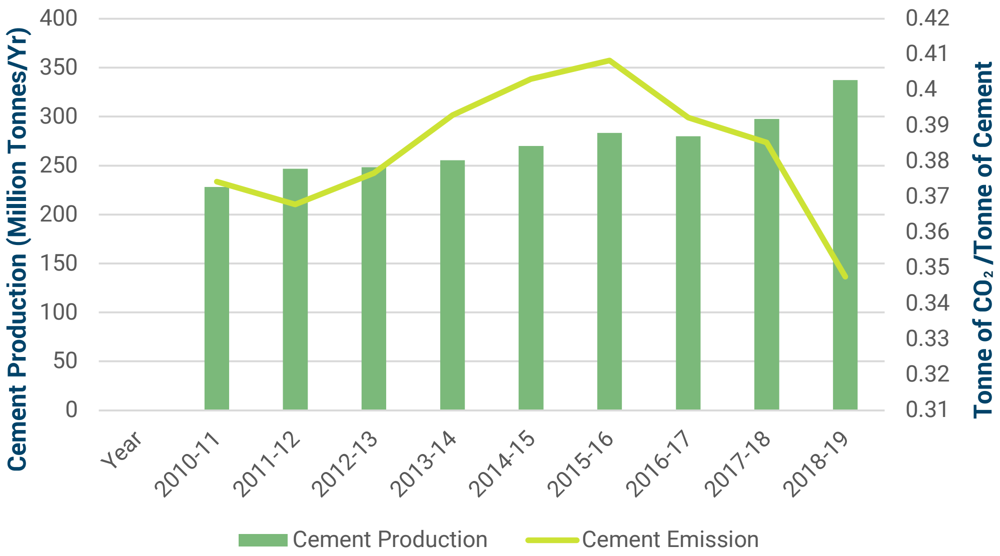

Figure 5: Emission Intensity of Cement Production per tonne[4]

Cement Export

India exported around 1.9 million tonnes of cement in FY2021-22. The largest export share was to Sri Lanka (84 percent), followed by Nepal (6 percent) and Bangladesh (5 percent). 99 percent of India's cement export share was split between 10 countries as shown in Figure 6.

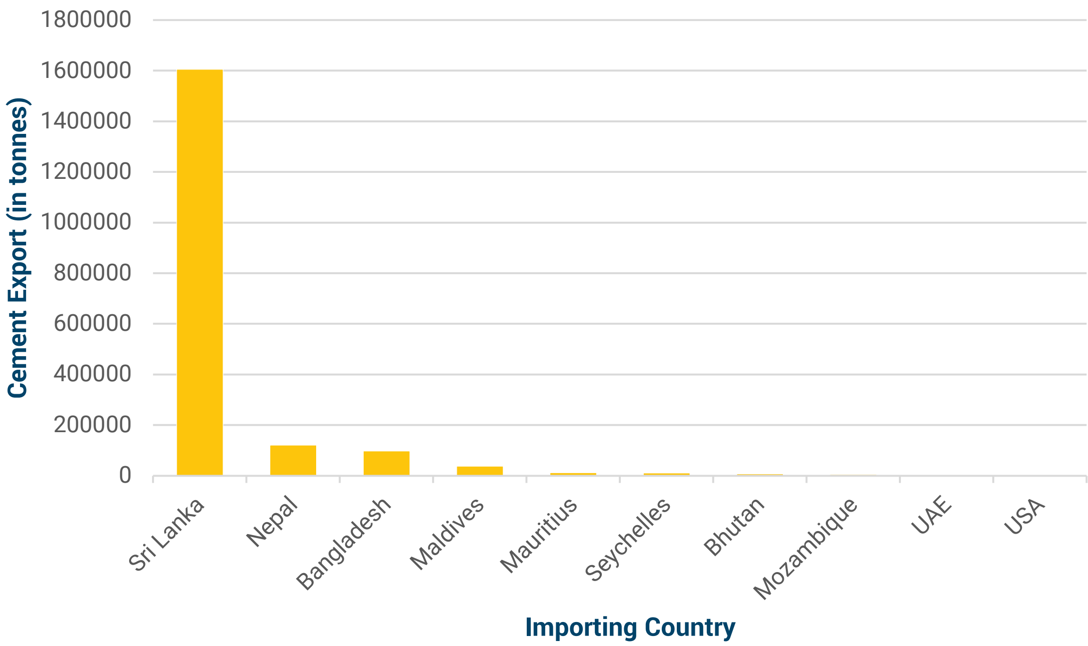

Figure 6: Top Importing Countries of Indian Cement[2]

Given the high energy consumption in Clinker production, it is also prudent to look at India's clinker exports. In FY2021-22, India exported 7,34,859 tonnes of clinker with a majority share to Sri Lanka (72.9%). A total of 6 countries were recipients of India's clinker exports as shown in Figure 7.

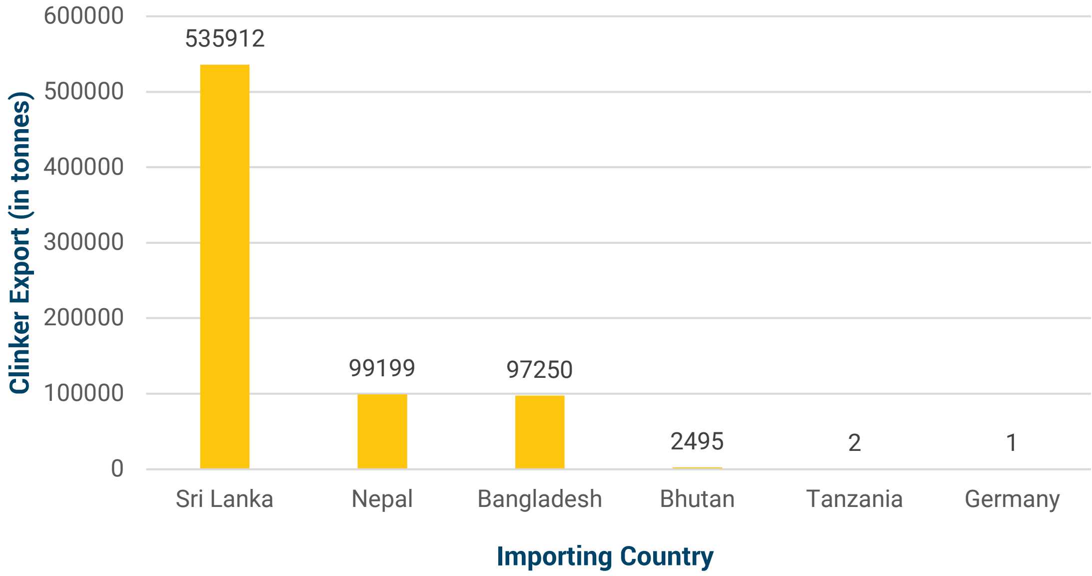

Figure 7: Top Importing Countries of Indian Clinker[2]

Cement Import

India imported around 2.02 million tonnes of cement in FY2021-22. Oman and UAE were the largest cement exporters to India with contributions of 33.53 and 30.55 percent respectively. Most of India's cement was imported from 10 countries as shown in Figure 8, with a relatively meagre cement import of 1464 tonnes from the rest of the world.

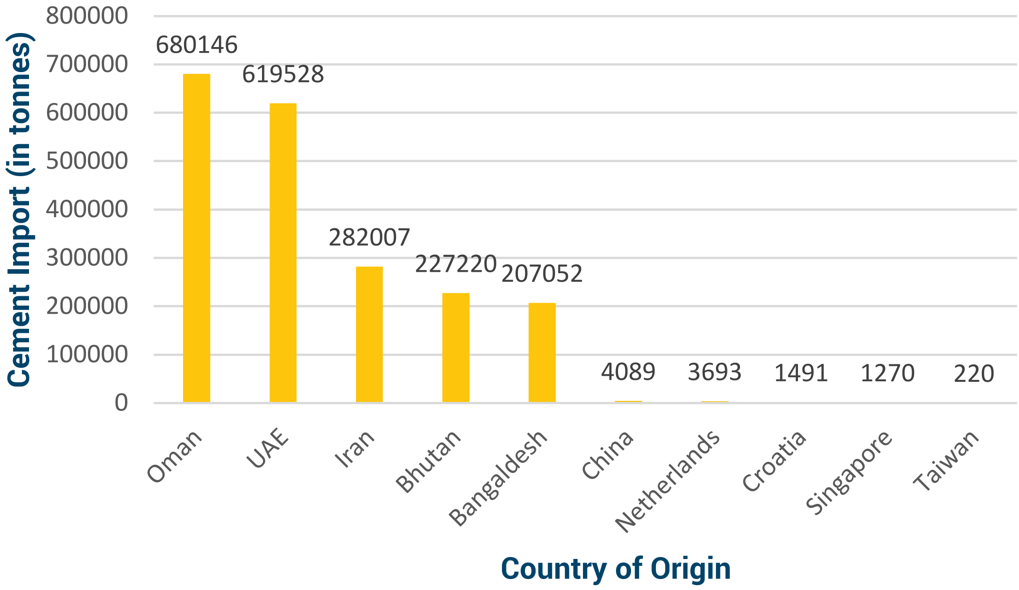

Figure 8: India's Cement Import by Country of Origin[2]

India also imported around 1.2 million tonnes of clinker in FY2021-22 from 7 countries as shown in Figure 9. Oman was the largest contributor with about 50 percent share.

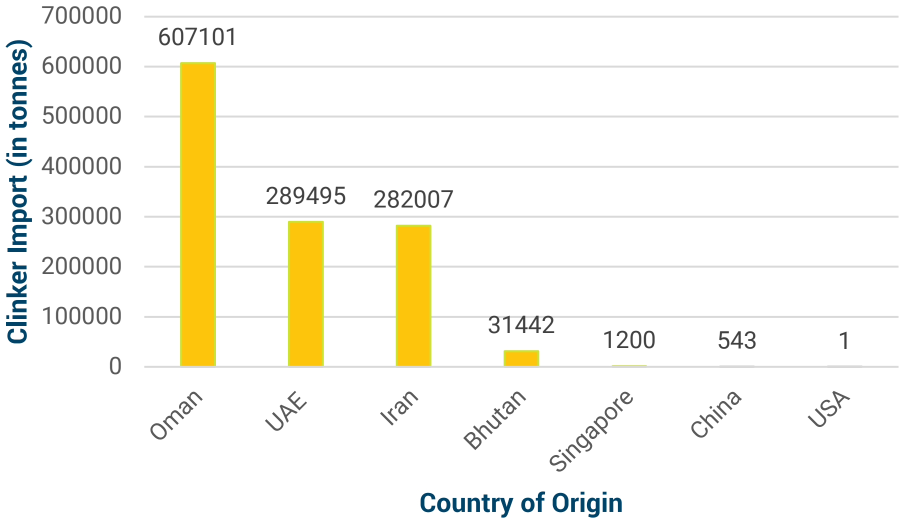

Figure 9: India's Clinker Import by Country of Origin[2]

There is a notable influx of cement and clinker imports due to the absence of import duties in the country. Meanwhile, domestic producers face additional costs due to imposed duties on raw materials, resulting in higher product prices[19]. Moreover, instances of cartelization among Indian cement producers have drawn government scrutiny, prompting reliance on imported cement for infrastructure projects[20, 21]. However, procurement follows a stringent bidding process, with contracts awarded to the lowest bidder after thorough evaluation.

Future Demand for Cement

Currently, over 65 percent[22] of India's cement demand is attributed to the housing and real estate sector. With the Government's emphasis on infrastructure development under the aegis of the smart cities program, and modernisation of around 500 cities, the cement demand is expected to rise. Households in India are expected to rise to 328 and 386 million in 2027 and 2037 respectivelty[23]. Correspondingly, the household built-up area is expected to rise to ~22 billion sqm by 2027-28[23]. The commercial built-up area is projected to increase from 1.16 billion sq. km in 2017-18 to 1.88 in 2027-28, and 3.09 billion sq. km. in 2037-38[23]. Correspondingly cement production is expected to rise at a rate of 6 percent, rendering an expected cement production of around 623.19 tonnes in 2030, as shown in Figure 10.

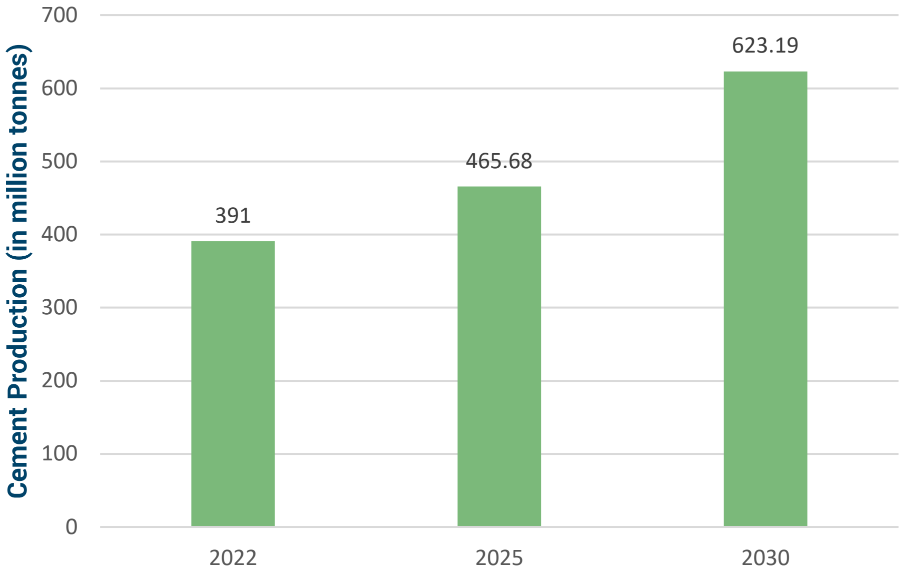

Figure 10: Expected Rise in Annual Cement Production[23]

Regulatory Scenario in India

The Indian cement industry is regulated by the Union Ministry of Commerce and Industry, specifically its Department for Promotion of Industry and Internal Trade. As of now, the government has yet to create a dedicated climate change abatement roadmap for the sector. However, existing initiatives such as the Perform, Achieve, Trade (PAT) scheme incentivize emissions reduction and energy efficiency improvements. PAT, initiated in 2012 under the National Mission for Enhanced Energy Efficiency, targets reduced energy consumption in energy-intensive industries like cement, awarding energy-saving certificates for surpassing set thresholds.

Notable gains in efficiency within the cement industry have been achieved through the adoption of waste heat recovery systems and vertical rolling mills. Recent amendments to the 2001 Energy Conservation Act, last revised in 2010, empower the government to mandate non-fossil fuel energy usage levels for cement and other industries, while also enabling direct purchase of renewable energy from producers. Additionally, the 2022 amendment[24] allows for the establishment of a carbon trading scheme, although specifics regarding its implementation timeline remain undisclosed.

Industry Initiatives

The Indian cement industry, a significant contributor to the country's revenues and a major stakeholder in the railway cargo movement, is set to benefit from dedicated corridors planned by the Ministry of Railways. These corridors, scheduled for development over the next decade until FY 2033, aim to link cement factories with their sources of raw materials like clinker, limestone, and fly-ash, reducing logistical and operational costs. In alignment with the Union Budget 2023-24, which allocated US$ 1.8 billion for essential infrastructure including safe housing, clean water, sanitation, and improved connectivity, the industry stands to gain from the anticipated 7 percent expansion in infrastructure between 2022 and 2027[22]. Notable mergers, such as the Adani Group's acquisition of Ambuja Cement and ACC from Holcim for $6.4 billion, have marked industry developments[25].

Furthermore, initiatives like the PM Gati-shakti plan, with a substantial ₹100 lakh crores outlay, encompassing infrastructure projects from various ministries and state governments, promise increased connectivity and competitiveness for Indian enterprises. The Budget 2022-23's focus on the Gati-Shakti program, aiming to add 25,000 kms to the nation's highways, also bodes well for cement manufacturers, as evidenced by initiatives such as the construction of 100 cargo facilities and 400 new Vande Bharat trains. Identified interventions for critical infrastructure gaps, particularly for bulk commodities movement, underscore the industry's role in the nation's infrastructure development, with mega projects worth ₹ 110 trillion in the National Infra Pipeline set to benefit under the PM Gati-Shakti framework[22].

Cement producers in India are actively engaging in various other initiatives such as RE100 and EV100. RE100 initiative is a global effort in which businesses unite to pledge 100 percent renewable electricity usage[26]. In India, numerous cement companies, including JK Lakshmi Cement, Dalmia Cement, Ultratech Cement, and others, are part of this commitment. Similarly, another initiative focuses on the electrification of the transport sector, with companies committing to transitioning to electric vehicles (EVs)[27]. Once again, several cement players, such as Dalmia Cement, JSW Cement, and others, have made commitments in this regard

3

Cement Production

3.1 Process Overview

In this section, we look into the various stages involved in manufacturing cement. Figure 11 showcases a typical schematic of the same. The various types of cement listed in Table 2, largely undergo the same manufacturing process albeit with a few modifications to derive the corresponding product.

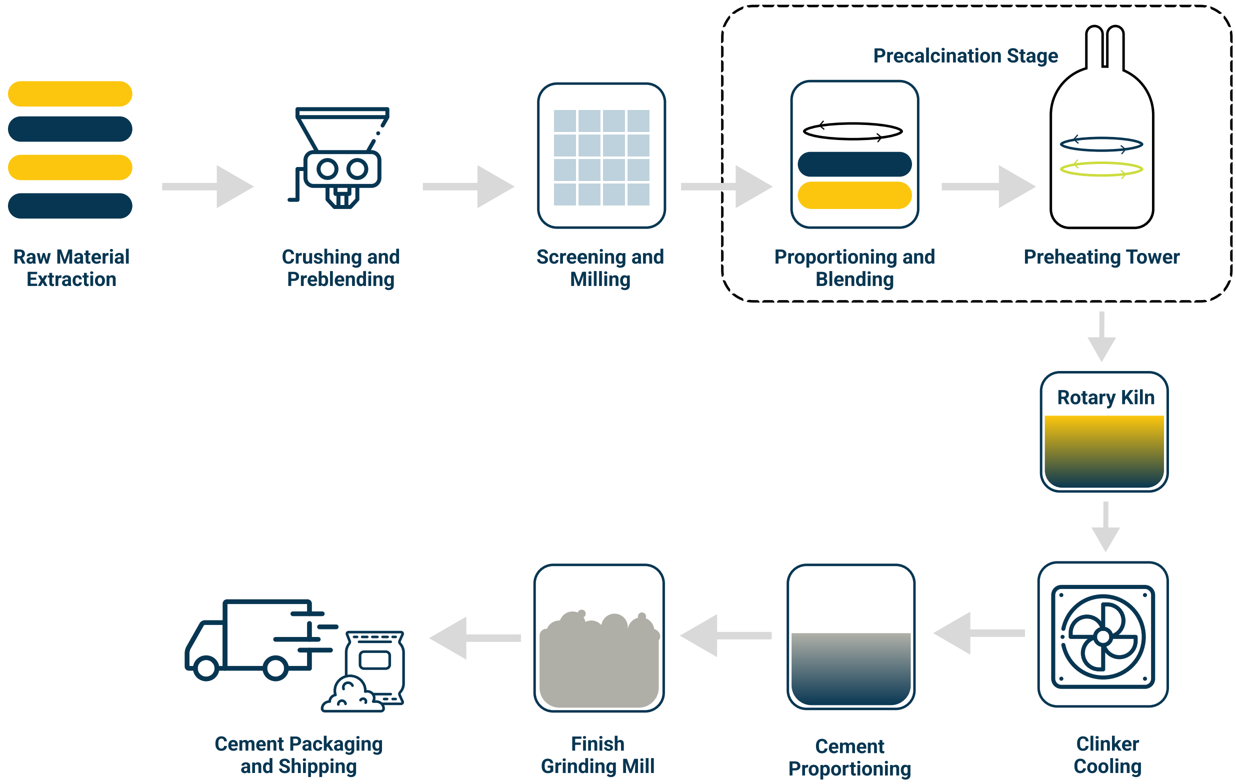

Figure 11: Schematic Representation of Processes involved in Cement Manufacturing[28]

Raw Material Extraction: Cement production initiates with the extraction of various raw materials such as high-grade limestone (abundant in calcium), clay (rich in silicon), and sand, among others. The mined limestone boulders are loaded onto either rail mounted dumpers, rubber-tired vehicles, belt conveyors, etc using excavators. The extracted. raw material is delivered to the site of the cement manufacturing plant for processing.

Crushing and Pre-blending: The mined raw materials are first subject to the crushing stage which occurs in two phases. The first crushing stage employs jaw crushers, crushing rolls, gyratory crushers, etc. to reduce the boulders into small chunks ranging from five to eight inches in size[28]. The second crushing stage employs equipment such as hammer mills and impact crushers, which further breakdown the raw material into chunks that range from 3/4th to 1 inch in size[28]. The resulting raw material chunks are blended with other minerals to arrive at the desired chemical composition of the clinker to be obtained.

Screening and Milling: In this stage, the blended raw mix is fed into a grinding mill which crushes the chunks into a fine powder. This is further screened to obtain the satisfactory particle size. Hot gases from the clinker burning unit are passed into the mill which separate fine particles from coarse particles. The coarse particles are resent back to the grinding mill, while the fine raw mix is conveyed to the next stage.

Proportioning and Blending: In this stage, blending is performed by mixing the fine powder using compressed air to obtain uniform chemical composition of the raw mix. This obtained product is then fed to the top of the preheater tower.

Preheater Tower : This involves a fire column with progressively increasing temperature from top to bottom. Typically, a pre-heater constitutes five sections. Each preheater section consists of a gas riser duct and a collection cyclone. The high temperature exhaust gases from the rotary kiln move up through the gas riser duct, and a swirl is created by the cyclone column which separates the raw mix from the gas. As the gases rise up, the raw mix moves to the next section. A similar process is repeated across the five sections in the preheater. Temperatures of up to 800°C[28] are achieved in the preheater tower leading to the decomposition of most of the limestone. The resulting raw mix is then fed into the rotary kiln.

Rotary Kiln: This stage has multiple zones namely – calcining zone, heating zone, burning zone, and sintering zone. The temperatures increase progressively across the zones to attain a temperature of 1400°C[28] in the sintering zone, where the raw mix is completely calcined[29]. Nodulisation of clinker begins in the burning zone itself where temperatures of 1300 - 1350°C are achieved[28]. Post sintering, the raw mix transforms into clinker compounds such as Alite (C_3S), Belite (C_2S), and Tricalcium aluminate (C_3A).

Clinker Cooling: The hot clinker compounds are then discharged from the kiln onto a cooler. This stage employs equipment such as planetary coolers, rotary coolers, graft coolers, etc., to bring the temperature down of the clinker to around 120°C[28]. The cooled clinker is then conveyed to silos for storage.

Cement Proportioning: In this stage, the cooled clinker is mixed with required additives such as gypsum, and fly ash in the desired proportions corresponding to the end-product. For example, manufacturing Portland Pozzolana cement (PPC) would constitute 60-65 percent clinker, 15-35 percent of fly-ash, and about 3 percent of gypsum[28].

Finish Grinding Mill: Typically, ball mills are used to grind the clinker and additives together. The two chambers of the mill have a certain quantity of ball charge of different sizes, which aids in the final mixing to produce the desired cement product. The resulting product is then passed onto a separator to obtain the fine product. The coarse product separated is sent back to the ball mill.

Cement Packaging and Shipping: This is the final stage where the manufactured cement is packed into bags via an automated system. Typically, stationary or rotary packers are employed in this stage. The bags are then mechanically sealed and loaded for dispatch.

3.2 Energy Requirement in Cement Manufacturing

Cement manufacturing has electrical and thermal energy requirements. While the electrical energy powers most of the equipment in the value chain, the high temperatures needed for production of clinker, requires thermal energy that is primarily produced from fossil-fuel-based sources. Figure 12 illustrates the energy required at various stages. To produce one tonne of cement 81.18 kWh of electrical energy is required. Thermal energy equivalent of 842.61 kWh/tonne of clinker (~725kcal/kg of clinker) is necessary. Assuming a clinker to cement ratio of 0.7[30], one tonne of cement would require 671 kWh of energy.

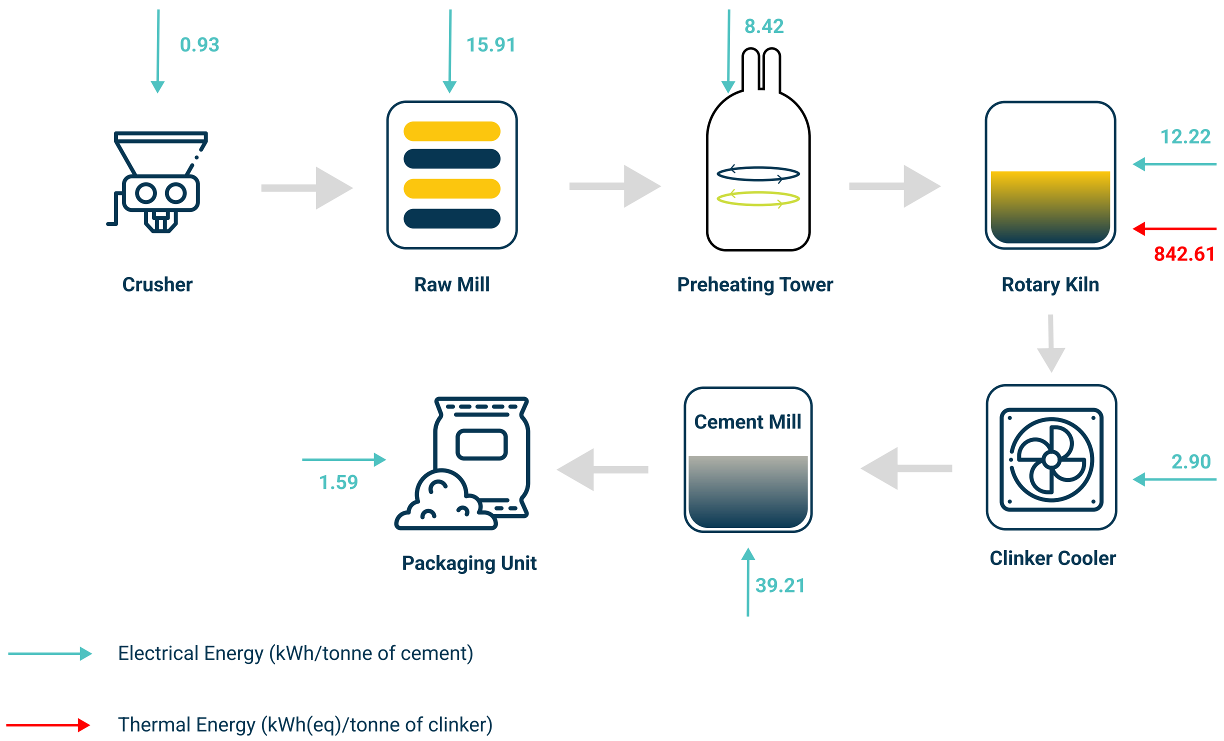

Figure 12: Energy Requirement at Major Stages of Cement Manufacturing[31]

Electricity is obtained either from the grid or generated internally by captive thermal or renewable energy plants. The primary source for thermal energy is coal which remains as an affordable fuel for the industry. Along with fuels such as petcoke, and natural gas, coal is combusted to provide the necessary high temperatures. Owing to its high calorific value it generates the intense heat required to drive the chemical reactions that convert raw materials into clinker. The heat also facilitates the evaporation of moisture content within the raw materials and results in the desired chemical composition of the clinker, thus making it the preferred fuel choice for use in the kiln.

3.3 Emissions from Cement Manufacturing

Typically, emissions arise from grid electricity owing to the current energy mix which primarily constitutes thermal power, and fossil-fuel use to generate thermal energy. As observed from Figure 12, the total electricity required for producing one tonne of cement stands at 81.18 kWh. Assuming this is entirely sourced from the grid (emission factor of 0.71 tCO_2/MWh)[32], we estimate emissions of about 57.63 $kgCO_2$/tonne of cement.

1 kg of clinker is estimated to require 725 kcal of thermal energy. Going by the clinker to cement ratio of 0.7, one kg of cement would require 0.7 kg of clinker, which would require 507.5 kcal. This translates to about 0.0021 TJ/tonne of cement[33]. Given the emission factor for coal used in the cement kiln is 95.63 tCO_2/TJ[5], we arrive at emissions of 0.2 tCO_2 (200.8 kg)/tonne of cement. Therefore, the total emissions (electrical + thermal) arising from the production of 1 tonne of cement is 258.43 $kgCO_2$. Figure 13 illustrates the emission arising from each stage of the cement manufacturing process.

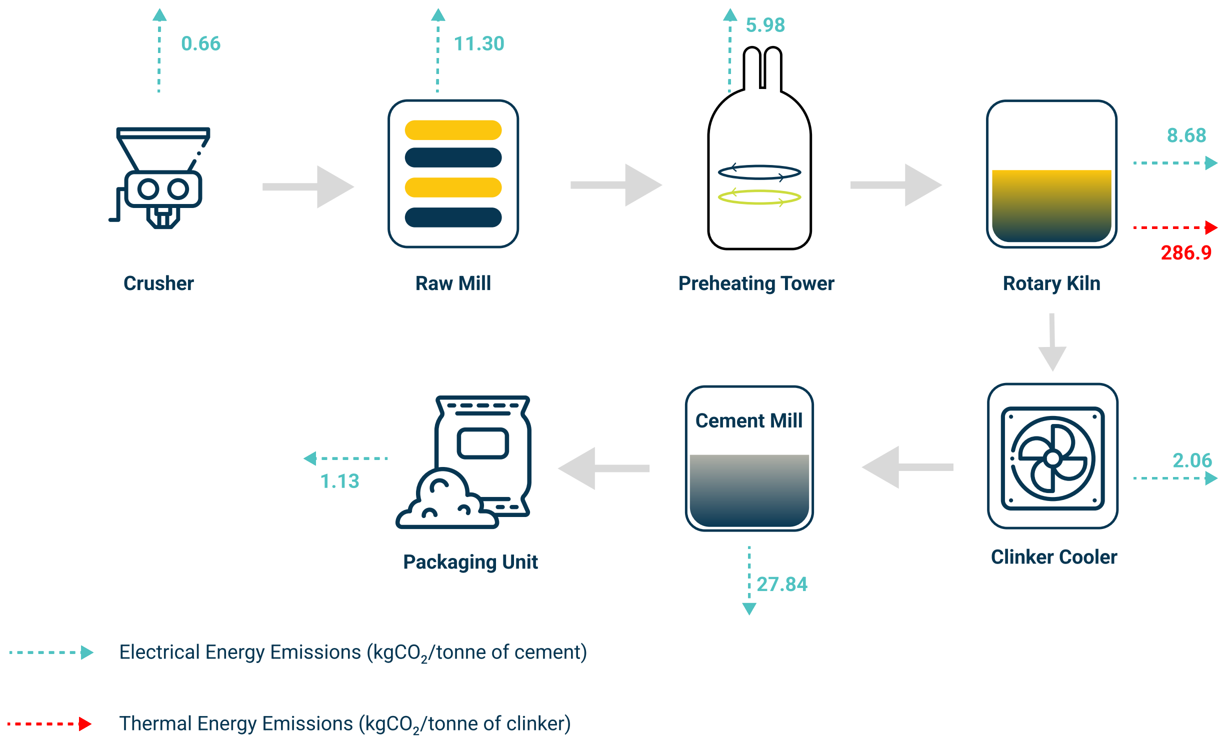

Figure 13: Emission Intensities of Major Stages of Cement Manufacturing

4

Technological Options for Decarbonising Cement

Typically, the reduction of carbon emissions in cement production has 4 pathways – improving energy efficiency, fuel switching, material substitution, and incorporating emerging technologies. Energy efficiency interventions involve the incorporation of latest technologies in the existing cement plants that result in overall reduction in energy consumption. Fuel switching involves the use of alternate fuels such as biomass to offset the carbon-intensive fuels in specific stages such as the cement kilns. Studies suggest that biomass can directly replace coal in these kilns by up to 20 percent without affecting cement quality[34]. For higher substitution rates, biomass may need pretreatment through pyrolysis, producing biochar with a similar energy density to subbituminous coal.

Material substitution is primarily aimed at reducing the amount of clinker required to produce one tonne of cement by increasing the use of blended materials. Alternative cements, while differing in composition from conventional cement like Ordinary Portland Cement (OPC), exhibit comparable structural properties and performance when used in concrete and mortar applications. Clinker, a primary component of cement, plays a crucial role in providing strength upon reacting with water. The amount of clinker in cement is defined by the Clinker to Cement ratio, representing the mass of clinker per unit of cement. In OPC, this ratio stands at 0.90[35], alongside constituents such as gypsum and fine limestone. Higher clinker content in cement leads to increased limestone consumption and associated greenhouse gas (GHG) emissions in its production. Some of the relevant options for alternative cements are discussed below in Table 6.

Table 6: Different Types of Alternative Cements in India[36]

Cement Type	Composition	Production Process	CO_2 Reduction Potential	Status of BIS Standards
Limestone Calcined Clay Cement (LC3)	Clinker, low-grade limestone, calcined clay, gypsum	Kaolinitic clay undergoes calcination at 700°C - 850°C in rotary kilns. Ground with clinker and other ingredients in required proportions. Requires 50% less clinker.	Lower CO_2 emissions due to reduced clinker usage, calcination at lower temperatures.	Draft Standard submitted to BIS
Geopolymer Cement and Concrete	Fly ash, GGBFS, LD slag, silica fumes, etc.	Activation of pozzolanic materials with alkaline solutions at required temperatures. Forms a solid structure with properties similar to OPC.	Over 80% CO_2 reduction compared to OPC.	In progress
Composite Cement	Portland clinker, fly ash, slag, gypsum	Portland clinker blended with fly ash, slag, and gypsum. Reduced clinker demand.	56% CO_2 reduction compared to OPC.	Available; IS 16415: 2015

Alternatively, decarbonisation could be led by the adoption of renewable power technologies such as solar and wind to incorporate renewable electricity use, and pave the way for fully electrified cement manufacturing. Here, the pre-calciner is electrified using resistive elements, magnetic induction, and plasma gas to provide high-temperature heat in the rotary kiln. This innovative method shows potential for significant cement production carbon footprint reduction, ensuring efficient and sustainable operations.

Emerging technologies such as green hydrogen production could be incorporated to repurpose waste heat for specific stages in the cement production value chain. Hydrogen could also be used to substitute natural gas usage in cement kilns. This shift eliminates all stationary combustion CO_2 emissions, resulting in water vapor generation. Implementing hydrogen may require kiln burner or geometry adjustments for efficient combustion and material durability.

An analysis by the International Energy Agency (IEA), estimated the potential of the aforementioned pathways to reduce carbon emissions by 2050. Assuming that necessary interventions to restrict global temperature growth to 2°C have been undertaken, Figure 14 showcases the corresponding share of carbon abatement potential. Incorporating emerging technologies stands as the most effective pathway to emission abatement with a reduction potential of 46 percent.

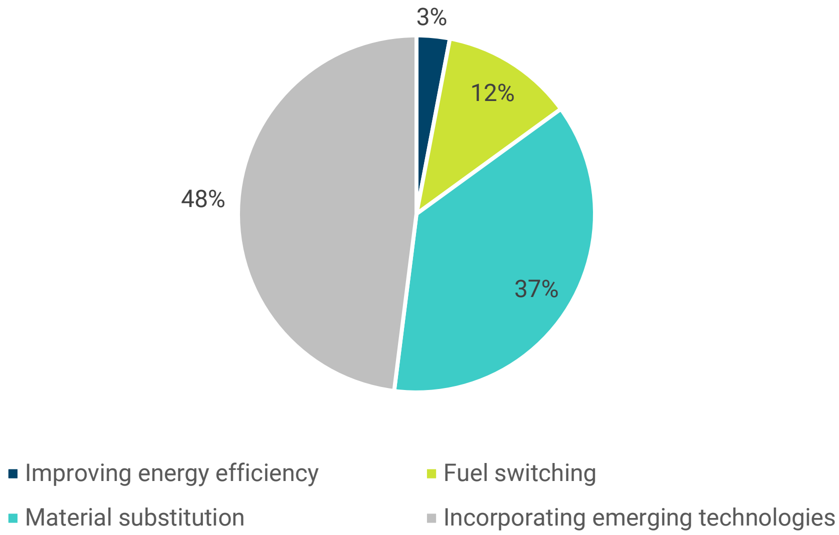

Figure 14: Carbon Abatement Potential of Various Pathways in the Cement Sector by 2050[37]

4.1 New Global Technology

Sublime Systems' Low-Carbon Cement
Sublime Systems is a US-based Startup that makes low-carbon cement, using electrochemistry instead of heat and combustion to transform minerals into the building material. Their technology uses an electrochemical process that can convert non-carbonate rocks and decomposed industrial waste into cement. This process can be achieved at ambient temperature, thus

eliminating the need for fossil fuels.

Their patented electrolyser is modelled on traditional water-splitting electrolyser. Performing similar function, one electrode produces a solution that extracts calcium from inert materials with reactive silicate as residue. The second electrode precipitates calcium as a pure, reactive solid. The derived product from the electrodes (reactive calcium and silicates) are then blended in an ambient-temperature process to make the final low-carbon cement product as illustrated in Figure 15. This cement is compliant with the American Society for Testing and Materials (ASTM) standard – ASTM C1157, which makes Sublime cement the first commercially available product which is zero carbon by avoiding CO_2 emissions, and the need for carbon capture technologies.

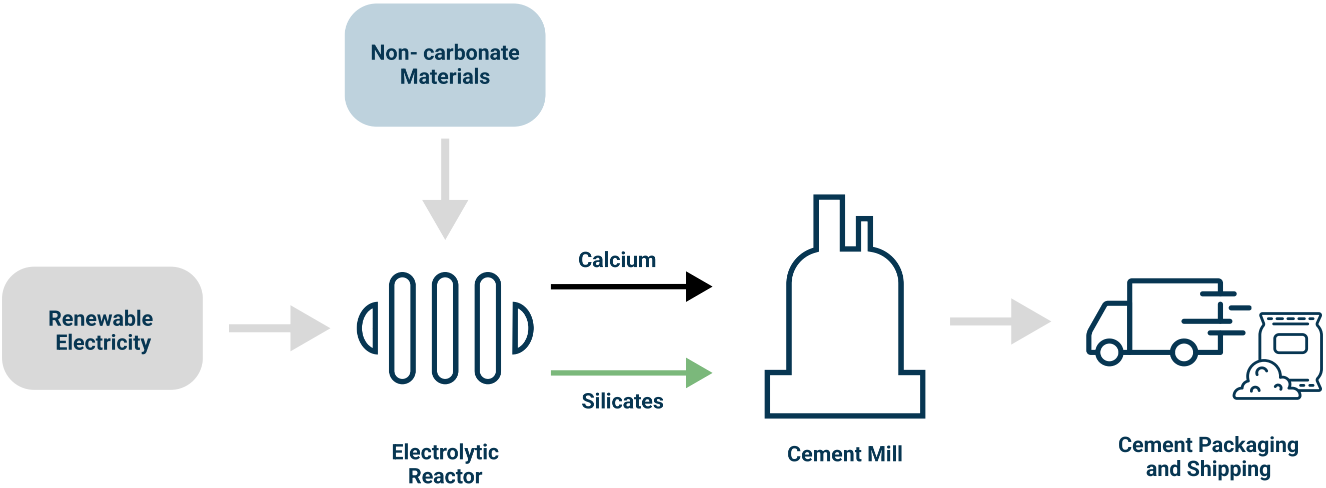

Figure 15: Schematic representing production of Sublime Cement[38]

FLSmidth's Green Hydrogen Burner Kiln
FLSmidth has been a provider of full flowsheet technology and services to the global mining and cement industries for over 140 years. They have initiated a Mission-Zero Programme, with a target of providing solutions for zero-emission mining and zero-emission cement production by 2030 to support a green transition built upon sustainable materials. In this regard, FLSmidth Cement's latest offering - the green hydrogen-fired burner kiln is set to revolutionise pathways to meet thermal energy demand.

They have piloted the World's first 100 percent hydrogen fired rotary kiln which posits as a green way to achieve mineral pyro-processing. Their rotary kiln pilot plant is capable of operating with a mixture of hydrogen and natural gas, or pure hydrogen, at temperature that range from 800 – 1300°C. The material can be fed directly into this kiln from the typical precalcination stage employing a cyclone preheater, to derive the cement product as illustrated in Figure 16.

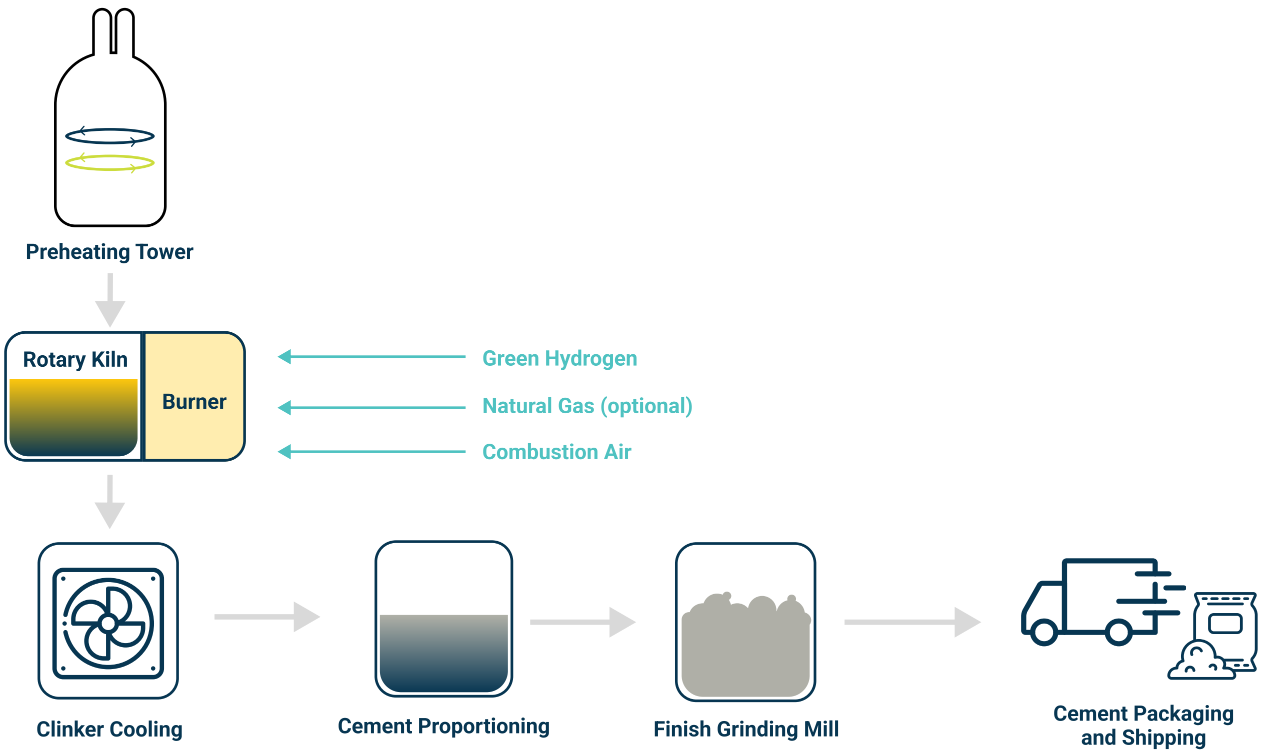

Figure 16: FLSmidth's Green Hydrogen-fired Combustion in Cement Manufacturing[39]

Coolbrook's RotoDynamic Heater Technology Coolbrook is a Finland-based heavy equipment manufacturer and have been pioneers in decarbonising industries. In collaboration with ABB, they have developed technology that has the potential to replace fossil fuels with renewable electricity to meet thermal energy demands of industries such as Cement production. Coolbrook's RotoDynamic Heater (RDH) technology is capable of heating gases to extremely high temperatures (up to 1700°C)[40] in processes such as clinker production. This is a significant leap over traditional resistive material powered through electricity which is capable of attaining temperatures up to a maximum of 600°C.

The key element to Coolbrook's RDH is the use of a turbomachine that increases the temperature of the gas internally. The gas is first heated to supersonic speed and then slowed down rapidly via a diffuser. This process converts electric energy to kinetic energy, and then the kinetic energy to thermal energy. By repeating this process, RDH is able to achieve significantly higher temperatures compared with existing electric heater solutions. RDH also posits as an economical intervention owing to its ability to be retrofitted into existing cement plants. Thus, enabling decarbonisation in existing cement plants by avoiding fossil-fuel usage.

4.2 Deep Electrification Pathways

In this section, we explore the possible direct or indirect electrified interventions that can substitute the thermal energy requirements. While the electricity is primarily sourced from a largely-thermal powered grid, we anticipate the eventual shift to renewable energy sources, will abate emissions completely from the cement production process. The impact of integrating the electrified intervention with the kiln is compared with the conventional kiln, and the varying energy requirement and corresponding emission intensity are described for each of the cases.

Green Hydrogen

Green hydrogen is a zero-emission fuel since it doesn't emit harmful emissions. Hydrogen may be a suitable substitute for carbon-intensive fuels in kilns in areas where the fuel supply is heavily dependent on imports from other nations. Regarding the usage of hydrogen as a source of process heat, it can present a potential for comparatively smooth integration into, or replacement of, process heat systems based on fossil gases, such as natural gas or LPG (liquid petroleum gas).

Meanwhile, various studies have revealed that using hydrogen as a fuel source for cement production in the H_2-based integrated system can lead to a reduction of 44% in CO_2 emissions compared to traditional coal-based methods[41]. This is because hydrogen enables carbon-free combustion, which only releases water vapor as a by-product. The use of by-product oxygen through water electrolysis during oxy-combustion integrated with CCS can significantly reduce the total CO_2 emissions (Direct and Indirect) in the case of cement production. The estimated reduction is up to 90% compared to a reference clinker production plant that combusts natural gas with air[41]. These findings demonstrate the potential for by-product oxygen from water electrolysis to make a significant contribution to reducing the carbon footprint of cement plants. Figure 17 represents an integrated cement production system with an alternative H_2-based fuel, consisting of the H_2 combustion to provide the required thermal energy for clinker production. The thermal energy generated from H_2 combustion with the air is utilized in the calcination for clinker production.

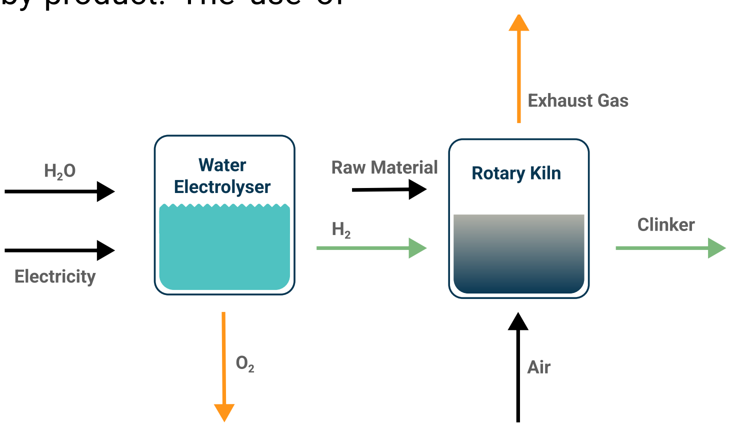

Figure 17: Conceptual Block Diagram of Clinker Production using Hydrogen[42]

Impact of Integration with Kiln: Green hydrogen is integrated on-site to meet the thermal energy demand of the rotary kiln of 725kcal/kg of clinker which translates to 3030.97 MJ/tonne of clinker[43]. Hydrogen has a calorific value of ~120 MJ/kg[44]. Thus, to meet the thermal energy demand, 25.26 kg of green hydrogen will be required per tonne of clinker. Further, the energy requirement to produce 1 kg of green hydrogen is about 55 kWh[45]. This translates to an electrical energy requirement of 1389.3 kWh/tonne of clinker. As the use of green hydrogen is devoid of emission release, the comparison of energy requirement and emissions released, with the conventional process is provided in Table 7.

Table 7: Energy and Emission Comparison of a Conventional Cement Kiln with a Green Hydrogen-Integrated Kiln

Process	Energy requirement per tonne of clinker (in kWh)	Emissions generated (kgCO_2/tonne of clinker)
Conventional	842.61	286.9
Green H2-integrated	1389.3	0

Renewable Electricity

The fully electrified system, as illustrated in Figure 18, combines resistive or inductive electricity with plasma technology. This design focuses on meeting the heat demand in the pre-calciner through a resistive element or magnetic inductio[46]. To maintain the same $CaCO_3$ calcination degree as the reference plant, the raw meal is heated to a higher temperature of 920°C, considering the elevated CO_2 partial pressure.

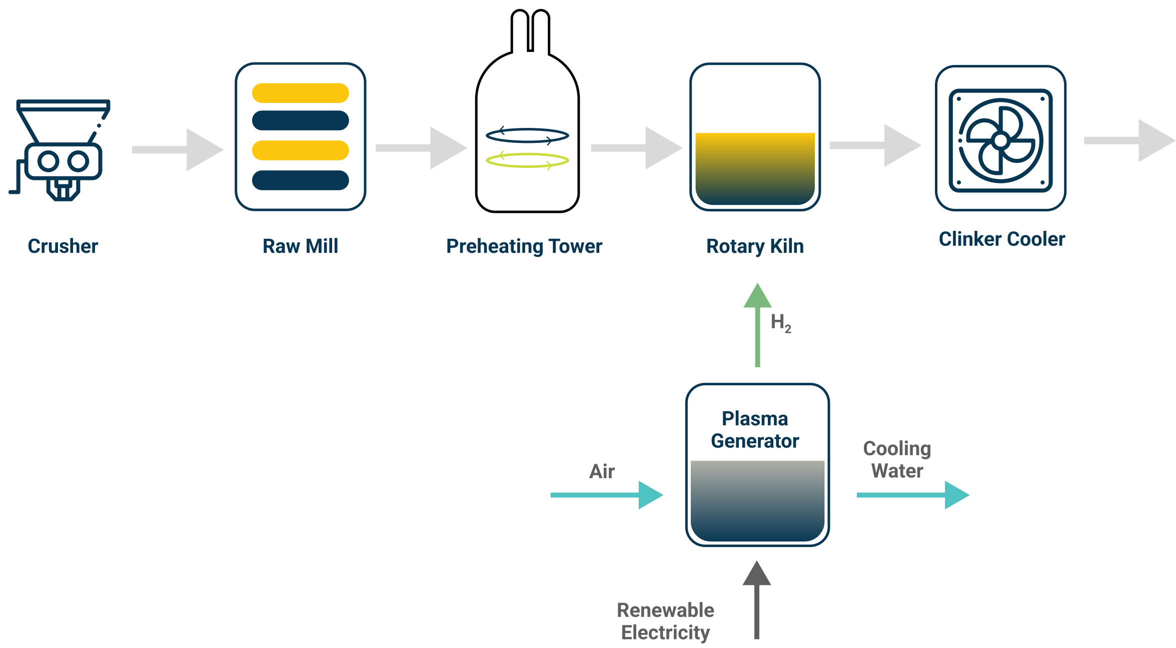

Figure 18: Schematic of the Fully Electrified System Plant[47]

Subsequently, the remaining calcination and clinker phase formation occur in the rotary kiln. Here, air acts as the plasma gas to meet the high-temperature requirements. Plasma burners are utilized to pre-heat ambient air to 3,470°C before it enters the kiln. This temperature choice aligns with the operating conditions of the plasma generators. The flow of plasma gas, combined with secondary air from the clinker cooler, is carefully controlled to achieve an outlet temperature of the clinker phases at 1,450°C.

Impact of Integration: Plasma burners consume energy to the tune of 1650 MJ/tonne of clinker[47]. The total energy demand attributed to the rotary kiln is 3060 MJ/tonne of clinker[47, 48], in this fully-electrified scenario. Thus, a total of 850.68 kWh[49] of electrical energy would be required to meet the energy demand of the rotary kiln, which is close to the conventional kiln's energy consumption. Table 8 compares the energy requirement and emissions generated from the conventional process to the fully electrified process.

Table 8: Energy and Emission Comparison of a Conventional Cement Kiln with a Plasma Electrified Kiln

Process	Energy requirement per tonne of clinker (in kWh)	Emissions generated (kgCO_2/tonne of clinker)
Conventional (thermal)	842.61	286.9
Plasma Generator (electricity from grid)	850.68	603.98
Plasma Generator (100% RE)	850.68	0

Biomass

The following options are available when using biomass in cement plants:

a) Direct combustion of biomass in pre-heaters / pre-calciners and in the kiln by part-replacing the fossil fuel used in raising the temperature of the raw meal.

This can happen in two ways: 1) By mixing crushed and pulverized biomass with coal or pet coke for use in the kiln. 2) By direct feeding of biomass in solid lump form (such as pellets and briquettes) into the rotary kiln and/or pre-heater/pre-calciner combustion chamber.

Utilizing biomass in cement plant pyroprocessing systems presents technical challenges. Biomass fuels require cleaning, preparation, drying, and homogenization to ensure consistent heating values. These fuels, whether in pieces of up to 150 mm diameter, pellets, or briquettes, can be directly burned in combustion chambers positioned between pre-heaters/pre-calciners and the kiln. However, modifying the kiln and pre-heaters/pre-calciners, especially the combustion chamber, is often necessary to accommodate biomass fuels effectively within the pyroprocessing system. Designing and integrating fuel preparation and cleaning units into the plant are crucial steps. Biomass can be utilized in pulverized or lump solid form, requiring the fuel-feed system and plant modifications to align with the chosen form of solid biomass.

b) Transforming biomass into biomethane (also known as 'synthesis gas' or 'syngas') and co-firing it in the kilns using a gas burner.

Biomethane, which is obtained by upgrading biogas, can be co-fired with fuel oil (furnace oil) in rotary kilns. As biomethane is indistinguishable from Natural gas, newly constructed plants can integrate biomethane co-firing systems into their design. However, existing plants may require modification by adding a gasification reactor and a gas injection and firing system to the kiln. While this presents challenges, it is a technically feasible option for utilizing biomethane. Additionally, biomethane can be effectively utilized in pre-calciners.

Major biomass feedstocks include meat and bone meal, woodchips, forest residues, sewage sludge, and various agricultural residues such as rice husk, wheat straw, coffee husk, bagasse, sawdust, coconut husks, palm nut shells, and corn stover. The diversification of feedstock options can facilitate sustained thermal substitution rates (TSR). However, the selection of feedstock should consider factors such as biomass availability, the specific energy requirements of burners (>14.0 MJ/kg for kilns and >8.0 MJ/kg for calciners)[50], as well as the physical (e.g., moisture content, size distribution) and chemical (e.g., volatile matter, ash content) characteristics of the biomass.

Impact of Integration: The thermal energy demand for producing one tonne of clinker stands at 3030.97 MJ. Biomethane which has a calorific value of 36 MJ/m^3 can be introduced as a fuel in the kiln. To support the kiln's thermal energy demand, 84.19 m^3 of biomethane will be required for the production of one tonne of clinker. Biomethane is derived from biogas which can be synthesised from biomass. Biogas upgrading has an efficiency of 60%[51]. Thus, to meet the thermal energy demand of clinker production 140.32 m^3 of biogas would be required to produce one tonne of clinker. The density of biogas is 1.15kg/m^3, thus translating 140.32 m^3 to 161.37 kg. The specific energy consumption of biogas upgrading process is 0.476 kWh/kg[52] of biogas. Given the specific energy consumption for upgrading, 76.81 kWh of electrical energy will be required to support the production of biomethane required to produce one tonne of clinker.

Concerning emissions, a conventional biogas plant has an emission intensity of 27gCO_2/MJ[53] translating to 81.83 kgCO_2/tonne of clinker. Thus, while supporting similar thermal demand, integrating biomass to produce biomethane for the kiln burner has the potential to reduce emissions **by 71.4 percent** from 286.9 kgCO_2/tonne of clinker emitted in the conventional cement production process. Table 9 shows the comparison of energy requirement and emissions released of the biomass-integrated kiln with the conventional kiln.

Table 9: Energy and Emission Comparison of a Conventional Cement Kiln with a Plasma Electrified Kiln

Process	Energy requirement per tonne of clinker (in kWh)	Emissions generated (kgCO_2/tonne of clinker)
Conventional (thermal)	842.61	286.9
Biomethane (biogas production + upgrading via grid electricity)	76.81	(81.83+54.6)
Biomethane (biogas production + upgrading via 100% RE)	76.81	(81.83+0)

Challenges of Incorporating Alternative Fuels and New Technologies

With respect to the aforementioned deep electrification pathways, several key challenges lie ahead that necessitate attention to mainstream the decarbonization concept in the cement sector. These challenges are listed below in no specific order:

- **Small portfolio of existing technology providers for commercial deployment:** Limited availability of established technology providers specializing in decarbonization solutions may slow down the commercial deployment of electrification pathways in the cement sector.
- **High complexity of implementation:** Implementing deep electrification pathways in cement production involves intricate technical and logistical challenges, further complicating the transition process.
- **Quality of biomass feed:** Biomass grades vary based on characteristics such as the crop variety, weather, and region from where it is sourced. This leads to varying quantity of biomass required corresponding to its quality to support similar energy demand. Thus, the heterogenous nature of biomass as a fuel is a challenge to its mainstreaming.
- **Lack of supply chain for biomass:** Biomass resources are often geographically dispersed. To sustain the demand of cement plants, there must be a reliable supply of biomass feed. Currently, as there is a lack of an established supply chain for biomass, it cannot be substituted as the primary fuel in meeting the energy requirement of cement plants.
- **Presence of competitive use:** Emerging technologies like green hydrogen are increasingly seen as effective energy vectors to abate emissions in energy-intensive sectors. Biomass is also being explored owing to its low-carbon energy characteristic. However, owing to the nascency of green hydrogen production, demand is bound to exceed supply in the intial stages, and might prevent economical transition for cement plants, owing to competing demand from other emission-intensive sectors. Similarly, biomass availability is finite, and might not be viewed as a reliable energy source for industries to adopt.

- **Lack of Infrastructure:** Green hydrogen incorporation in existing production lines will require additional infrastructure to manage its volatile nature. Facilities must be available for storage and transportation of green hydrogen. In cases where business sense prevails, the hydrogen production could also be co-located in the end-use facility, requiring necessary infrastructure.

- **Cost of Integration:** The high costs of green hydrogen production coupled with additional burden of adding supporting infrastructure will require cement plants to undertake additional financial burden. Also, incorporation of fully electrified technologies such as a plasma generator to supply thermatic fluids to the kiln is currently not economical. Cement plants may struggle to justify immediate financial benefits from transitioning to decarbonization pathways, potentially hindering adoption.

- **Insufficient Regulatory Support:** Policies that encourage industries to adopt Renewable Energy such as tariff incentives are necessary. Further, meeting round-the-clock energy requirements must also be addressed to posit RE as a reliable source of electricity for cement plants. Further, given the upcoming Indian carbon market, guidelines must be established to ease the participation of energy-intensive sectors such as cement production.

5

Impact Analysis of Deep Electrification Alternatives

In this section, our objective is to assess the potential emission reductions resulting from the implementation of the aforementioned deep electrification interventions and their impact on the overall energy consumption within an operational plant. To gather relevant data for this analysis, we conducted a comprehensive site visit to a plant located in the southern region, where we engaged in detailed discussions with plant officials. Figure 19 presents some visual highlights from our visit. Our observations revealed that the plant operates with high efficiency, with only specific areas identified for targeted decarbonization efforts.

Figure 19: Snapshots from Visit to Cement Plant

The data collected from this plant visit has been integrated into our analysis as observed in Table 10. The rotary kiln of the conventional cement plant is assumed to be powered by coal with an emission factor of 95.63 tCO_2/TJ. The operational capacity of the kiln in this plant is assumed to be 1800 tonnes per day (TPD). The energy utilized per kg of Clinker is around 660 kCal/kg. The plant meets its electricity demand through the grid in the conventional case with a grid emission factor of 0.71 tCO_2/MWh. For all the deep electrification interventions electricity is assumed to be through a captive RE plant that is capable of delivering round-the-clock power.

Table 10: Operational Parameters of Reference Cement Plant

Thermal energy consumption (MJ/tonne of clinker)	2761.44
Electrical energy consumption (kWh/tonne of cement)	67
Clinker to Cement Ratio	0.71
Cement produced per day (in tonnes)	2535.21
Total thermal energy consumption per day	4.97 (in TJ)
	1380.55 (in MWh)
Total emissions from thermal energy (in tCO_2)	475.28
Total electrical energy consumption per day (MWh)	169.85
Total emissions from electrical energy (in tCO_2)	120.59
Total plant-level energy consumption per day (in MWh)	1550.4
Total plant-level emissions per day (in tCO_2)	595.87

Case 1: Fully Electrified using a Plasma Generator Using conventional fuel, the cement plant requires 1550.4 MWh of energy per day. In the fully electrified case, where the plasma generator is integrated to the rotary kiln, 603.98 kWh/tonne of cement of energy is to be supplied to meet the thermal demand. The total energy consumption to produce one tonne of cement is 670.98 kWh (603.98 kWh of thermal + 67 kWh of electrical). Thus, the total energy consumption to meet the cement plant's energy requirement per day is 1701.07 MWh. In this case, we observe a 9.7 percent increase in energy consumption as shown in Figure 20. Further, as the fully-electrified case is powered by RE, the emission intensity is nil as compared to the conventional case.

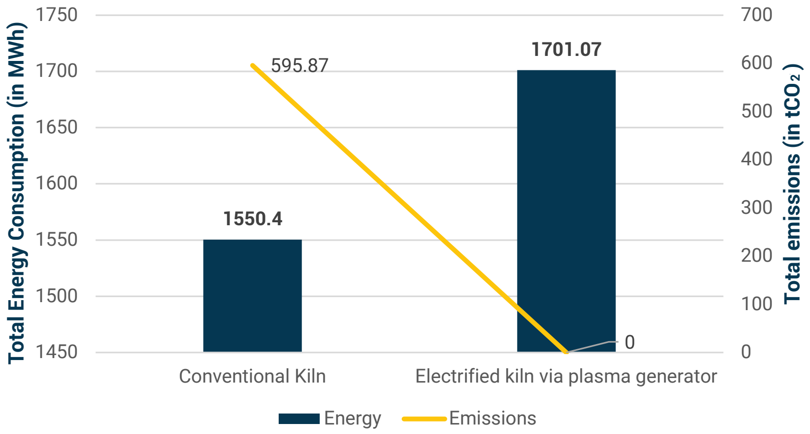

Figure 20: Impact on Energy Consumption and Emissions in Fully-Electrified via Plasma Generator Case

Case 2: Integrated with Green Hydrogen Using conventional fuel, the cement plant requires 1550.4 MWh of energy per day. Green hydrogen is integrated on-site to meet the thermal energy demand of the rotary kiln. To meet the thermal energy demand, a thermal energy equivalent of 1265.66 kWh/ tonne of clinker is necessary. According to the clinker-cement ratio considered, the thermal energy demand per tonne of cement stands at 898.61 kWh. The total energy consumption to produce one tonne of cement is 965.61 kWh (898.61 kWh of thermal + 67 kWh of electrical). Thus, the total energy consumption to meet the cement plant's energy requirement per day is 2448.02 MWh. In this case, we observe a 57.9 percent increase in energy requirement as shown in Figure 21. Further, as the kiln is powered by green hydrogen, the emission intensity is nil as compared to the conventional case.

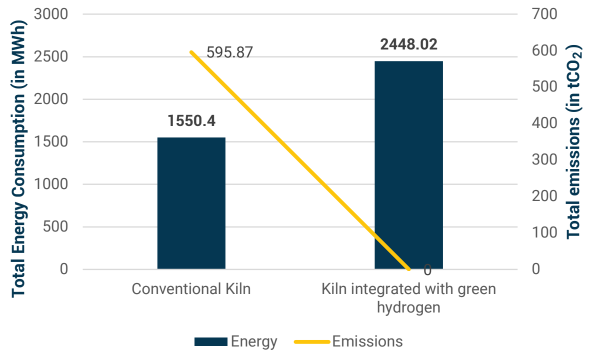

Figure 21: Impact on Energy Consumption and Emissions in Kiln Integrated with Green Hydrogen Case

Case 3: Integrated with Biomass Using conventional fuel, the cement plant requires 1550.4 MWh of energy per day. Given the specific energy consumption for upgrading of 0.476 kWh/kg of biogas, 69.98 kWh of electrical energy will be required to support the production of biomethane required to produce one tonne of clinker. According to the clinker-cement ratio considered, 49.68 kWh will be required to meet the thermal energy demand per tonne of cement. The total energy consumption to produce one tonne of cement is 116.68 kWh (49.68 kWh of thermal + 67 kWh of electrical). Thus, the total energy consumption to meet the cement plant's energy requirement per day is 295.82 MWh. In this case, we observe an 80.9 percent decrease in the energy requirement as shown in Figure 22. Owing to the emission intensity of the biogas plant, which translates to 74.55 kgCO^{2}/tonne of clinker, we derive the emissions per tonne of cement as 52.93 kgCO^{2}. This translates to a total emission intensity per day of 134.18 tCO^{2}.

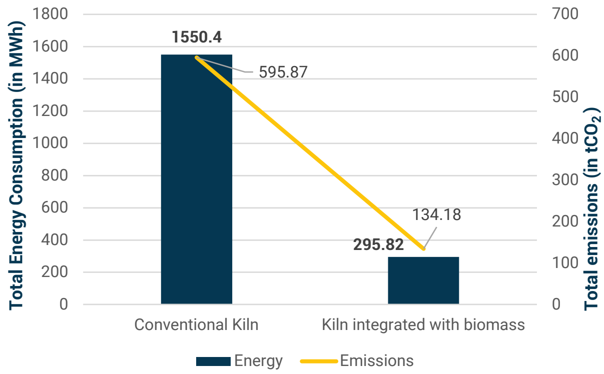

Figure 22: Impact on Energy Consumption and Emissions in Kiln Integrated with Biomass Case

6

Recommendations and Conclusion

The decarbonization of the cement sector stands as a critical imperative on the global stage, with nations striving to align industrial growth with sustainability goals. In the context of India, a country experiencing rapid infrastructure development, the need to transition towards cleaner and more efficient cement production processes is paramount. This report presents a comprehensive set of deep electrification strategies tailored to the Indian cement industry, aimed at reducing carbon emissions and enhancing sustainability. From promoting the adoption of alternative cement types to incentivizing renewable energy integration and developing sustainable feedstock supply chains, these recommendations are designed to catalyze a shift towards greener practices. Another pivotal measure is reducing the clinker content in cement which contributes the most to its carbon footprint, and is achievable through substitution with supplementary cementitious materials. Furthermore, suggestions for innovative financing options, procurement mandates for green cement, and the gradual adoption of green hydrogen underscore a multifaceted approach to cement decarbonization. Collaborative efforts, training enhancements, and strategic partnerships are also highlighted as key pillars to empower the sector with the knowledge and tools needed for a sustainable future. As India charts its path towards a low-carbon economy, the implementation of these strategies promises not only environmental benefits but also economic resilience and technological advancement within the cement industry.

Recommendations related to these strategies are mentioned below:

- **Inclusion of Cement Sector in the National Green Hydrogen Mission[54] :** The National Green Hydrogen Mission (NGHM) document, released in January 2023, adopts a phased approach. Phase 1, spanning from 2022-23 to 2025-26, targets refineries, fertilizers, and city gas distribution segments, emphasizing R&D projects focused on green hydrogen in hard-to-abate sectors. Scheme guidelines have been issued for executing pilot projects within the shipping and steel sectors. Given the availability of technology solutions in the market, it is advisable for the NGHM to broaden its scope by incorporating the cement sector and issuing scheme guidelines for pilot projects in this domain as well.

- **Develop value chain for sustainable feedstock:** Support the development of sustainable biomass supply chains by working with local agricultural sectors, forestry industries, and waste management systems. Provide funding for research into efficient biomass processing technologies and infrastructure development for biomass utilization in cement plants.

- **Enable and Incentivise use of RE:** Provide tariff incentives to cement plants such as waivers of Inter- state transmission system (ISTS) charges, and promotion of open-access RE to encourage the adoption of renewable electricity at the site of production.

- **Procurement mandates on Green Cement:** Regulations that lay down a minimum annual purchase mandate of green cement for state-funded infrastructure projects must be developed. This approach aligns with global practices, such as the UK government's agreement with the Construction sector, initiated in November 2017[55]. This will demonstrate the demand signal to cement producers, encouraging them to invest in clean technologies.

- **Decreasing the Clinker Factor :** Incorporation of alternative materials stands out as a crucial strategy for decarbonizing cement production for both mitigating costs and GHG emissions. Presently, the cement industry has successfully integrated fly ash and BF-BoF slag into the mix as substitutes for clinker. However, further investigation into the viability of utilizing bottom ash and other slags (like EAF/IF slag) as an alternative clinker material is warranted.

- **Leveraging Voluntary Carbon Markets (VCMs):** One of the key aspects of the VCM is to provide financing for hard-to-abate sectors like cement to decarbonize. In 2023, India introduced the 2023 Carbon Credit Trading Scheme (CCTS), encompassing both compliance and voluntary sectors. The cement industry in the future can leverage the VCM to direct much-needed financing to the sector and make the decarbonization technologies discussed in this report economically viable.

- **Enhancing Training and Collaboration for Cement Sector Decarbonization:** To effectively decarbonize the cement sector, it is recommended to ensure comprehensive training that covers diverse areas of modern cement plant operation and management. This includes expertise in manufacturing technology, machinery herandling, and understanding input materials. A robust training regimen should be maintained through regular activities, backed by experts and relevant study materials. This can be achieved by aligning company-specific skills initiatives with state and national skill development programs, and exploring funding opportunities through engagement with local governments. Additionally, strategic partnerships with non-profit organizations, including academic institutions, for collaborative research projects and knowledge-sharing initiatives, can provide valuable technical assistance. Such collaborations can lead to improved operational processes, production efficiency, and the development of training materials without significant resource investment from the organization.

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