Evaluating Net-zero for the Indian Cement Industry

Marginal Abatement Cost Curves of Carbon Mitigation Technologies

Kartheek Nitturu, Pratheek Sripathy, Deepak Yadav, Rishabh Patidar, and Hemant Mallya

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Contents

Cement plants need heat at elevated temperature conditions and is referred to as hard-to-abate sector of the economy.

Image: iStock

Executive summary

India is the second-largest producer of cement in the world. The current emphasis on infrastructure development in the country is expected to drive cement demand further. The Indian cement industry has established itself as one of the frontrunners in driving efficiency measures and setting ambitious net-zero targets. The successful implementation of the PAT scheme has played a key role in adopting energy-efficient technologies. However, it is imperative to look beyond energy efficiency to meet India's climate goals.

Process emissions contribute to ~56% of total emissions from the cement industry

A. CO_2 emissions are inherent to the cement production process

Cement manufacturing is an emission intensive process. The cumulative CO_2 emissions from manufacturing 337 million tonnes of cement in 2018-19 were estimated at 218 million tonnes. Our baseline estimates show that nearly 56 per cent of the total 0.66 tonnes of CO_2 per tonne of cement produced is due to the calcination of limestone in the kilns. Most of the remaining emissions, 32 percent is due to the combustion of fuels for process-heating applications, while only 12 per cent is due to the electricity used for manufacturing.

B. Four categories for decarbonising the cement industry

The technological options for decarbonising the cement industry can broadly be classified into four categories.

Energy efficiency (EE): Adopt measures that reduce energy consumption per unit output (thermal and electrical) while also increasing the waste heat recovered in each step of the manufacturing process.

Alternative fuels and raw material (AFR): Use of renewable energy and alternative fuels such as biomass and municipal solid waste instead of fossil fuels.

Clinker factor reduction (CF): Reduce the clinker factor by increasing the share of additives such as steel slag and fly ash in the cement.

Carbon management: Mitigate emissions through carbon capture, storage and utilisation, or afforestation.

C. Key insights

Carbon management measures are key to achieving a net-zero cement industry

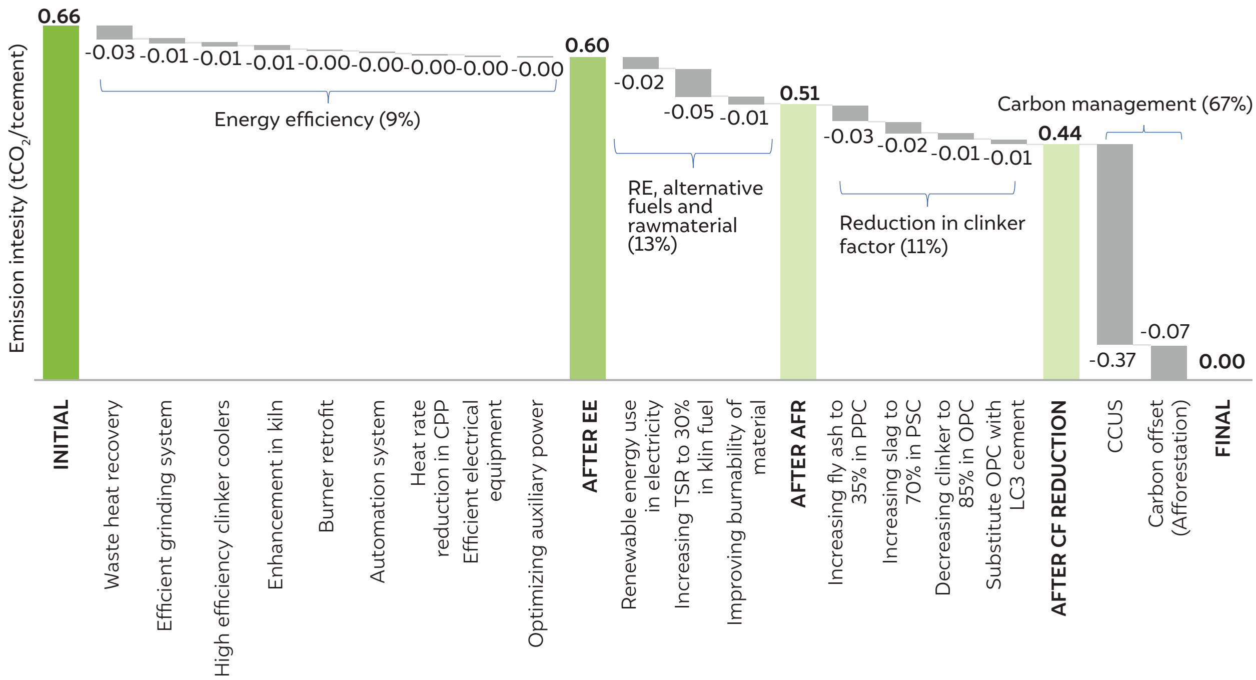
Figure ES1 shows the trajectory for achieving net-zero in the cement industry by deploying the carbon mitigation measures listed prior. To begin, the emissions intensity of cement can be reduced by 9 per cent from 0.66 to 0.60 tonnes of CO2 per tonne of cement by adopting energy-efficient technologies. It can be further reduced to 0.58 tonnes using renewable energy (RE), and then to 0.51 tonnes using alternative fuels such as municipal solid waste (MSW) and biomass. The emissions intensity can further be brought down to 0.44 tonnes of CO2 per tonne of cement by boosting fly ash utilisation to 35 per cent (from 27 per cent) in pozzolana portland cement (PPC), the slag rate to 70 per cent (from 40 per cent) in portland slag cement (PSC), switching to limestone calcined clay cement (LC3) (replacing 10 per cent of ordinary portland cement (OPC) cement sales), and lowering the OPC clinker factor to 0.85 (from 0.90) with additional additives. The remaining emissions can only be mitigated by adopting carbon capture, utilisation, and storage (CCUS) solutions. However, even with a peak capture efficiency of 85 per cent across the CCUS pathway, carbon offset mechanisms such as afforestation must be deployed to achieve net-zero.

Supply chain management of clinker substitution material is key to reducing the average clinker factor in India

Carbon capture, utilisation, and storage have the potential to abate a significant amount of emissions

The marginal abatement cost (MAC) curve in Figure ES2 plots all the decarbonisation measures evaluated in this study and their respective CO2 abatement potential. Between mitigation measures ranging from improving electrical equipment efficiency to reducing the clinker factor in PPC, there are 13 decarbonisation measures that have a negative cost of mitigation. Of these, nine are energy efficiency technologies, one relates to the use of alternative raw materials, and three pertain to the reduction of the clinker factor. Technologies with a negative cost of mitigation can reduce the emissions intensity of cement from 0.66 to 0.53 tonnes of CO2 per tonne of cement. They provide a net financial benefit for the plant implementing it. However, there would be supply chain challenges in reducing

Figure ES1 Carbon management will play a significant role in achieving a net-zero cement industry

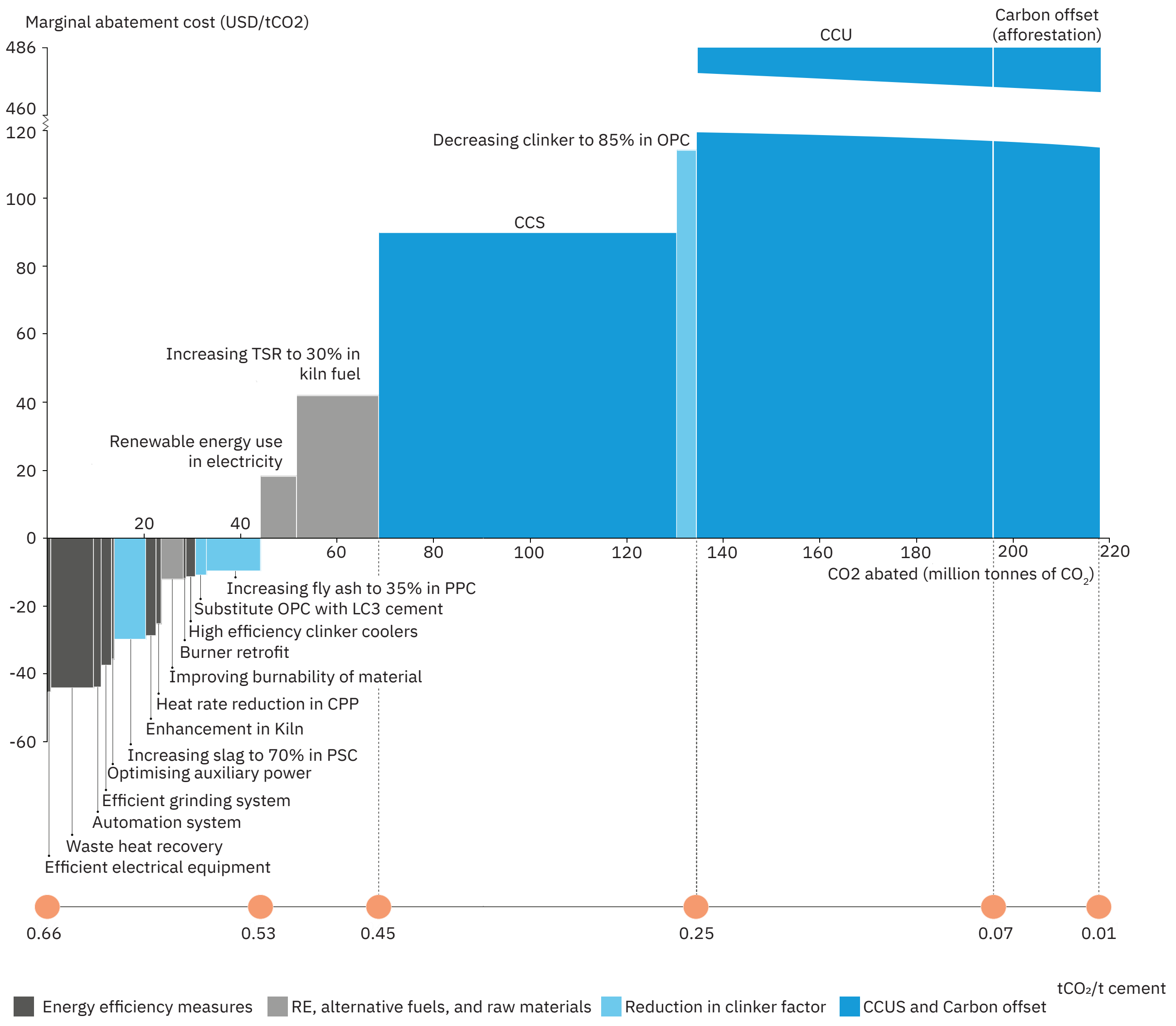


Source: Authors' analysis

the clinker factor in PSC and PPC. The Bureau of Indian Standards has not approved the production of LC3. Several technologies have positive mitigation costs, such as RE, increasing the thermal substitution rate (TSR), further reducing the clinker factor in OPC by using alternative additives, and implementing carbon-management technologies.

The emissions from using fossil fuels for thermal energy account for 32 per cent of the total emissions from cement production. These emissions can be reduced by adopting alternative sources of energy such as biomass and municipal solid waste. However, alternative fuels are more expensive than coal/petcoke, which are currently primarily used in the cement industry. Although alternative fuels can abate 28 million tonnes of CO2, the cost of abatement is approximately USD 42/tCO2 (MSW and biomass).

Figure ES2 Emissions reduction trajectory for the cement industry



Source: Authors' analysis

Note: The MAC for afforestation is only representational as an option for carbon mitigation without getting into the cost of mitigation.

Captive or grid electricity, which constitutes approximately 12 per cent of the total emissions from the cement industry, can be replaced with electricity sourced from wind and solar power plants. We estimate that for producing 337 million tonnes per annum (MTPA) of cement, 1.3 GW of round-the-clock (RTC) RE capacity will be required. In this study, we have considered only a 40 per cent replacement of electricity demand by RTC RE. This is because a 50 per cent reduction in power demand can be achieved by adopting energy efficiency measures, including waste heat recovery units. The remaining 50 per cent can be replaced by RTC RE. Though recent RTC RE tenders have an annual availability of 80 per cent (Thacker et al. 2020) and more, the cost of power increases significantly due to RE oversizing and the use of batteries. It is assumed that the remaining power will be drawn from the grid. We have considered the corresponding emissions intensity of grid power in our analysis.

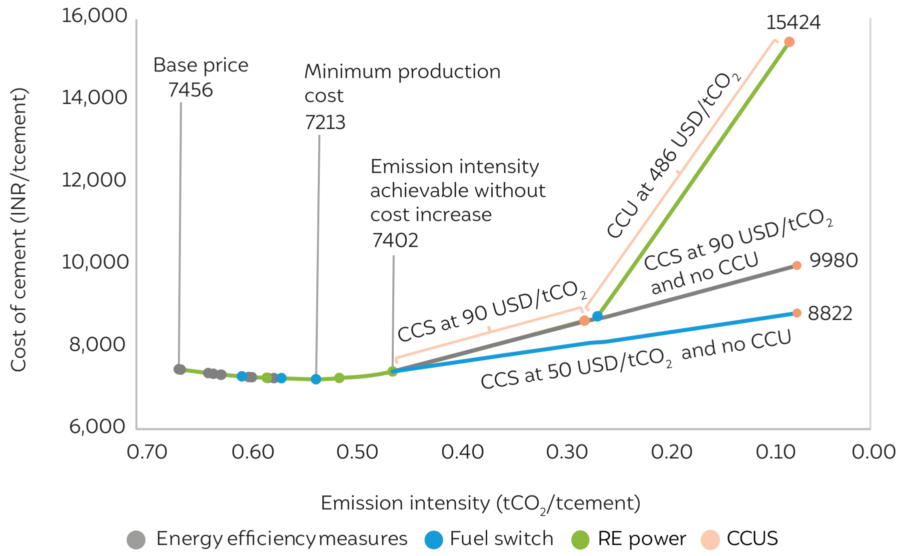
Energy efficiency and clinker substitution material can reduce the average emissions intensity of cement by ~32% without any cost increase

Approximately 56 per cent of the emissions typically come from process emissions during clinker making. Since CO_2 is released through a chemical reaction (calcination), it cannot be eliminated by alternative fuels or adopting energy efficiency measures. The cost of mitigation from the CCUS pathway is significantly higher than adopting alternative fuels or moving to RTC RE. Right-of-way impedes scaling up the CO_2 transportation infrastructure, which is necessary for scaling up the carbon capture and storage (CCS) pathway in India. Our assessment shows that about 50 per cent of cement plants in India need access to natural gas pipelines. Therefore, as of today, these cement plants cannot opt for CCS, assuming that these pipelines or new ones utilising the same right-of-way will carry CO_2 to the storage sites. Therefore, we assume that these cement units use the carbon capture and utilisation (CCU) pathway to achieve net-zero emissions. While there are multiple pathways and processes for CCU, the study considers CO_2-to-methanol production to be a CCU application. This is because of the multiple use applications that green methanol provides, such as fuel for blending in gasoline, the petrochemical industry, the building block for sustainable aviation fuel (SAF) and producing green olefins. However, CCU has the highest cost of mitigation primarily due to the high cost of green hydrogen today (assumed to be USD 4.2/kg).

Thirty two per cent of emissions can be reduced without increasing the cost of cement

The transition to net-zero cement will significantly increase the cost of the final commodity to the consumer. This can be attributed to a CAPEX of INR 25 lakh crore and an annual OPEX of INR 29,580 crore required to achieve net zero in the cement industry. Figure ES3 shows the variation in cement price due to various decarbonisation measures across different emission intensities. **The analysis indicates that with the adoption of decarbonisation measures having a negative cost of mitigation, the cost of cement reduces by 3 per cent while also ensuring a 20 per cent decrease in emissions intensity. Further, with the use of measures that have a positive cost of mitigation, a breakeven can be achieved with the current cost by reducing the emissions intensity by 32 per cent.** However, with the use of expensive decarbonisation options such as CCS and CCU at USD 90 and USD 486 per tonne of CO_2, respectively, there is a 107 per cent increase in the cost of cement to the consumer. This increase in cost can be reduced to 34 per cent if all cement plants have access to CCS infrastructure. Further, if the cost of CCS reduces to USD 50 per tonne of CO_2, then the cost of net-zero cement is expected to be only 19 per cent higher than the current costs.

Figure ES3 Emissions intensity of cement can be reduced by 32% without increasing the cost of cement



Source: Authors' analysis

D. Recommendations to achieve a net-zero cement industry

To summarise, we recommend the following measures to achieve net-zero in the cement industry.

- Mandate the use of the best available energy efficiency technologies under the recently announced Indian Carbon Market (ICM) scheme to achieve reduction at no cost increase in the price of cement since all the energy efficiency measures are commercially available. Additionally, all greenfield investments should receive approval only with these best available technologies as a standard option.
- Evaluate the suitability of EAF/IF slag as an additive in cement production in addition to the current use of fly ash and BF-BOF slag and build a supply chain for their utilisation.
- Develop supply chains for the collection and delivery of alternative fuels such as biomass and MSW, which will enable a substantial reduction of emissions from kilns.
- Develop a robust MRV framework to estimate GHG emissions at a process, equipment, and plant level to measure progress and potentially benefit from the carbon market being developed in India.
- Incentivise RE as it will play a pivotal role in decarbonisation through lower or no transmission charges at the centre and state levels.
- Develop a CCS ecosystem in India for full decarbonisation as that is the cheapest alternative available to mitigate process emissions.
- Formulate favourable policies to build a CCU ecosystem in the country to provide an alternative for plants at which CCS may not be an option.
- Build a research and development (R&D) ecosystem for the cement industry to evaluate new technologies such as LC3 and electrification of the kiln.

The Indian cement sector should prioritise reducing the clinker factor by promoting blended cements, such as LC3 cement, to achieve sustainability goals effectively.

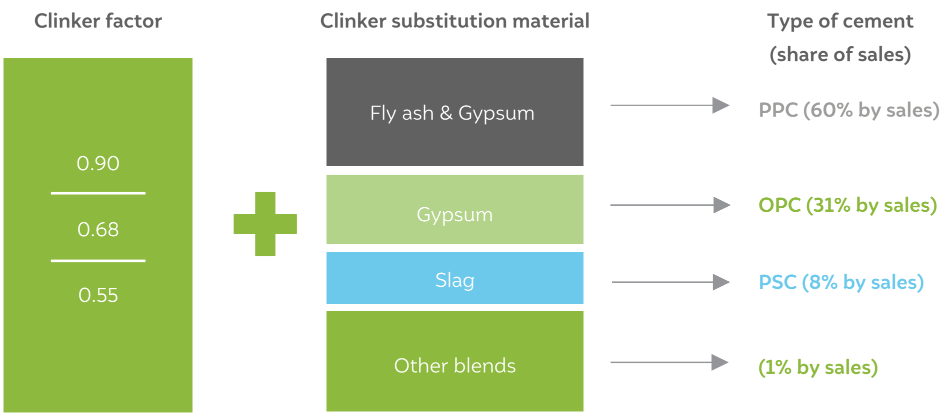
Image: iStock

1. Introduction

Cement plays a vital role in the economic development of a country. India is the second-largest producer of cement, next only to China. However, the annual per capita consumption is only 195 kg compared with the global average of 500 kg (Bureau of Energy Efficiency 2023). The industry is expected to have strong growth in the coming decades, with increased private- and public-sector spending on infrastructure in the country. As of the fiscal year 2018–19, the total installed capacity and production of cement are 557 MTPA and 337 MTPA, respectively (India Bureau of Mines 2018). Studies indicate that cement production capacity in India could double in the coming decades (International Energy Agency 2009).

Clinker is the intermediary product that is produced from cement kilns where limestone is heated in a controlled environment along with materials such as bauxite, clay and others (IFC 2012). By mixing different proportions of clinker with different additives such as gypsum, fly ash, limestone, and slag, various types of cement with different properties are produced. The ratio of clinker to additives is referred to as the clinker factor. Broadly, cement can be categorised as Pozzolana Portland Cement (PPC), Ordinary Portland Cement (OPC), and Portland Slag Cement (PSC). This classification and their respective compositions are schematically represented in Figure 1. Approximately 60 per cent of the cement sold in India is the PPC type, while OPC and PSC make up 31 and 8 per cent of sales, respectively (World Business Council for Sustainable Development 2012).

Figure 1 **Types of cement categorised by their clinker ratio**



Source: Authors' compilation

The average specific energy consumption (SEC) in Indian cement plants stands at 741 kcal/kg clinker (thermal) and 83.7 kWh/tonne cement (electrical), while the global average is 836 kcal/kg clinker (thermal) and 91 kWh/tonne cement (electrical) (BEE, IGEN, and CII 2018; SS et al. 2012). Indian plants fare particularly well against global cement plants since they have adopted technologies such as high-efficiency kilns with preheaters and pre-calciners that reduce SEC in cement production. A significant share of existing cement production capacity was commissioned post 2005 and have therefore deployed energy-efficient manufacturing systems.

OPC, PPC, and PSC are the major types of cement produced in India

Most cement plants in India, nearly 99 per cent by capacity, have adopted the energy-efficient dry kiln technology as against the less efficient wet kiln technology. In addition, Indian cement plants produce a higher share of blended cement that has less clinker than other parts of the world. However, the energy consumed in the cement manufacturing process is largely sourced from fossil fuels, predominantly coal and petcoke, which contribute significantly to the emission footprint of the country. In addition, CO_2 emissions are inherent to the production process (termed process emissions) due to limestone processing which cannot be eliminated by using alternative sources of energy.

Industry at a glance

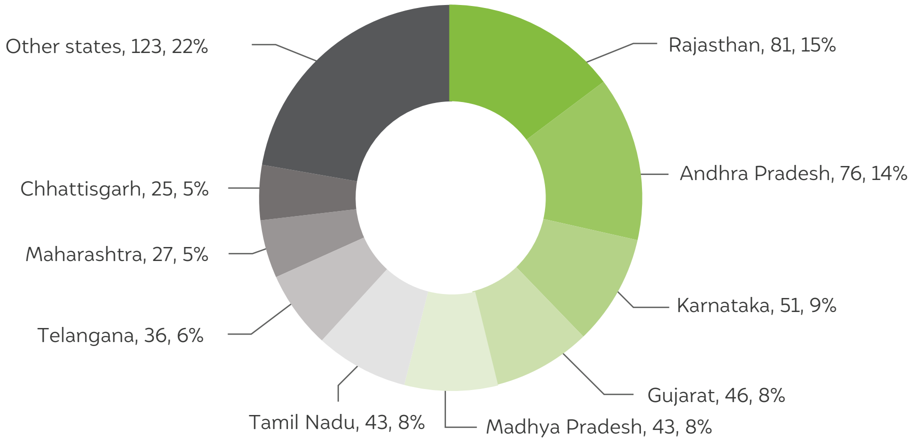
Cement production plants are typically located in regions that have large limestone deposits since it is a key ingredient. Cement is manufactured in integrated facilities that house cement kilns that produce clinker and grinding units that grind the clinker and mix them with different proportions of additives to produce a variety of cement. Cement is also produced in standalone grinding units that procure clinker from the market.

As seen in Figure 2a, Rajasthan, Andhra Pradesh, and Karnataka have the highest cement production capacities in India. The cumulative production from large cement plants that produce more than 1 MTPA accounts for 88 per cent of the total production. In addition, there are 62 grinding plants spread across the country with a production capacity of 83 million tonnes per annum (India Bureau of Mines 2018). However, the capacities of many integrated cement and grinding plants are not available due to a lack of accurate data in the public domain (India Bureau of Mines 2018).

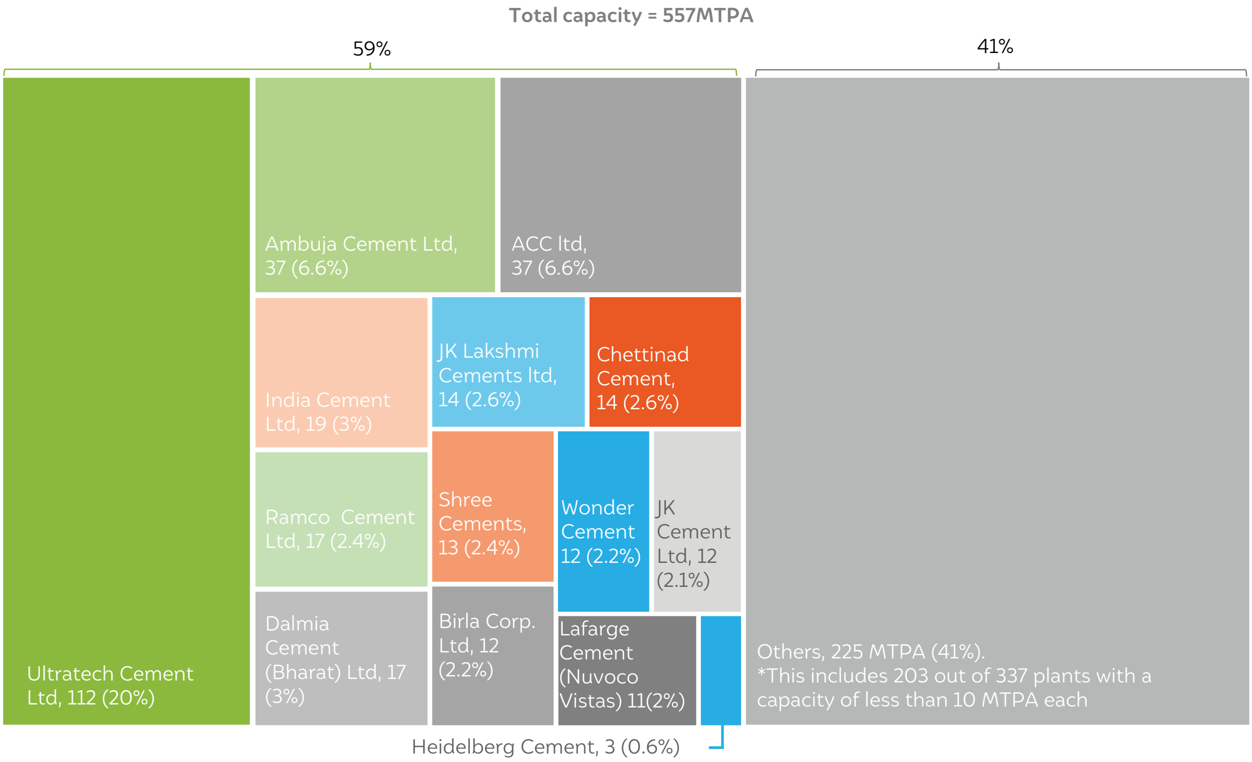
Of the total 337 cement plants in India, 134 (owned by 13 companies) account for 59% of the country's cement production capacity (Figure 2b), which stood at 157 MTPA (Rajya Sabha Secretariat 2011) in 2005 and rose to 557 MTPA by 2018 (India Bureau of Mines 2018).

Figure 2 Rajasthan and Andhra Pradesh have the highest production capacity in the country

(a) State-wise distribution of cement production capacity (state, production (MTPA), share (%)



(b) 13 companies account for 59% of the country's cement production capacity

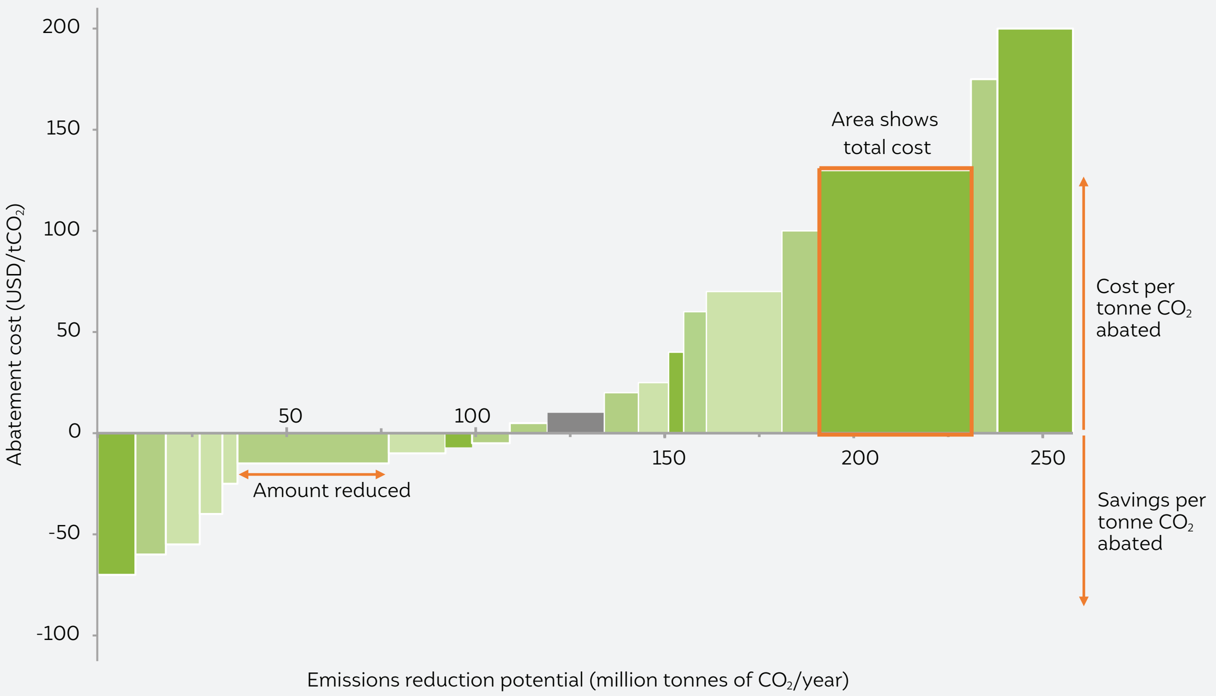


Source: Authors' compilation of production capacities (MTPA) and share of production from IBM 2019

Box 1 Utility of a MAC curve

The marginal abatement cost (MAC) curve plots the annualised CO_2 mitigation cost (USD/tCO_2) of a given carbon mitigation technology (y-axis) against the total mitigation potential (tCO_2) of that technology (x-axis). The area of each block/bar represents the annualised cost to mitigate emissions with a particular option. The annualised cost includes both the CAPEX annualised at a specific discount rate and the lifetime of the equipment and annual OPEX. Figure 3 shows the schematic of a generic MAC curve. The mitigation cost ranges from negative to positive; a negative cost indicates a net economic gain from deploying that technology, while a positive cost indicates that the entity will incur additional expenses to mitigate its emissions. Typically, the sum of all values of each bar on the y-axis indicates the total price per unit of emissions for achieving net-zero emissions, whereas the sum of all x-axis values indicates the total CO_2 emissions (or mitigation potential) for the base year used to develop the curve.

Figure 3 Schematic of a generic MAC curve



Source: Authors' analysis

2. Baseline emissions

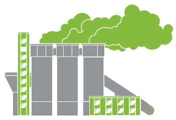
Image: iStock

The primary objective of this analysis is to examine the options available to the cement industry to achieve net-zero. To analyse the potential pathways for decarbonisation, a baseline has to be established as a reference point. This reference point will aid in measuring the difference in specific energy consumption (SEC) and emissions intensity of cement production in a business-as-usual and the proposed net-zero scenarios. However, there is no national-level GHG accounting mechanism that utilises real-time data rather than extrapolations or theoretical calculations to estimate sector-specific emissions. Therefore, after an extensive literature survey, 2018–19 was chosen as the baseline. This choice can be justified by the fact that the data collated by the Indian Bureau of Mines for the year 2018–19 is more comprehensive than the successive years. Further, we wanted to avoid any pandemic-related disruptions in cement production and fuel prices. The post-pandemic values have not been considered primarily due to significant increases in fuel prices that will portray very optimistic gains from energy efficiency and alternative fuels that might not be realisable in the long term.

Currently, the cement manufacturing process chain uses thermal and electrical energy that is primarily sourced from fossil fuels. At the same time, some facilities do use a mix of fuels and a share of electricity generated through renewable sources. A lack of granular plant-level data regarding these has necessitated certain overarching assumptions. Consequently, different types of cement have varying electrical and thermal energy consumptions due to their unique clinker factor. In this study, we normalised the clinker factor per tonne of cement rather than per tonne of clinker and measured by production quantities for the three main types of cement — PPC, OPC and PSC.

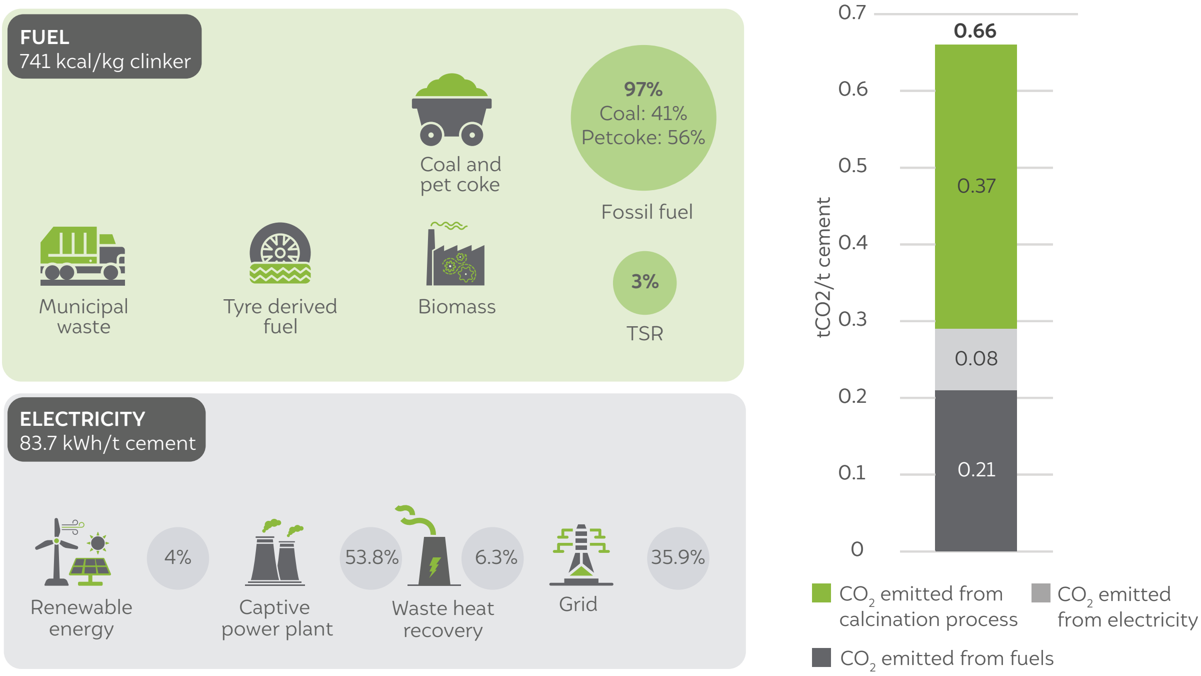
However, these estimations account for scope 1 and 2 emissions only and are limited to the plant boundary. As seen in Figure 4, we have considered that coal and petcoke provide 97 per cent of the thermal energy required in the plant, while the remaining 3 per cent is sourced through alternative fuels such as biomass and municipal solid waste (WBCSD 2012). The extent of use of alternative fuels is referred to as the thermal substitution rate (TSR). Coal is also used in captive power plants that produce electricity onsite in the production unit. Based on data compiled from various sources, we consider that 53.8 per cent of the electricity required to produce 1 tonne of cement is obtained from captive power plants, while 35.9 per cent is sourced from the grid; literature also indicates that the use of RE is a mere 4 per cent of the overall mix. The remaining 6.3 per cent is considered to be obtained from electricity produced through waste heat recovered in the plant (IBM 2021; Environment Clearance 2017; UltraTech 2020).

Based on these calculations, we estimated the cumulative CO_2 emissions from manufacturing 337 million tonnes to be 218 million tonnes**.** Our baseline estimations, seen in Figure 4, show that nearly 56 per cent of the total 0.66 tonnes of CO_2 per tonne of cement produced is due to the calcination of limestone in the kilns. Most of the remaining 32 per cent of emissions is due to the combustion of fuels for process heating applications, while only a small portion – 12 per cent precisely – is due to the electricity used for manufacturing. The break-up of electricity consumption in the cement manufacturing process (for a clinker ratio of 0.73) can be seen in Figure 5. The assumptions and their consequent effects are discussed in detail in section 4.4, respectively.



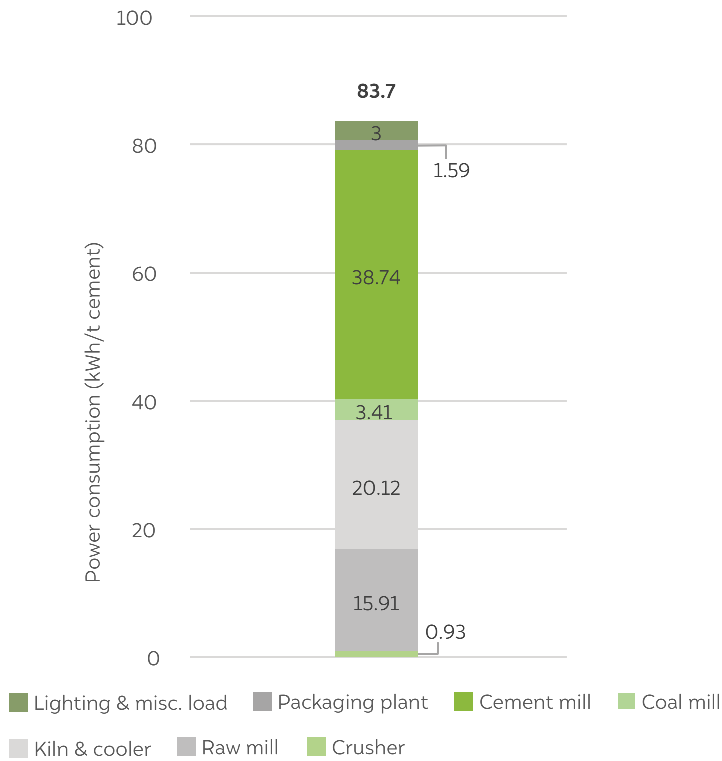
The Indian cement industry emitted approximately 218 million tonnes of CO_2 in the year 2018-19

Figure 4 **The calcination process accounts for the highest share of overall CO_2 emissions**



Source: Authors' analysis

Figure 5 **The cement mill accounts for the highest power consumption in the manufacturing process**



Source: Authors' analysis; CSTEP

Process emissions and the use of fossil fuels to meet thermal energy requirements and power demand are the primary sources of emissions in the cement industry.

Image: iStock

3. MAC estimation methodology

The technological options for the decarbonisation of the cement industry can largely be classified into four categories. The first is energy efficiency measures that reduce the energy consumption per unit output (thermal and electrical), including the waste heat recovered in each step of the manufacturing process. The second is the use of alternative fuels and raw materials – such as biomass and natural gas – for fossil fuels and other raw materials – such as fluorides, chlorides, and sulphates – to reduce kiln temperature requirements. The third is the reduction in clinker factor by increasing the share of additives such as steel slag and fly ash in the cement. The fourth is emission mitigation through carbon capture, storage, and utilisation or afforestation. The schematic in Figure 6 lists the different technologies that are available across each category.

Figure 6 Four categories for decarbonising the cement industry

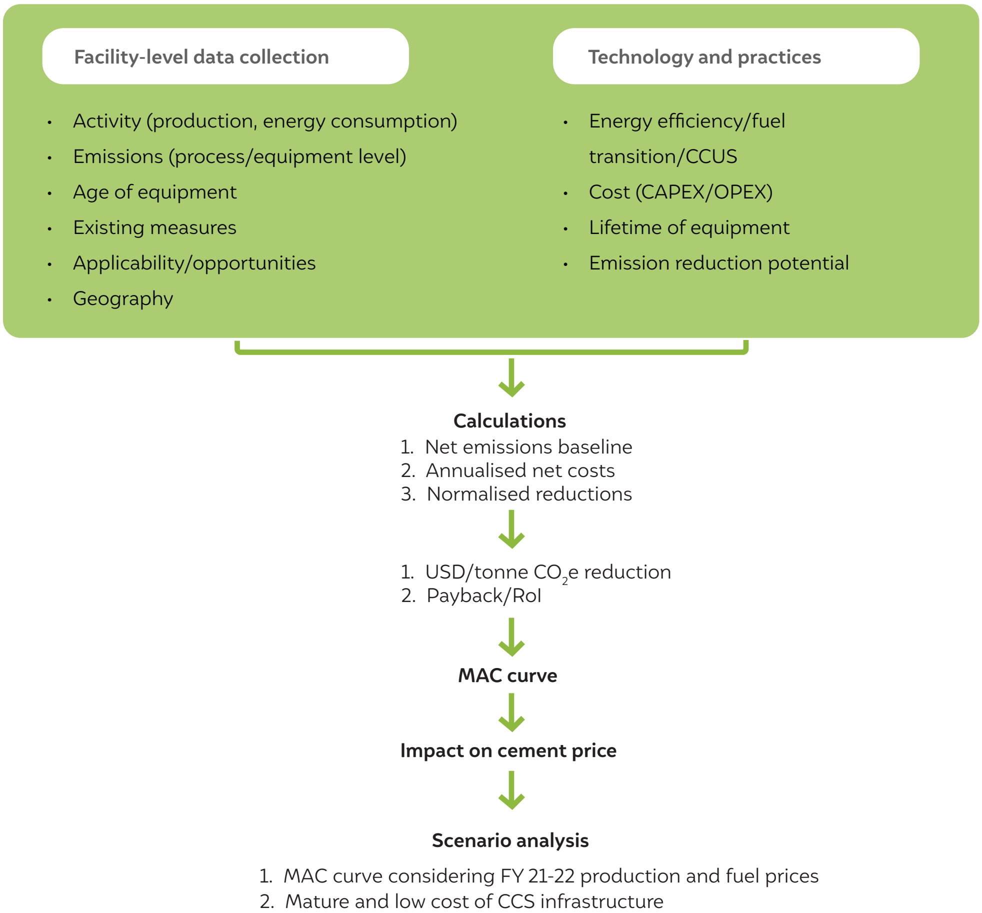
9 Energy efficiency technologies	• Waste heat recovery • Increased grinding system efficiency • High efficiency clinker coolers • Efficiency improvement in kiln and preheater • Burner retrofit • Automation system • Efficiency in captive power plants • Electrical equipment efficiency • Auxiliary equipment
4 Alternative fuels and raw material	• Increasing TSR from 3% to 30% • Switching to NG • Renewable energy use • Advanced raw material
4 Pathways for reducing clinker factor	• Increased utilisation of fly ash in PPC (from 27% to 35%) • Increased utilisation of steel slag in PSC • Increased utilisation of copper, zinc-lead etc. in OPC • Use of LC3 cement in OPC
3 Carbon management	• CCS • CCU • Carbon offset (afforestation)

Source: Authors' analysis

We analysed nine energy efficiency technologies, of which, waste heat recovery in kilns, enhanced preheaters and kilns, high-efficiency clinker coolers, and burner retrofits are specifically applicable to the clinker production stage of cement manufacturing. The vertical roller mill grinding system is an energy-efficient technology for use in processing clinker to produce cement, and the remaining technologies provide efficiency improvements across the whole process. We considered four alternative fuels — biomass, municipal solid waste (MSW), tyre residues, and natural gas — as alternatives to petcoke and coal that are typically used in kilns. The third category looked at reducing the clinker factor for different types of cement as a means of emission reduction. We have also proposed increased utilisation of fly ash and steel slag content in the respective type of cement and the use of a new blend of limestone calcined clay cement (LC3) instead of OPC. Lastly, the use of carbon management techniques such as CCS, CCU and afforestation have been taken into consideration for residual emissions. We assumed a ranked order of application of these mitigation measure categories. For instance, we first apply energy efficiency measures, followed by the use of alternative fuels and raw materials, then focus on the reduction in clinker factors, and finally, invest in carbon management for residual emissions mitigation.

The evaluation of the abatement cost for each of the mitigation options, shown in Figure 7, involves two steps. First, collecting the facility-level data and using the collected data to estimate the MAC. Second, plotting the MACs of the mitigation technology against the emission reduced if each of the technologies analysed was adopted. To evaluate the MAC, we considered a discounted payback period for the required CAPEX over the lifetime of the equipment. We considered a scaling factor to estimate the capital cost of the energy-efficiency equipment, proportional to the plant size (MIT 2018). Based on industry feedback, the operating costs for the equipment were assumed to be a percentage of the CAPEX or as a function of the net fuel or electricity (after accounting for the savings on account of the adoption of the energy efficiency or decarbonisation measure) used to operate the equipment.

Figure 7 Schematic of the methodology



Source: Authors' analysis

3.1 Energy efficiency in cement manufacturing

One of the key takeaways of this study is that the adoption of **energy efficiency technologies alone can reduce 9 per cent of the emissions** compared to the baseline. A compilation of various technologies that were assessed and their subsequent effects are discussed in Table 1. The thermal and electrical energy savings from each of the technologies are shown in Figure 8. After implementing these technologies, the total energy demand is projected to reduce from 741 kcal to 693 kcal per kg clinker of thermal energy and from 83.7 kWh to 65.2 kWh per tonne of cement of electrical energy.

Certain key technologies – such as power generation through waste heat recovery, replacement of grinding and cooling systems with efficient ones, and enhanced preheater and kiln technology – provide significant benefits in terms of energy savings, which in turn means lesser emissions due to fossil fuel combustion. It can be seen from Figure 8 that significant thermal energy savings (20 kcal per kg of clinker) can be obtained if efficient clinker coolers are installed. Similarly, the use of efficient grinding systems can result in power savings of 8 kWh per tonne of cement, followed by equipment automation.

Waste heat recovery alone has the potential capacity to generate roughly 1,000 MW of power across the entire industry. On conducting an exhaustive literature review of sustainability reports of cement companies, we found that just 285 MW of this potential has been used (Energy Star, 2013). The high-temperature heat, along with waste heat recovered from kilns, can be used to generate electricity and ultimately reduce net power consumption. Reduced demand for electricty would mean that when the switch to RE power happens, a smaller installed capacity would be required, thereby reducing costs.

Table 1 Energy savings due to energy efficiency technologies

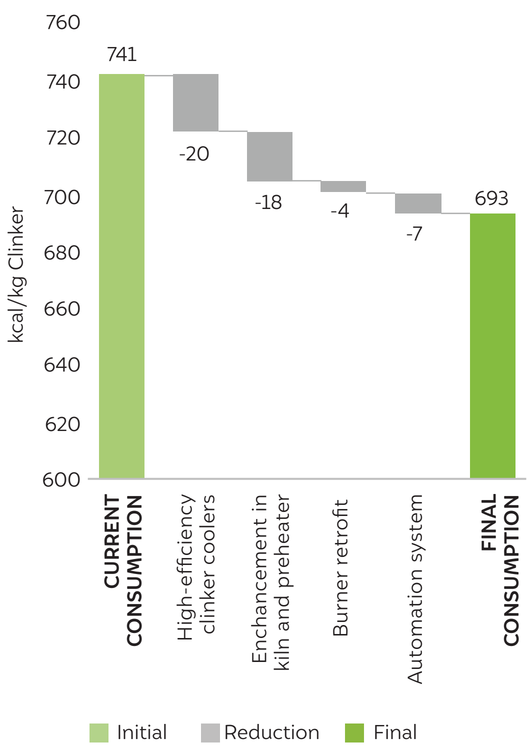
Sr no	Energy efficiency measure	Emission reduction potential ($kgCO_2$/t cement)	Remarks
			Electrical energy savings
1	Waste heat recovery	27	As of 2019, only 285 MW of the potential 1,000 MW waste heat recovery capacity has been utilised as a source of energy. For every MTPA of cement produced, ~3.5 MW of power can be potentially generated using waste heat while saving 23.4 kWh of electricity per tonne of cement.
2	Efficient grinding systems	7	The use of a vertical rolling mill would reduce power consumption by 8 kWh/t cement while reducing ~1.08 per cent of emissions compared to the baseline case, i.e., ball mill.
3	Electrical equipment efficiency	2	The use of an energy management system, high-efficiency motors, and voltage optimisation would all aid in lowering overall electricity consumption in the plant by about 2 kWh/tonne of cement, consequently reducing CO_2 emissions.
4	Optimising auxiliary power con-sumption	1	Optimising the power consumption of auxiliary equipment such as conveyors, elevators, blowers, compressors and pumps will reduce overall electricity demand by 0.75 kWh per tonne of cement in the plant.
			Thermal and electrical energy savings
5	High-efficiency clinker coolers	6	The deployment of high-efficiency cross-bar coolers would reduce power consumption by 0.5 kWh per tonne of cement and thermal energy consumption by 20 kcal per kg clinker.
6	High-efficiency kiln and preheater	6	By increasing the number of stages in the preheater and with improved heat insulation, the pressure drops in the cyclone and the energy requirement reduces. This results in thermal energy savings of 17.5 kcal/kg clinker and electrical energy savings of 2.5 kWh/kg clinker.

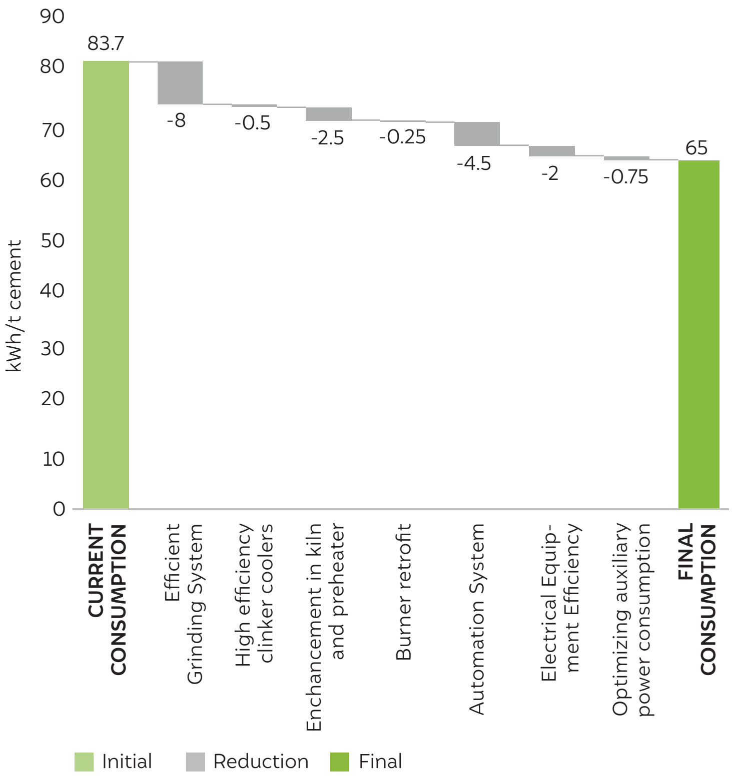
Sr no	Energy efficiency measure	Emission reduction potential (kgCO_2/t cement)	Remarks
7	Automation system	5	An advanced automation and control system can significantly improve the overall performance of the kiln (with an energy reduction of 7 kCal/kg clinker and 4.5 kWh/t cement), ensure efficient management of free lime concentration in the clinker and improve heat recovery efficiency.
8	Burner retrofit	1	Retrofitting traditional burners with modern multi-channel burners increases flame controllability and allows the use of a range of fuels such as MSW or biomass. This results in a reduction in thermal energy by 4 kcal/kg clinker and electrical energy by 0.25 kWh per tonne of cement.
			Thermal energy savings
9	Heat rate reduction in CPP plants	3	In theory, the heat rate of captive power plants can be reduced from the industry average of 3,200 to 2,600 kcal/kWh (Environmental Clearance 2022). However, practical considerations of small-scale units limit this decrease to 3,025 kcal/kWh (WBCSD 2012). Adopting energy efficiency technologies, such as the adoption of circulating fluidised bed combustion (CFBC) boilers, auxiliary power demand reduction and heat recovery, are expected to be the prime drivers for efficiency gains and hence emissions mitigation in CPP units.

Source: Compiled from IFC (2012) and communication from industry sources; authors' analysis

Recently, cement companies have been focusing on converting their coal-based captive power plants to captive renewable power plants. Consequently, energy efficiency measures related to coal power plants have been a low priority. However, until fossil-based captive power plants are phased out and completely replaced by RE, efficiency measures such as decreasing the heat rate of power plants should be actively implemented to reduce emissions. Similarly, deploying measures such as improved kilns and preheaters have been found to reduce 0.95 per cent or 6.3 kg of CO2 /tonne of cement.

Figure 8 Efficient clinker coolers and grinding systems result in substantial energy savings



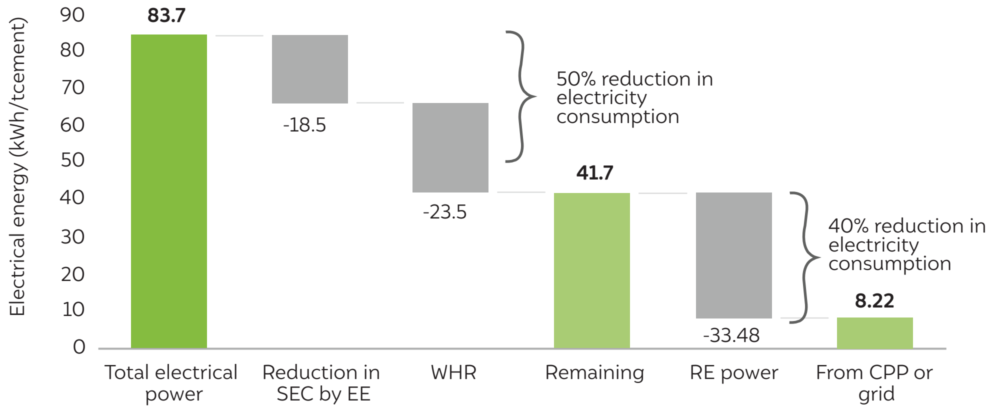


Source: Authors' analysis

3.2 Renewable power and alternative fuels

The emissions due to the use of fossil fuel for thermal energy account for 32 per cent of the total emissions, while only 12 per cent of emissions are due to electricity consumed for cement production. Emissions from fossil fuels used for meeting thermal energy requirements in the kiln can be reduced by alternative sources of energy such as biomass and municipal solid waste. Additionally, the emissions from the use of captive or grid electricity can be eliminated by using electricity sourced from wind and solar power plants.

Figure 9 **Energy efficiency measures in cement plants can reduce the RE requirement by 50%**

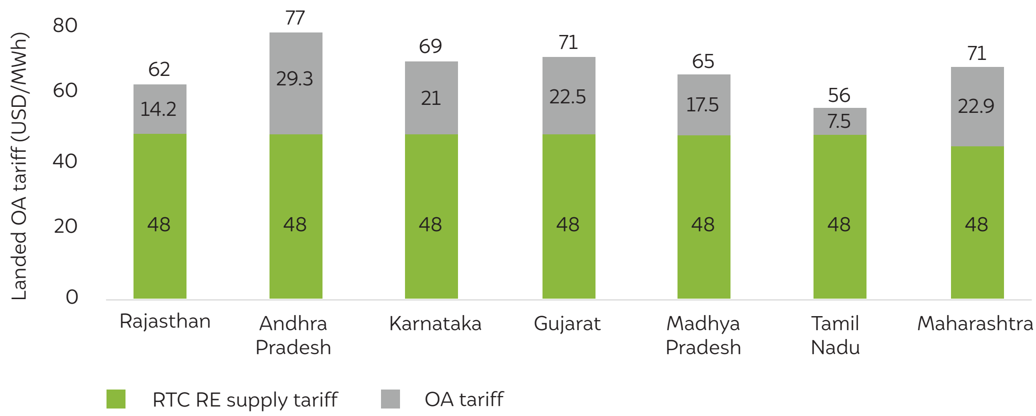


Source: Authors' analysis

Renewable power

Figure 9 reveals that approximately 40 to 50 per cent of the power demand can be met by using electricity produced from waste heat recovery and implementing energy efficiency measures. However, the exact magnitude of power that can be potentially generated depends on the energy efficiency technologies being used at each facility. The remaining 50 to 60 per cent of power demand can be met through RE. We estimate that, for producing 337 MTPA, 1.3 GW of round-the-clock RE capacity will be required. However, in this study, we have calculated that only 40 per cent of the electrical demand will be replaced by round-the-clock RE. This is despite the recent RTC RE tenders having an annual availability of 80 per cent (Thacker et al. 2020). Beyond this availability limit, the cost of power increases significantly due to RE oversizing and storage. It is assumed that the remaining power will be drawn from the grid. We have considered the corresponding emissions intensity of grid power in our analysis.

Figure 10 **Landed open access tariff is the least for an RE-rich state such as Tamil Nadu**



Source: Authors' analysis

To estimate the cost of replacing captive power with RE, we assumed a base tariff of INR 3.6 per kWh (USD 0.04 per kWh) for RE power, based on a tender floated for a 400 MW round-the-clock power generation capacity (Thacker et al. 2020). However, as seen in Figure 10, the power produced in RE-rich areas has to be wheeled to areas of demand – in this case, the cement plants. The power transmission from generation points to cement plants will result in an added tariff component called open access (OA) charges along with the base tariff of 3.6 INR per kWh (USD 0.04 per kWh). For the assessment, we considered the top seven cement-producing states in India that together constitute 66 per cent of national production.

Based on the CEEW open access tool (CEEW 2023), the weighted average (where the weights were the cement production in the state) cost of RE power was estimated to be INR 5.07 per kWh. Adopting RE power for cement production can result in the abatement of 3 per cent of total CO_2 emissions or 20 kg of CO_2 per tonne of cement.

Alternative fuels and raw materials

Increase in thermal substitution rate

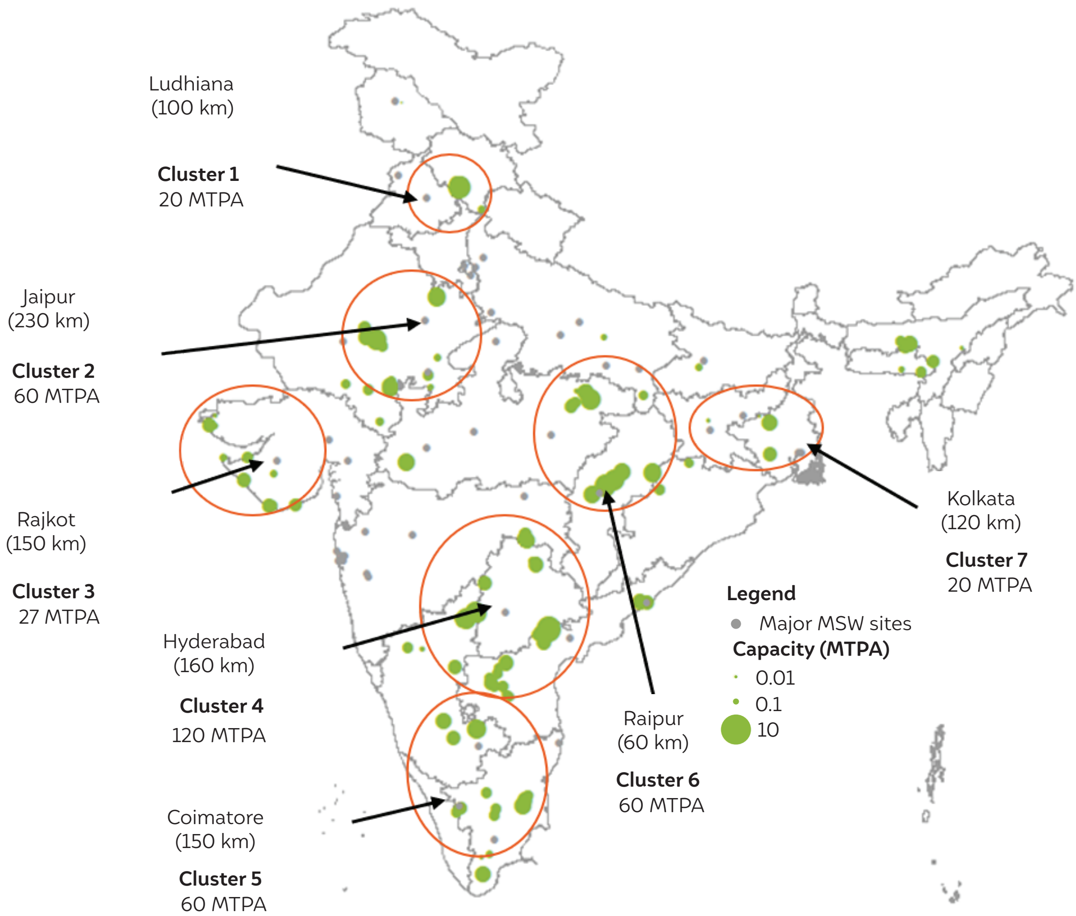
In a cement kiln, coal or petcoke is used as the source of thermal energy. However, they can be partially replaced with materials such as biomass, municipal solid waste, and other hazardous waste materials. The share of thermal energy that can be sourced from alternative fuels is defined as the thermal substitution rate (TSR), which is currently at 3 per cent (WBCSD 2018). In this analysis and as an industry-wide thumb rule, it is assumed that for every 1 per cent increase in TSR, the specific energy consumption (SEC) for clinker production rises by 2 to 3 kcal per kg of clinker. With this as a constraint, the industry has set a target of substituting 25 per cent of the energy required in the kiln with alternative fuels. However, if pre-processing steps that eliminate undesirable by-products such as chlorine (produced due to the combustion of these fuels) are introduced, this can be increased to 30 per cent (25 per cent from biomass and 5 per cent from MSW). In certain countries such as Germany and the United Kingdom, the TSR is as high as 65 per cent and 45 per cent, respectively (Sharma, Sheth, and Mohapatra 2022). In this study, based on industry feedback, we considered a maximum TSR of 30 per cent, given the practical supply chain constraints for both MSW and biomass.

The Indian cement industry is aiming for 25% TSR by 2030 while the average TSR in Austria is 79%

Although the use of alternative fuels in kilns is possible in theory, there are practical challenges to implementing them. One of the major barriers to its use is the cost of biomass and MSW, which is significantly higher than petcoke. As seen in Figure 11, the cost of MSW and biomass is approximately 43 per cent and 84 per cent higher, respectively, than pet coke. This cost includes the cost of transportation within a cluster zone (shown as circles in Figure 11) of 200 km for MSW and biomass from the source of generation to the cement plant. We considered crop residue as biomass for use in cement plants.

Based on the location of cement plants and district-wise availability of crop residue (TIFAC 2018) for major cement clusters, prima facie, it is seen that the TSR requirement is met within 200 km for most cement plants, wherever it was available in sufficient quantities. However, this is based on the assumption that crop residue is uniformly distributed within this 200 km cluster. A detailed supply chain optimisation model and GIS mapping of crop residue are needed to validate this hypothesis. The delivered cost of biomass is obtained based on clustering, as indicated in Figure 11. Our assessment indicates that the cost of treating MSW before it can be used as a fuel has significant implications on its delivery cost, followed by the cost of its collection and transport. A similar scenario is observed in the case of biomass. The exact cost breakdown for MSW and biomass is shown in the graph in Figure 11.

Figure 11 Cost of collection and transport contribute significantly to the delivered cost of MSW and biomass



Note: Distance denoted are average value between MSW source and cement plant

Source: Authors' analysis

Fuel switching with natural gas

We found that approximately 301 MTPA (>50 per cent of total production capacity) of cement production capacity in the country lies within a 100 km radius of a natural gas pipeline and therefore has access to it. Assuming 30 per cent of the energy requirement in the kiln is sourced from TSR, one-half of the remaining 70 per cent of the thermal energy requirement can be supplied from other natural gas, while the other half could remain petcoke. In the future, if supply chain constraints for coal persist and the cost of coal reaches parity with the cost of natural gas, the switch to natural gas would be commercially feasible.

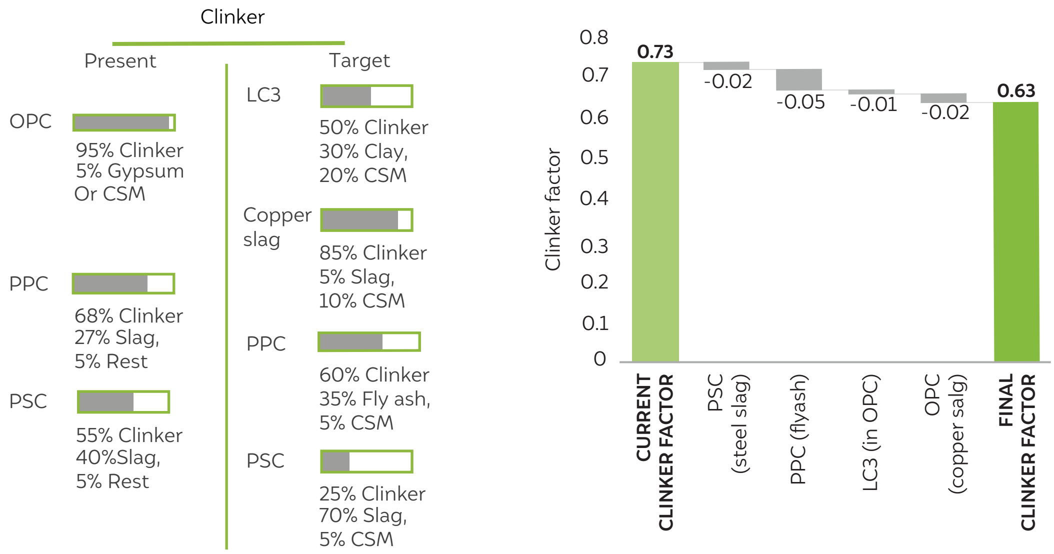
Alternative material

The clinker production process can be further enhanced by using mineralisers such as fluorides, fluorosilicates, and chlorides that reduce the burnability of limestone in the kiln (WBCSD 2012). By reducing the kiln temperature requirement by 50 degree Celsius, thermal energy savings of 13 kcal per kg of clinker can be obtained, in addition to electricity savings of 1 kWh per tonne of cement (WBCSD 2012).

3.3 Reduction in clinker factor

The calcination of limestone in the clinker production process emits CO2, which is inherent to the process and hence hard to abate. The emissions intensity of PSC is the least at 312 kg of CO2 per tonne of cement since it has the lowest clinker ratio of 0.55. In contrast, OPC has the highest clinker ratio of 0.9 and, therefore, has the highest emissions intensity at 740 kg of CO2 per tonne of cement (CEMNET,2022). According to our estimate, the average clinker ratio in India is 0.73, while the global average is 0.77 (GCCA,2023). With relevant interventions such as blending cement with additives, the average clinker factor in India can be further reduced to 0.63, and as a consequence, the emissions intensity of cement will also reduce. It can be seen from Figure 12 that clinker in PPC can be reduced from 68 per cent to 60 per cent (WBCSD,2012) through the use of fly ash. Similarly, in PSC, the clinker factor can be reduced from the present share of 55 to 25 per cent (WBCSD 2012) by increasing slag content. Additives such as copper slag and clinker substitution materials (CSM), including BF-BOF slag, gypsum and limestone, can reduce the clinker ratio of traditionally available OPC from 90 to 85 per cent (WBCSD,2012).

Figure 12 **PSC has the lowest clinker factor**



Source: Authors' analysis
Note: *CSM - clinker substitution material

Bottom ash or pond ash can potentially be used as an additive in the cement production process if the ash meets specific criteria, such as low carbon content and a fine particle size distribution. However, it is essential to conduct a detailed analysis of the ash to ensure that it does not contain high levels of impurities which might be unsuitable for use as an additive.

The usability of slag produced in steel plants depends on its end-use application. Granulated blast furnace slag (or any granulated slag with similar material properties) has latent hydraulic properties and the ability to reduce heat evolution during cement hydration and therefore has a significant potential to replace clinker in cement in the manufacture of PSC. Typically, with every tonne of hot metal produced, approximately 0.45–0.50 tonne of granulated blast furnace slag (GBFS) is generated. If the hot metal production in 2018–19 is considered, the total blast furnace slag output would have been approximately 33 million tonnes (Indian Bureau of Mines 2020). Based on the amount of PSC produced in India, the total blast furnace slag consumption is estimated to be 11 MT, which is just 33 per cent of the total production in a year. This implies that there is significant scope for increasing the consumption of GBFS in India. A potential reason for the low uptake of GBFS could be attributed to the high cost of grinding units used for granulation and the quantity of clinker absorption.

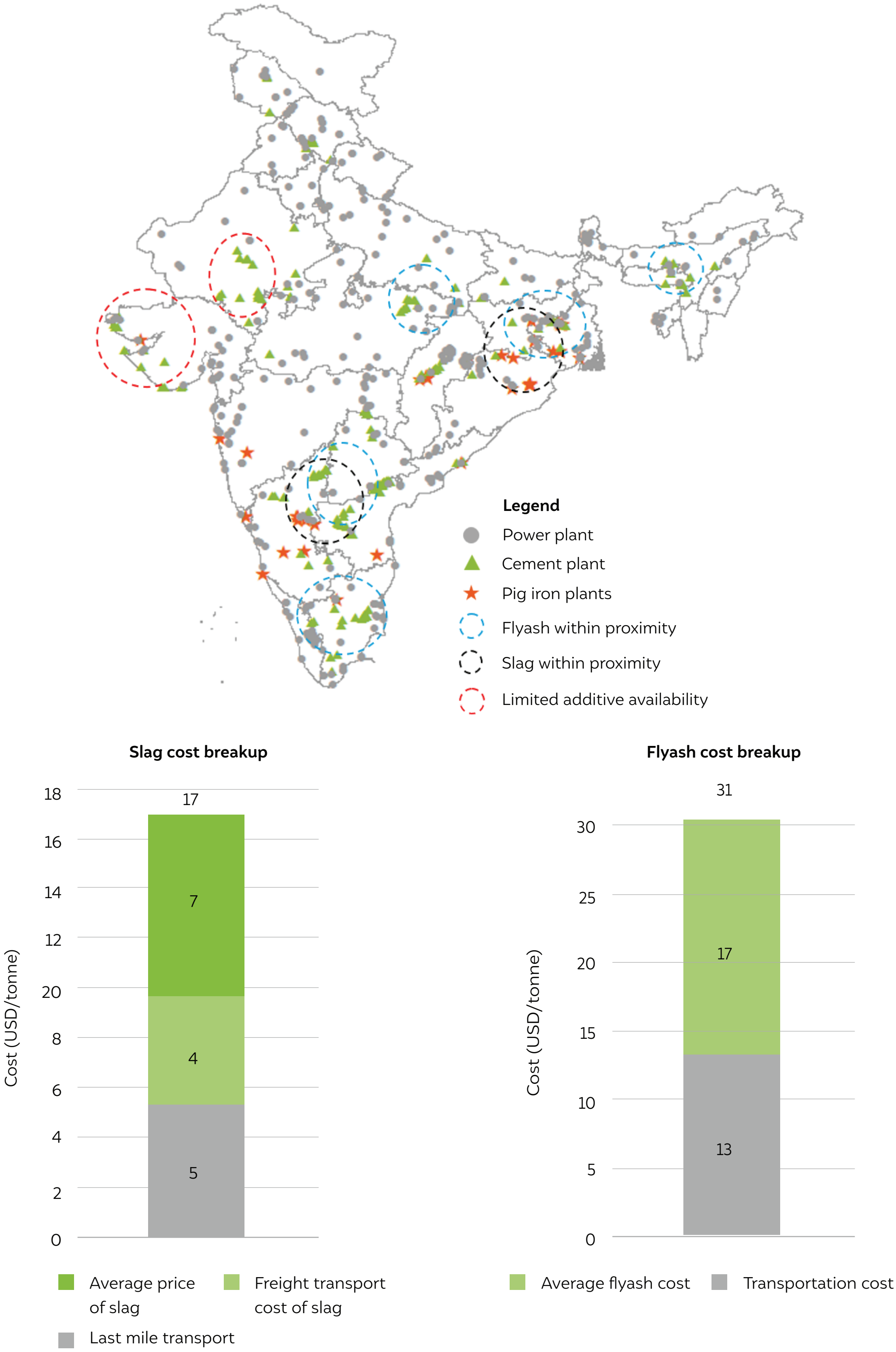
Sponge iron slag (direct reduced iron, DRI), on the other hand, has a lower content of reactive silicates and aluminosilicates and therefore has limited pozzolanic activity. This implies that it reacts with calcium hydroxide in a limited way in the presence of water to form calcium silicate hydrates, which is a key component of concrete strength and durability (WBCSD, 2012). Further, DRI slag contains high levels of iron oxide and is, therefore, highly reactive when exposed to heat. When it is added to a cement kiln, it can burn and cause problems such as excessive build-up in the kiln. DRI slag also contains char which is first directly used in waste heat recovery boilers for the generation of steam to meet captive power demand. As a result, DRI slag is not typically used as a raw material in cement production.

Replacing clinker in cement with additives comes with its own challenges. Sourcing additives such as slag and fly ash from far away pig iron production plants and coal-fired power plants poses a major bottleneck in its implementation. Regardless, in 2018–19, approximately 27 per cent of fly ash produced in the country was consumed by the cement industry, followed by applications such as land reclamation (~14 per cent), brick and tile production (10 per cent), etc. (CEA, 2019). As per the existing rules, fly ash is procured by cement plants through a competitive bidding process. Currently, research is underway to find ways to use the bottom ash produced in thermal power plants, and this could potentially reduce the logistical costs associated with the use of fly ash in the cement industry.

Addressing supply chain issues in GBFS and ash utilisation unlocks potential to further reduce clinker factor

As seen in Figure 13, cement plants are scattered across the country, while pig iron plants are concentrated in certain eastern states and Karnataka. For cement plants in states such as Karnataka, Andhra Pradesh or Tamil Nadu, thermal power plants are more easily accessible to cement plants than in states such as Rajasthan. Transporting these additives from their sources to cement plants increases their delivered cost and, in some cases, costs more than producing the clinker itself. Reduction of the clinker ratio in cement can only be financially viable if the delivered cost of additives is lower than the cost of the clinker, which is at present approximately INR 2,000 (USD 30) per tonne. The transportation cost indicated in Figure 13 is the average cost for transporting the additives from the source to the plant, wherever available.

Figure 13 **Fly ash and slag utilisation has a high potential if supply chain bottlenecks are removed**



Source: Authors' analysis

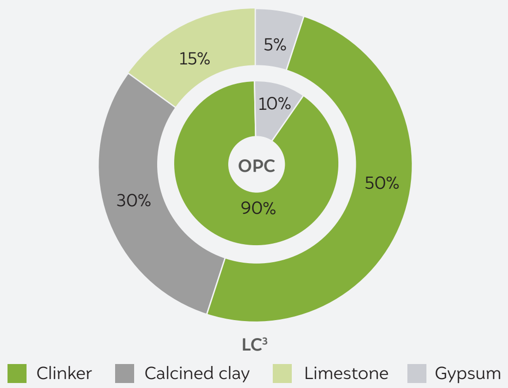
Box 2 What is LC3?

Materials such as fly ash, blast furnace slag, limestone and calcined clay (heat-treated clay) are some of the most commonly used additives with clinker to produce cement. The use of fly ash and steel slag particularly has proven useful in reducing the share of CO_2-intensive clinker in cement. However, there are constraints to their unlimited use as cement manufacturing, particularly in India, is expected to grow many folds in the coming decades. In India and elsewhere, cement production is many times over the amount of steel produced. Consequently, steel slag currently is and will be in short supply. Similarly, fly ash can only replace 35 per cent of clinker. Furthermore, with the decommissioning of thermal power plants (Ganesan and Narayanaswamy 2021), the availability of fly ash might be a constraint in the future. This necessitates novel methods to reduce clinker in modern-day cement.

LC3, or limestone calcined clay cement, is a new family of cement that has 40 per cent lower emissions per tonne of cement (Scrivener et al. 2019). This type of cement consists of a unique blend of 50 per cent clinker, 30 per cent calcined clay, 15 per cent limestone, and 5 per cent gypsum. The critical innovation in this cement is the use of 30 per cent low-grade kaolinite clay, which is abundantly available in India, with 15 per cent crushed limestone. The mineral kaolinite, found in the clay, when heat-treated at temperature ranges between 600–900 degrees centigrade, forms kaolinite clay. During the heat treatment, kaolinite undergoes dehydroxylation to produce metakaolin, which is a pozzolanic material and is therefore used for blended cement.

The creation of the LC3 is a result of collaborative research between the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, and the Centro de Investigacióny Desarrollo de Estructurasy Materiales (CIDEM) of the Universidad Central "Marta Abreu" de Las Villas, Cuba. In addition, IIT Delhi partnered with them to play a pivotal role in the development and commercialisation of LC3 globally. Approximately 40 tonnes of LC3 was produced during its first trial in a small cement mill in West Bengal in 2013. The cement showed promising performance, as was demonstrated by the structure built by TARA at its premises in Orchha in 2014. This proved that LC3 could serve as a sustainable alternative to existing cement technologies.

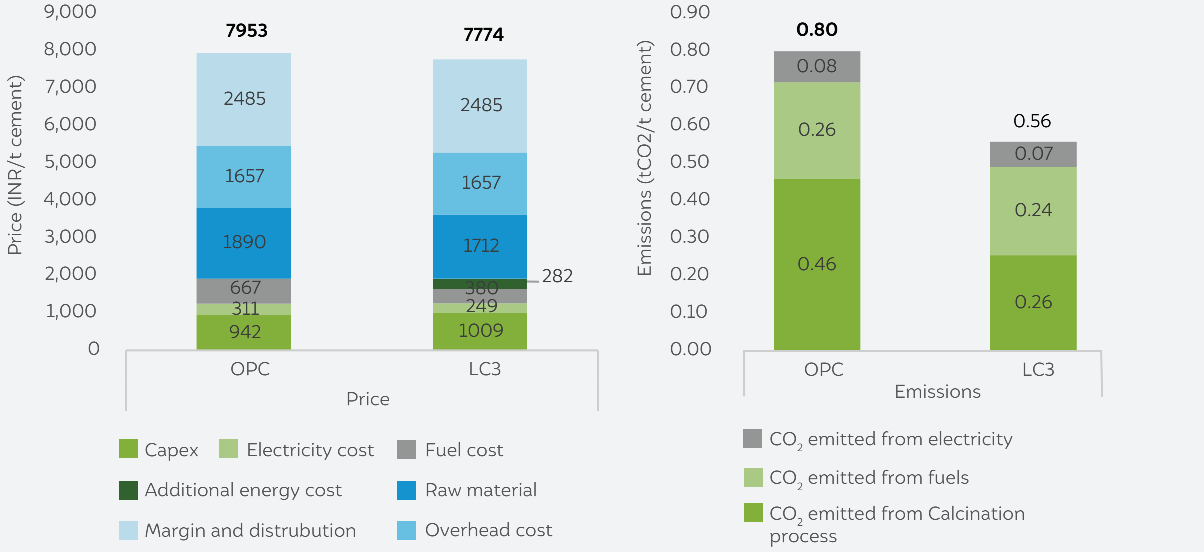
Figure 14 **LC3 has 50% clinker as compared to OPC, which has 90% clinker**



Source: Authors' compilation

This new blend has the same mechanical strength and performance as its alternative, the ordinary Portland cement (OPC). The only competing product for the LC3 is the OPC since the targeted clinker factor is already the least for the PSC cement. On the other hand, the clinker factor in PPC is higher than in the LC3. However, fuel is required for the production of calcined clay, thereby increasing its cost. In contrast, fly ash is easily obtainable from power plants. Therefore, from an economic standpoint, LC3 will not be able to replace PPC. This is represented as a pie chart in Figure 14.

Figure 15 **LC3 is estimated to be cheaper than OPC**

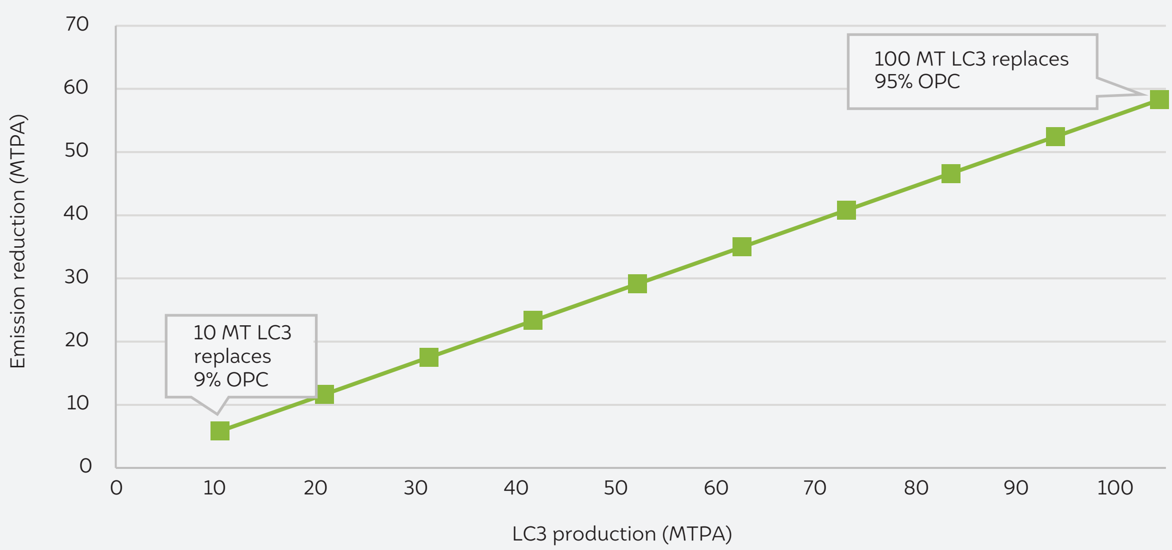


Source: Authors' analysis

Compared to OPC, LC3 costs less due to the lower cost of its raw material (Figure 15). Further, as a result of its reduced clinker usage, the emission per tonne of cement is also lower. In addition, the calcination of clay has lower heat loss, and the temperature required to process it is also lower than that required for producing clinker. Manufacturing this blend does not require significant additional capital investment and can be produced in existing facilities. LC3, therefore, offers a unique opportunity for the Indian cement industry since a sizable amount of research has already been carried out locally and is commercially viable for mass production.

A sensitivity analysis to determine the share of the LC3 replacing the OPC and the corresponding change in carbon mitigation is presented in Figure 16. At the low base of 10 per cent of LC3 replacing OPC, which amounts to 10.4 MTPA, approximately 2.5 million tonnes of CO_2 would be abated. At a moderate share of 50 per cent (52.2 MTPA production), 12.6 million tonnes of CO_2 would be abated. If the entire share of OPC (104 MTPA) is replaced by LC3, 25 million tonnes of CO_2 or 11 per cent of the cumulative cement industries emissions will be mitigated.

Figure 16 **LC3 will have lower emissions intensity than OPC**



Source: IIT Delhi 2022, Authors' analysis

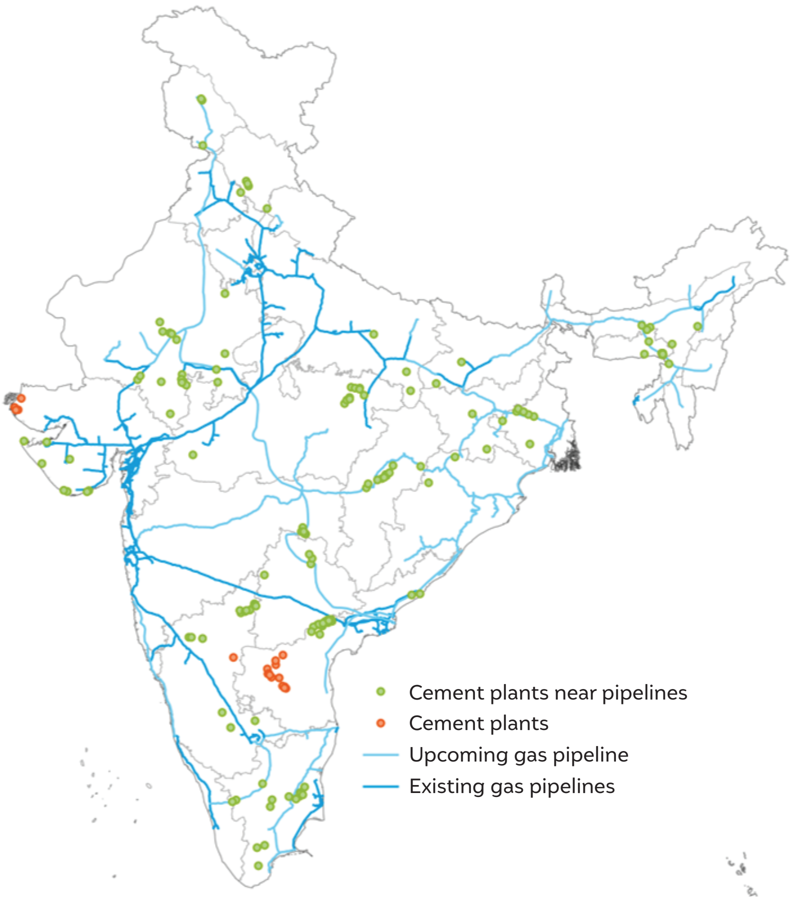
LC3 is a technology under development. As of today, its role in the construction sector is not well established. Therefore, for this study, we considered that 10 per cent of the OPC sales (of the total 31 per cent OPC) in the country would be replaced by LC3. This number can go up due to supply chain constraints for fly ash and slag (used in PPC and PSC cement as additives) in a net-zero trajectory (due to decommissioning of coal-based steel and power plants). However, the usage of LC3 is yet to be approved by regulatory authorities such as the Bureau of Indian Standards (BIS).

CO_2 transport pipelines parallel to the natural gas pipelines will eliminate right-of-way issues and accelerate the establishment of a CCS ecosystem in India

3.4 Post-combustion emissions mitigation

The use of clinker in cement is inevitable, given the intended properties of cement. Therefore, the emissions due to the limestone calcination process to produce clinker in the kiln cannot be eliminated. Alternative CO_2 abatement measures such as carbon capture, utilisation and storage (CCUS) are essential for the cement industry to ultimately achieve net-zero status. In order to calculate the MAC for these technologies, it is assumed that cement plants in proximity to natural gas pipelines will not have issues related to the right-of-way for transporting CO_2 to storage locations. The pipelines and their distance from cement plants can be seen in Figure 17. Our analysis shows that only 50 per cent of cement plants, by production, were found to be within a 100 km radius of natural gas pipelines and, therefore, will not face right-of-way issues related to laying CO_2 pipelines. Therefore, we assume that this 50 per cent of cement plants can opt for CCS in geological sequestration reserves. The cement plants located beyond the threshold of 100 km (remaining 50 per cent) have to employ a carbon capture and utilisation (CCU) pathway to achieve net-zero. Nonetheless, the CCUS pathway has a peak capture efficiency of 85 to 90 per cent. The remaining CO_2 could be mitigated using offset mechanisms such as afforestation or direct air capture (DAC).

Figure 17 Half the cement production capacity in the country has access to natural gas pipelines



Source: Authors' analysis

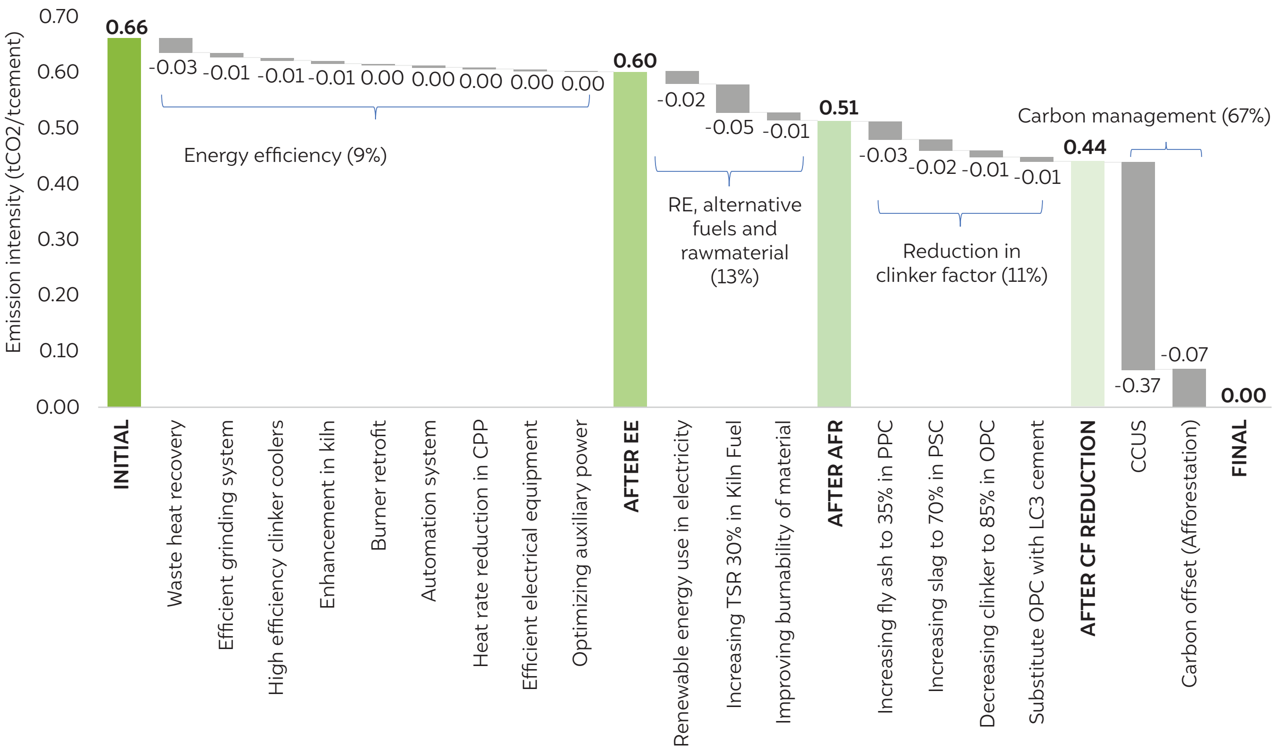
Limestone is the primary raw material used for cement production.

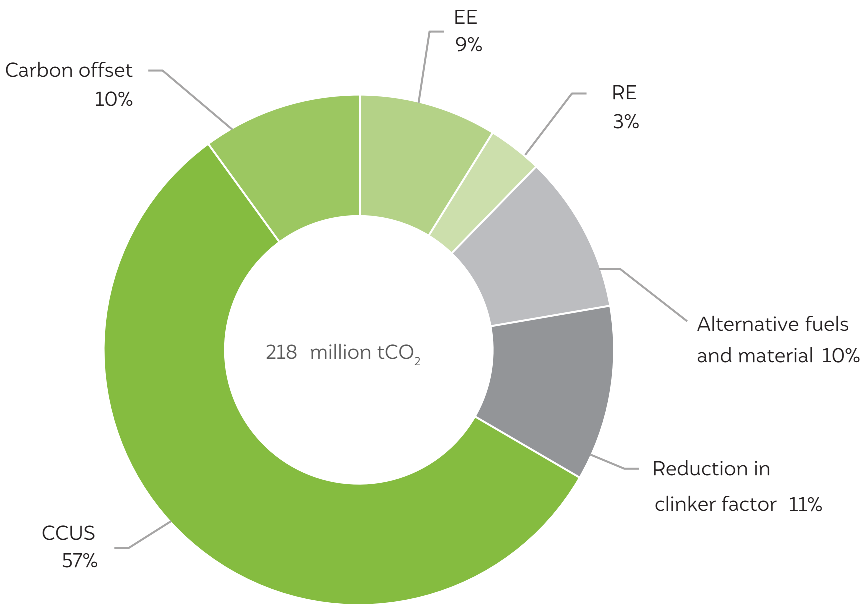
Image: iStock

4. MAC for the cement industry

Net zero cement manufacturing can only be realised by deploying a host of carbon abatement measures. Figure 18 shows the trajectory for achieving net zero in the cement industry. According to our calculations, the 218 million tonnes of CO2 (from 337 MT of cement production) that the cement industry currently emits could be abated by adopting just four of the prior-discussed decarbonisation measures. The emissions intensity of cement can be reduced from 0.66 to 0.60 (9 per cent reduction) tonnes CO2 per tonne cement by the adoption of energy efficiency technologies. The emissions intensity can be further reduced to 0.58 tonnes of CO2 per tonne of cement first by the use of RE and then to 0.51 tonnes of CO2 per tonne of cement by using alternative fuels such as MSW and biomass. This can be reduced to 0.44 tonnes of CO2 per tonne of cement by increasing the fly ash utilisation to 35 per cent (from 27 per cent) in PPC, the slag rate to 70 per cent (from 40 per cent) in PSC, switching to LC3 (replacing 10 per cent of OPC sales), and lowering the OPC clinker factor to 0.85 (from 0.90) with additional additives. The remaining emissions can only be eliminated by using carbon capture solutions. However, even with a peak capture efficiency of 85 per cent across the CCUS pathway, carbon offset mechanisms such as afforestation need to be deployed to reach net zero.

Figure 18 The use of carbon management techniques is inevitable in a net-zero scenario for the cement industry

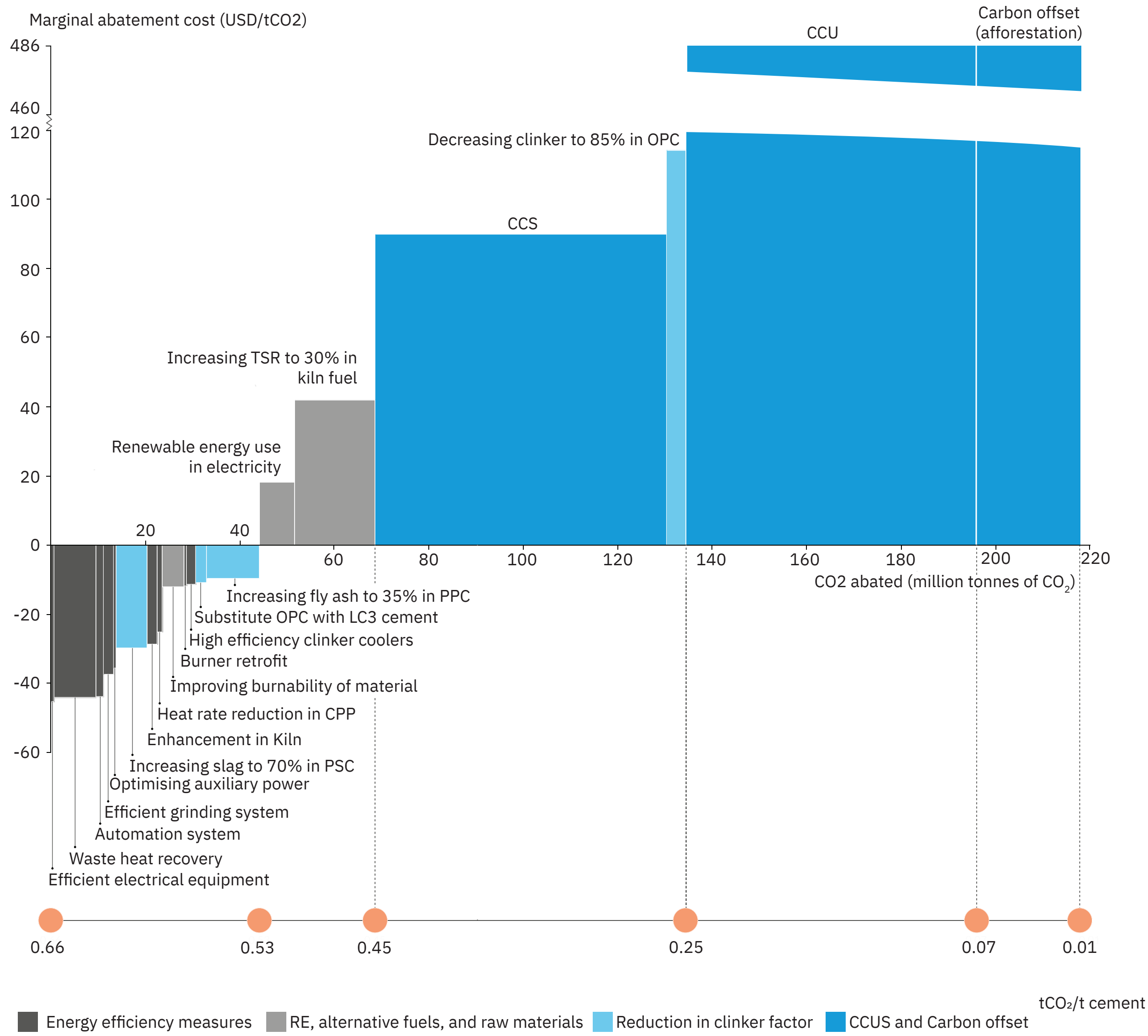




Source: Authors' analysis

The MAC curve, seen in Figure 19, indicates all the decarbonisation measures evaluated in this study and their respective CO2 abatement potentials. It can be seen that between mitigation measures ranging from electrical equipment efficiency to reducing clinker factor in PPC, there are 13 decarbonisation measures that have a negative cost of mitigation. Of these, nine are energy efficiency technologies, one for the use of alternative raw materials, and the rest pertain to the reduction of clinker factor. The technologies having a negative cost of mitigation can reduce the emissions intensity of cement from 0.66 to 0.53 tonnes of CO2 per tonne of cement, i.e., approximately a 20 per cent reduction, and provide a net financial benefit for the plant implementing it. However, there are challenges in the supply chain when reducing the clinker factor in PSC and PPC. The Bureau of Indian Standards is yet to approve the production of LC3. Nonetheless, several technologies have positive mitigation costs such as RE, increasing the TSR, further reducing the clinker factor in OPC by the use of alternative additives, and implementing carbon management technologies.

Figure 19 Emissions reduction trajectory for the cement industry

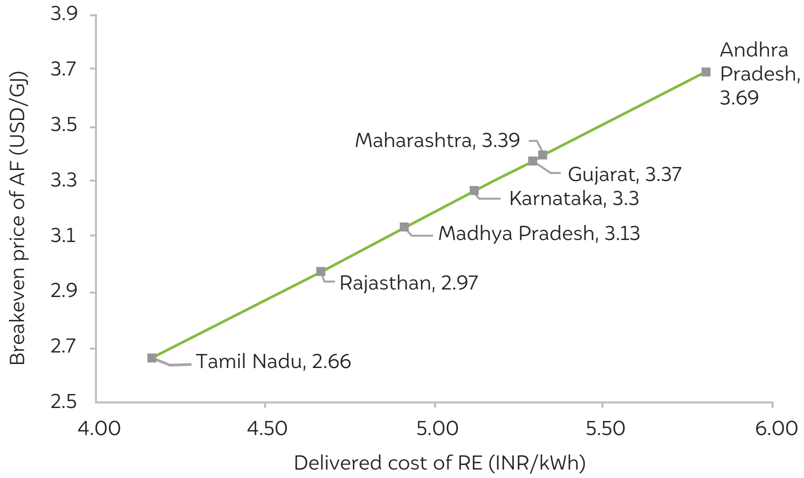


Source: Authors' analysis

Note: The MAC for afforestation is only representational as an option for carbon mitigation without considering the cost of mitigation.

The use of RE to offset fossil-based captive power plants is more cost-effective than using alternative fuels (Figure 20). The industries can choose to utilise alternative fuels or procuring RE through open access mechanisms depending on the state in which the plant is located. Figure 21 provides the breakeven cost of using alternative fuels such as biomass and MSW as a function of the delivered cost of RE at the plant location. It reveals that the cost of alternative fuels could be as low as USD 2.66 per GJ in Tamil Nadu, while it could be as high as USD 3.69 per GJ in a state such as Andhra Pradesh, to be preferred over RE uptake for offsetting captive/grid power.

Figure 20 **The selection of alternative fuels depends on the delivered price of RE at the location of the plant**



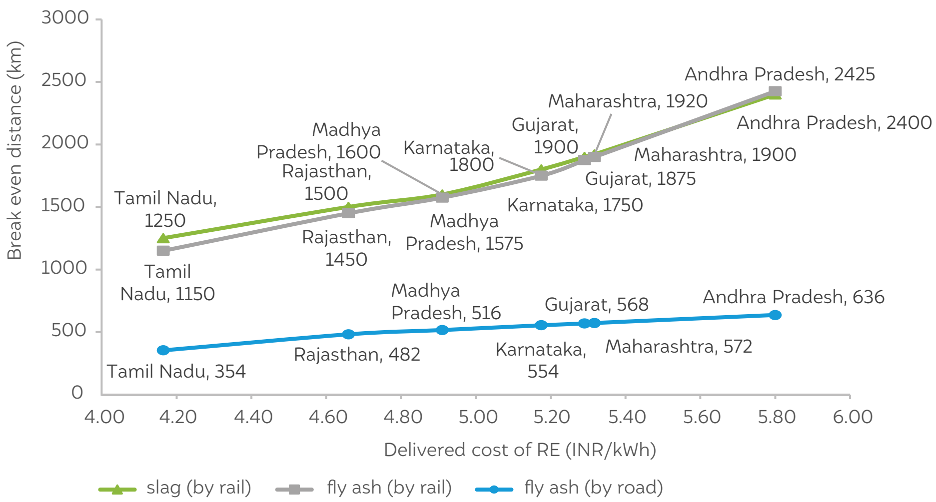
Source: Authors' analysis based on data from the literature (India Bureau of Mines 2018; connect2india 2023)

Note: Fly ash cost at TPP: INR 1.3/kg; slag cost: INR 0.544/kg of slag

The breakeven distance of ash and slag transport for becoming a priority over the use of RE to offset captive power demand can be seen in Figure 21. For an RE-rich state such as Tamil Nadu, the breakeven distance for fly ash transport via road is the least at 354 km, while it is the highest for Andhra Pradesh at 636 km. The breakeven distance for fly ash and slag transport via rail is much higher in comparison to the road, but the trends remain similar when compared state-wise. In Tamil Nadu, the breakeven distance is the least at 1,250 km for slag and 1,150 km for fly ash. It is the highest in Andhra Pradesh at 2,425 km for slag and 2,300 km for fly ash. According to the data accessed from Indian Railways, the cost difference between fly ash and slag transport via rail increases disproportionately with increasing distance (Indian Railways 2023). While the cost of road transport increases linearly with distance, the per tonne-km cost of transporting slag and ash by railway decreases with an increase in distance.

The priority of decarbonisation solutions varies across states depending on the delivered cost of AF, RE and CSM

Figure 21 **The selection of additives depends on the delivered price of RE and the proximity of the source from the plant**

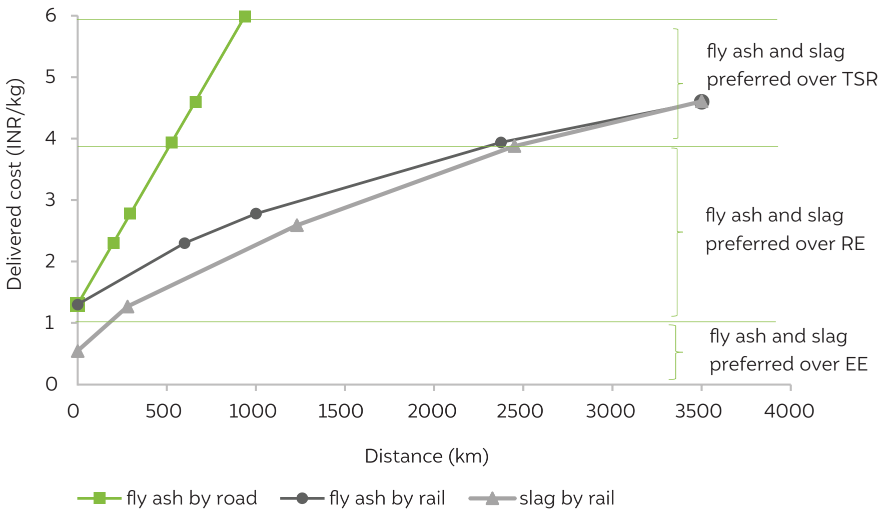


Source: Authors' analysis based on data from the literature (India Bureau of Mines 2018; connect2india 2023)

Note: Fly ash cost at TPP: INR 1.3/kg; slag cost: INR 0.544/kg of slag

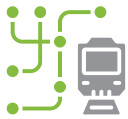
Figure 22 shows the delivered cost of fly ash and steel slag as a function of transport distance. For using fly ash and slag as a substitute for clinker, rail transport is preferred. For the same quantity of fly ash at a delivered cost of INR 4 per kg, a distance of 500 km can be covered by road. In contrast, for the same delivery cost, a distance of up to 2,500 km can be covered via rail. Fly ash and steel slag will be preferred over other decarbonisation measures such as energy efficiency, RE power, or TSR, depending on the distance between the cement plant and the source of fly ash or slag, delivered cost of RE in the state, and the type of energy efficiency technology being deployed. Our assessment indicates that the delivered price of fly ash and slag should be less than INR 1,000 per tonne to become competitive with energy-efficiency technologies. Similarly, the delivered cost of slag should be INR 1–4 per kg to be preferred over the use of RE to offset captive/grid power demand. Finally, the delivered cost of fly ash and slag should be INR 4–6 per kg to be preferred over the use of alternative fuels.

Figure 22 **Transporting fly ash and slag by rail is cheaper than via road**



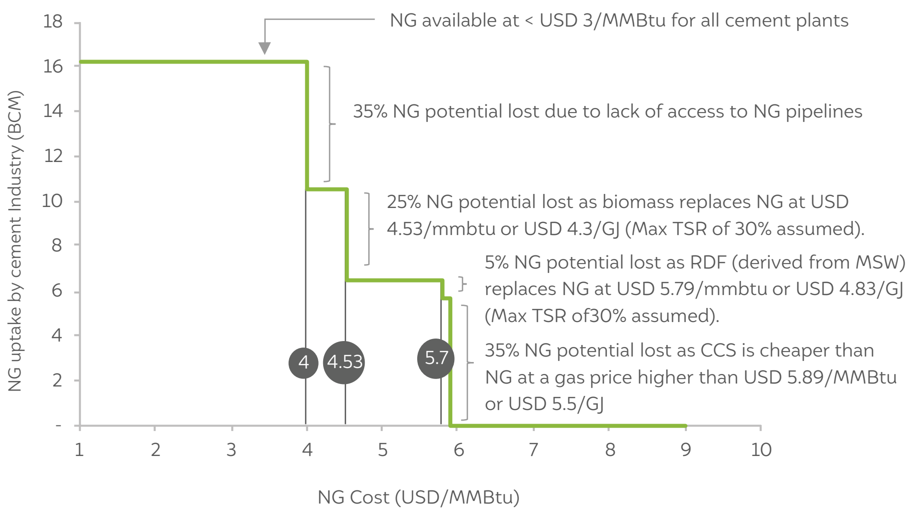
Source: Authors' analysis

The viability of natural gas (NG) use in the cement industry is represented in Figure 23. Our analysis shows that the cement industry can potentially consume 16 BCM of natural gas if it is available at a price less than USD 3 per MMBtu by replacing all the petcoke or coal consumed in the cement kiln. However, due to a lack of access to natural gas pipelines, 35 per cent of this potential is lost. If the uptake of alternative fuels such as agricultural waste and MSW is limited to 30 per cent (25 per cent biomass and 5 per cent MSW) of thermal energy requirement in the kiln, the natural gas uptake in the cement industry will further reduce by 30 per cent for a natural gas price of USD 4.53 to 5.79 per MMBtu. The use of natural gas becomes completely unviable if its price increases beyond USD 5.89 per MMBtu since CCS becomes more economically viable beyond this price range for a delivered price lower than USD 5.9/MMBtu. If NG becomes available at USD 5.3 and CCS remains at USD 90 per tonne of CO_2, then NG uptake is viable; NG uptake is not favourable at a price higher than this.



India can leverage its vast railway networks for transporting CSM and help cost-effective rapid decarbonisation of the industry

Figure 23 **The cement industry can consume natural gas only if the delivered price is lower than USD 6/MMBtu**



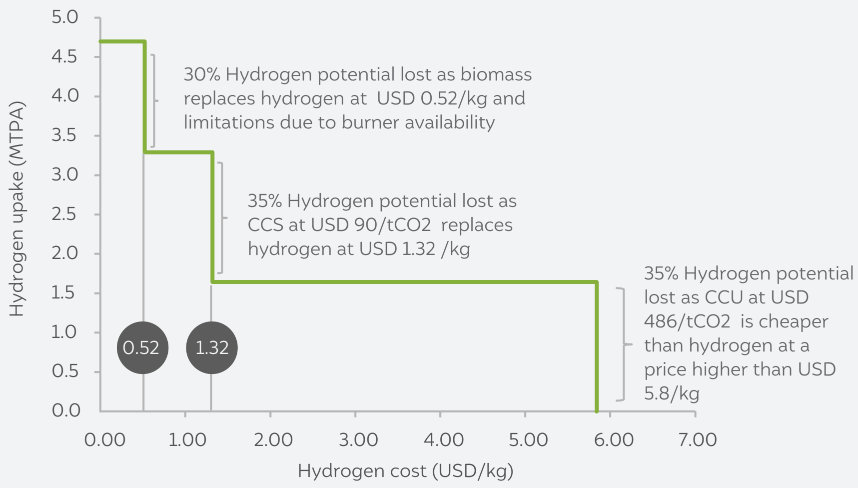
Source: Authors' analysis

Box 3 Is green hydrogen a decarbonisation solution for the cement industry?

Efforts to decarbonise the cement industry typically focus on energy efficiency measures or the use of alternative fuels, such as biomass and natural gas, for clinker production. Green hydrogen is considered a potential decarbonisation solution for steel, refineries, fertiliser, and petrochemical industries. Recent pilot studies have shown encouraging results on the technical feasibility of using green hydrogen in cement kilns. Up to 74 per cent hydrogen was used in a trial study in the UK, with the remaining per cent of energy provided by biomass and other alternative fuels (Heidelberg 2021). However, it was concluded that substituting traditionally used fuels such as petcoke with hydrogen has its own challenges. The study showed that the hydrogen combustion flame had a different heat profile than fuels such as natural gas. In addition, the heat dispersion from these flames was inadequate for use in cement kilns, and the typical burner designs used in kilns have proved to be insufficient in this context.

According to our analysis, the cement industry could potentially use around 4.7 million tonnes of green hydrogen, assuming the injection level remains at 74 per cent. However, the cost of hydrogen is the major limiting factor for its use in cement kilns. The switch to hydrogen can happen if the burner technology can accommodate a blend of hydrogen and biomass, and if it costs less than USD 0.52 per kg, above which, it becomes cheaper to use biomass, and consequently, 30 per cent potential is lost. Furthermore, a potential of 35 per cent is additionally lost to CCS (at the cost of USD 90 per tonne of CO_2) if hydrogen costs more than USD 1.32 per kg. Similarly, if it costs higher than USD 5.8 per kg, the remaining 35 per cent potential is also lost to CCU (at the cost of USD 486 per tonne of CO_2). Figure 24 shows the viability of hydrogen used for cement manufacturing as a function of its cost. By 2040, the price of green hydrogen is anticipated to be USD 2 per kg (Biswas, Yadav, and Baskar 2020). Given that the cost of abatement using CCS is expected to decline from its current level, green hydrogen may only have a minor impact on cement's net-zero emissions. In the future, hydrogen might also have to compete with horizon technologies that are being developed to electrify the cement kiln (UltraTech 2022).

Figure 24 Viability of hydrogen use in the cement industry

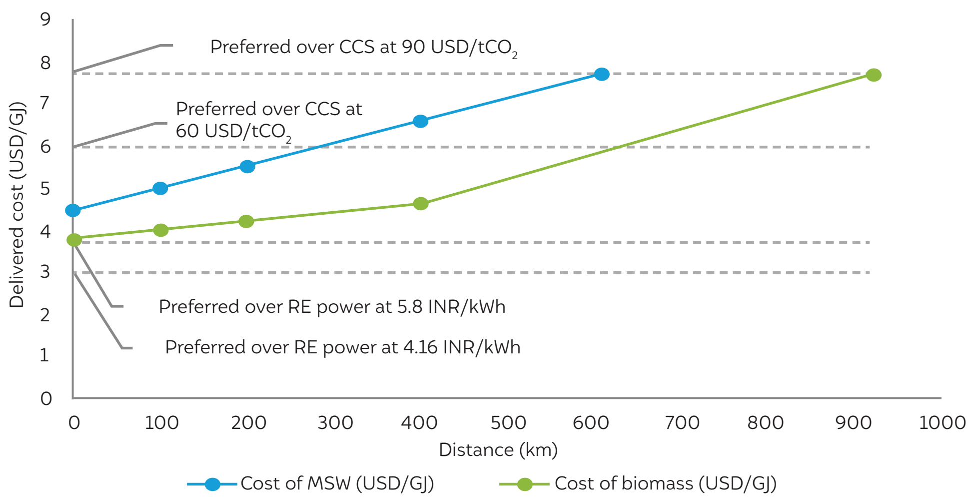


Source: Authors' analysis

Transporting MSW from a distance of up to 600 km and biomass from a distance of up to 900 km is more viable when compared to the cost of using CCS (taken as USD 90 per tonne of CO2) (Figure 25). The delivered cost of biomass and MSW should be as high as USD 7.5 per GJ (INR 563 per GJ) for CCS to be preferred by the cement industry. In states such as Tamil Nadu, the cost of biomass and MSW would be competitive since the cost of RE is lower at INR 3.69 per kWh. In contrast, in Andhra Pradesh, where RE cost is higher at INR 4.16 per kWh, transporting MSW or biomass from distances less than 150 km would be a favourable option for decarbonising when compared to RE.

As shown in Figure 20, the breakeven cost of alternative fuels (MSW and biomass) against the delivered cost of RE is the highest for Andhra Pradesh at USD 3.69 per GJ. However, it should be noted that if the cost of CCS reduces to USD 60 per tonne of CO2, the delivered cost of MSW and biomass will have to be even more cost competitive, and will be economically viable only over a shorter transport distance of 300 km and 600 km, respectively.

Figure 25 Transporting MSW and biomass is cheaper than using CCS



Source: Authors' analysis

Beyond alternative fuels, the cement industry would depend on the development of CCS infrastructure for decarbonisation. This step would need support from the government, especially for identifying and characterising sequestration reservoirs and building CO_2 pipelines for transport. According to our estimates, the CCS pathway can reduce roughly 123 million tonnes of CO_2 (56 per cent of total emissions) from the cement sector as a whole. Although more expensive than CCS, we also considered the uptake of copper, lead, and zinc slag in the cement industry. However, the cost of mitigation with slag obtained from non-ferrous industries such as copper, zinc, and minerals is higher due to the higher cost of slag and longer transportation distances as compared to steel slag (WBCSD, 2018; IFC 2012). We believe that 10 per cent of clinker in OPC can easily be replaced with industrial waste from industries such as copper. It can even be increased up to 15 per cent. Nevertheless, in the absence of CCS infrastructure and adequate availability of steel slag, it is expected that slag from the non-ferrous industry will find takers in the cement industry to achieve decarbonisation goals.

Further research is needed to explore alternative methods of cement production, such as electrification, to enhance sustainability

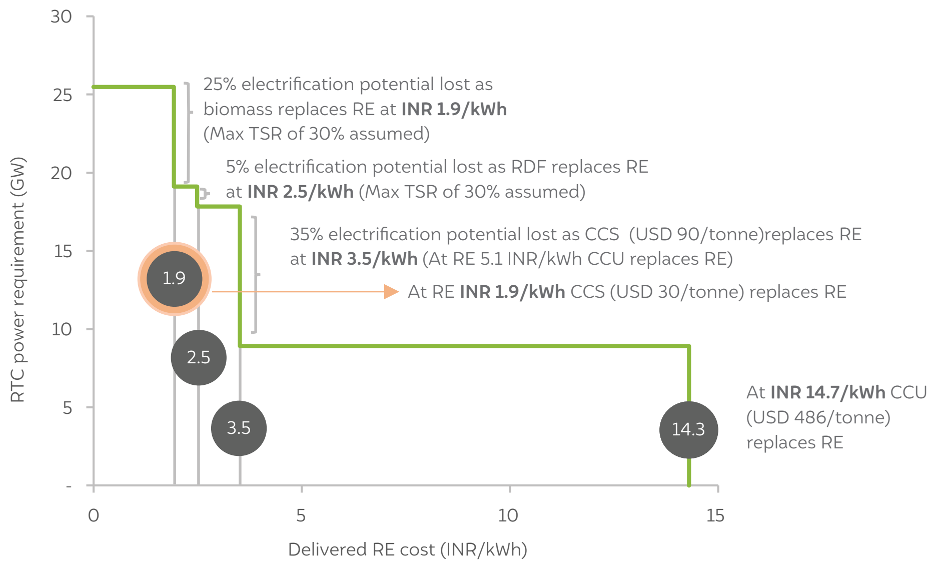
The cost of mitigation with CCU is significantly higher than CCS today, primarily due to the high cost of green hydrogen. While there are multiple pathways and processes for CCU, we considered CO_2-to-methanol production as a CCU application, given the multiple-use applications that green methanol provides. Their uses include fuel for blending in gasoline, the petrochemical industry, a building block for sustainable aviation fuel (SAF), and producing green olefins. Currently, CCU has the highest cost of mitigation, primarily due to the high cost of green hydrogen (assumed at 4.2 USD/kg). It is also worth noting that the peak capture efficiency for CCUS is about 85 per cent. Consequently, to produce net-zero cement, carbon offset technologies such as direct air capture or afforestation must be adopted to mitigate the remaining CO_2. However, we did not consider their offset costs in the present study due to uncertainties in critical parameters such as land availability or price of direct air capture.

4.1 Electrification of clinker production

The cement industry has been exploring ways to decarbonise its process heating demand to meet its net-zero targets. Horizon technologies, such as heat generation through plasma and microwave energy, with the electrification of clinker production, are on the rise. Heidelberg Cement's subsidiary Cementa, located in Sweden, is currently conducting a pilot study that uses electricity to supply heat during the clinker production process using plasma technology. However, the production costs of cement are estimated to double (Global Cement 2019) with the electrification of the kiln. To electrify the kiln, we estimate a potential RTC RE power requirement of 741 kcal per kg of clinker (95 per cent electricity to heat efficiency in the cement kiln) with a clinker factor of 0.73.

Approximately 25 GW of RE power capacity is required, in theory, to offset coal and petcoke consumption in cement kilns by 100 per cent electrification (Figure 26). The viability of electrification of the clinker process depends on the delivered cost of RE. For a price higher than INR 1.9 per kWh, 25 per cent of the 25 GW potential is lost to biomass, and a further 5 per cent is lost to MSW and biomass at a rate of INR 2.5 per kWh. Similarly, 35 per cent potential is lost to CCS (taken as USD 90 per tonne CO_2) at a delivered price of RTC RE at INR 3.5 per kWh, while at an even higher rate of INR 14.3 per kWh, it will be replaced by CCU (taken as USD 486 per tonne CO_2), making it completely unviable to use RE power. We estimate that 0.21 tonnes of CO_2 per tonne of cement can be abated using electricity in clinker production if the entire capacity is electrified. Consequently, what remains is only the process emissions, which sum up to 0.37 tonnes of CO_2 per tonne of cement.

Figure 26 **Electrification potential depends on technology development and delivered cost of RE**



Source: Authors' analysis

4.2 Investment sizing the net-zero transition in the cement industry

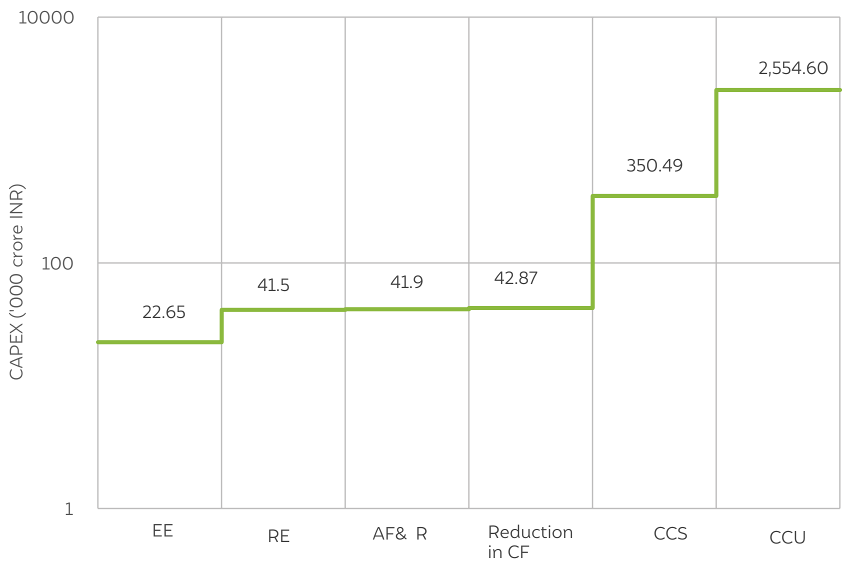
This section highlights the capital investment requirement and the operational expenditure that will be incurred to achieve net-zero in the Indian cement industry. The cost of deploying CCU and CCS requires the highest capital expenditure of approximately INR 22 lakh crore (USD 293 billion) and INR 3 lakh crore (USD 41 billion), respectively, to capture ~123 million tonnes of CO2 produced by the cement industry as a whole (Figure 27). According to our estimates, only 50 per cent of the cement production facilities have access to natural gas pipelines that could be used for CO2 transport (and therefore can adopt the CCS path), while the remaining half opt for CCU. In contrast, the CAPEX is much less for implementing energy efficiency. We estimate that energy efficiency in the cement industry will need an investment of INR 23,000 crore (USD 3 billion).

The uptake of alternative fuels in the cement industry will need modifications in burner design and the addition of equipment, such as a hot disc reactor for alternative fuel injection, belt conveyors, etc., requiring an investment of INR 400 crore (USD 100 million). The installation of 1.3 GW of RTC RE to offset captive power requirements is expected to cost INR 19,000 crore (USD 2.5 billion). However, the uptake of RE power (procured through open access mechanism) becomes viable only at a price of INR 5.07 per kWh. Further, the cost of biomass and MSW is currently higher than coal and petcoke at INR 415 per GJ (USD 5.53/GJ) and INR 323 per GJ (USD 4.3/GJ), respectively.

Net-zero cement manufacturing requires approximately 5.3 MTPA of MSW and 24 MTPA of biomass (Figure 28). If the current cost of each of these products is calculated (Figure 28), the net increase in cost affirms that these alternative fuels are expensive, and they increase the cost of transition by INR 13,200 crore per annum (USD 1.76 billion). The OPEX also includes capturing nearly 123 MTPA of CO2 through CCS and CCU, which is expected to cost approximately INR 9,992 crore and INR 14,182 crore per annum, respectively. The total OPEX cost is expected to increase by INR 29,580 crore per year (USD 3.95 billion). There is also a marginal reduction in OPEX estimates, primarily due to the increased adoption of fly ash and slag.

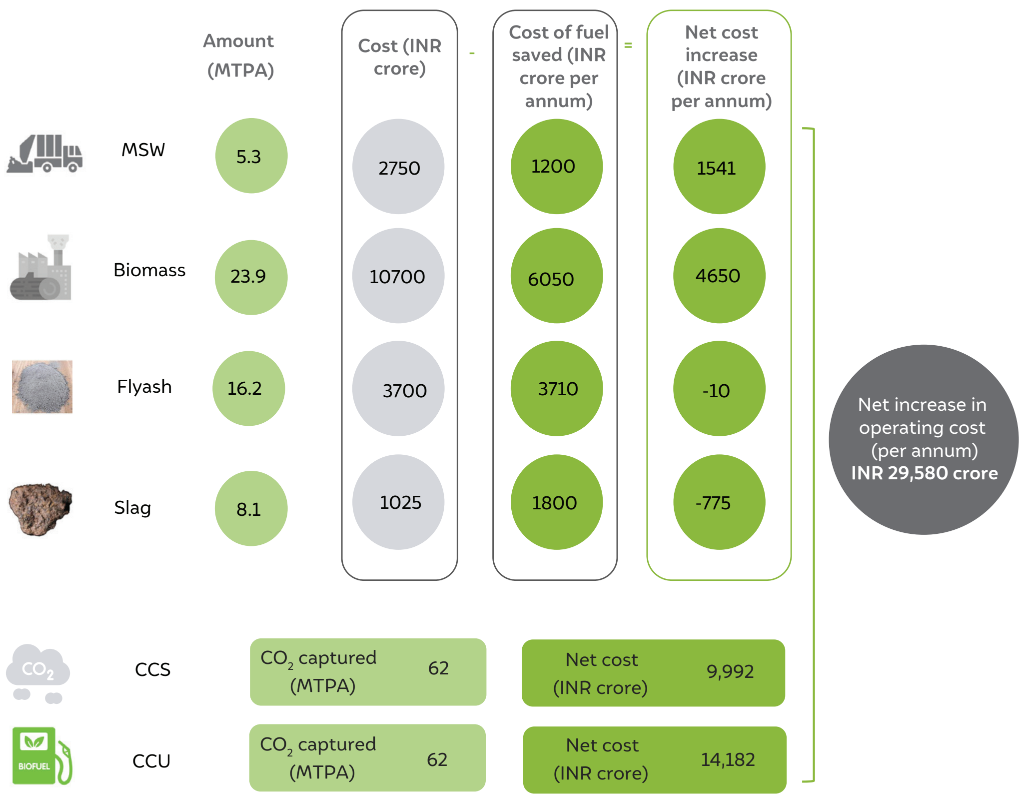
The increase in cost for clinker factor reduction is only marginal even though the delivered cost of additives such as steel slag and fly ash is currently high. This increase in cost due to a higher share of additives is partially offset by the savings as a result of lower clinker demand. The same explanation holds true for using alternative fuels such as MSW and biomass. However, supply chain bottlenecks for additives (steel slag, fly ash, etc.) and alternative fuels (agricultural waste, biomass, MSW, etc.) hinder their widespread usage.

Figure 27 The cost of deploying CCU and CCS requires the highest capital expenditure



Source: Authors' analysis

Figure 28 The total OPEX cost is expected to increase with the adoption of alternative fuels



Source: Authors' analysis

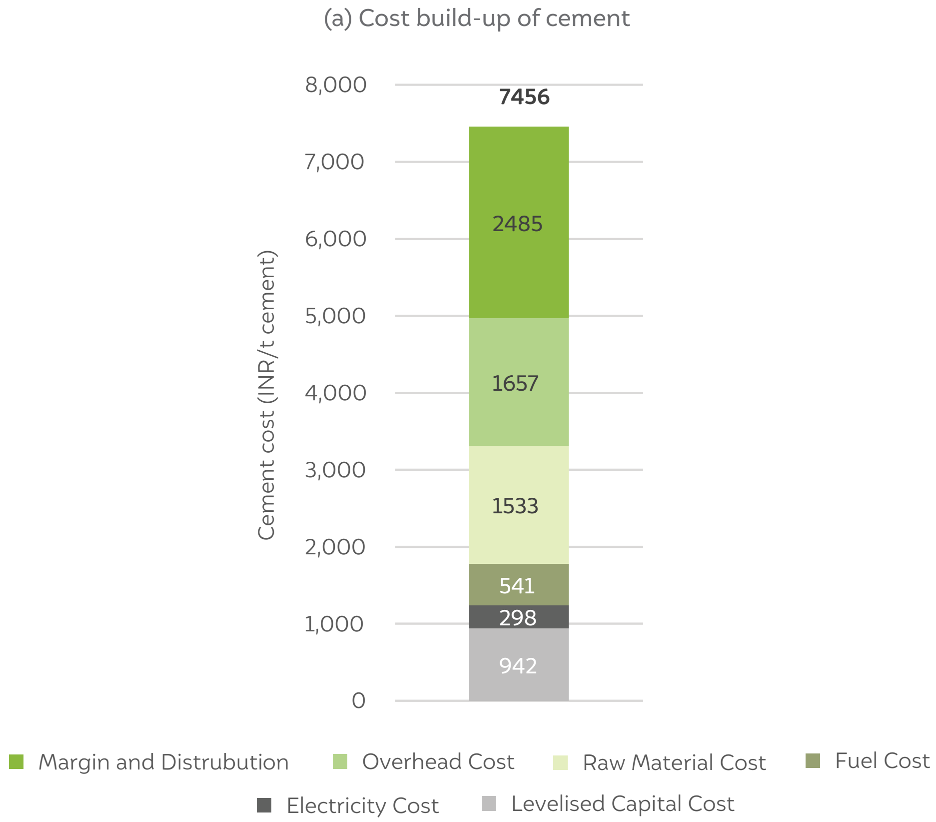
Note: This infographic does not include the open-access charges for RE power which amounts to INR 1000 crore

4.3 Effect on cement prices

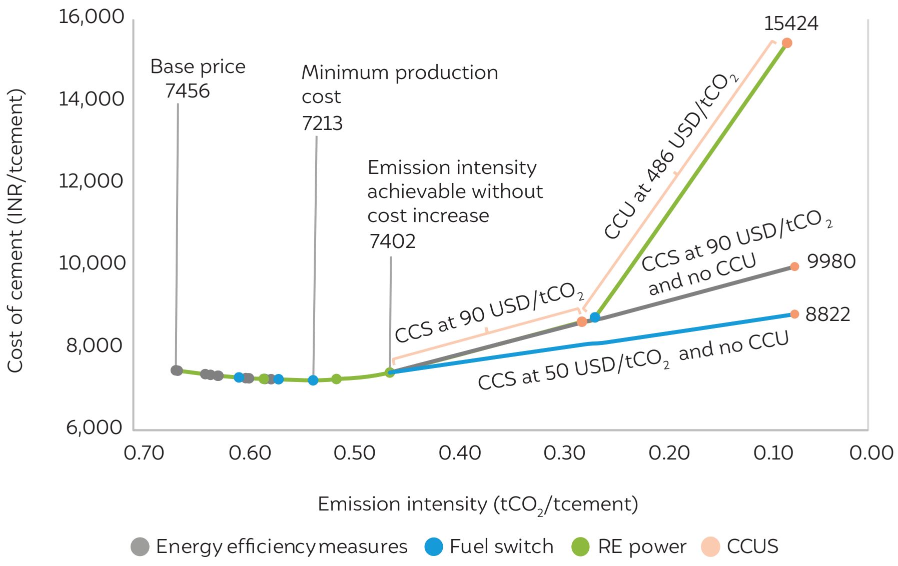
The price build-up for cement can be seen in Figure 29 (a). The bulk of the delivered price is due to margins, distribution costs (INR 2,485 per tonne), and operation costs (INR 2,371 per tonne). The operation costs include the cost of raw materials, fuel, and electricity (INR 1,533, INR 541, and INR 298 per tonne, respectively) and overhead costs (INR 1,657 per tonne), including labour costs and other expenses incurred to run the manufacturing unit (based on communication with industry sources). In addition, an annualised CAPEX of INR 942 also adds to the total cost of cement per tonne at INR 7,456.

As seen in Figures 29 (b) and (c), the price of cement per tonne decreases from INR 7,456 to INR 7,213 with the implementation of decarbonisation measures such as waste heat recovery, enhancement in kiln and preheater, and reduction of clinker factor by increasing fly ash content. Utilising RE and increasing the TSR rate to 30 per cent in kilns increases the price marginally, to INR 7,402 per tonne. However, with further adoption of measures such as CCUS, the price increases steeply to INR 15424 per tonne. Therefore, 32 per cent of emissions (0.45 tonne CO2/tonne cement), compared to the baseline, can be reduced without any increase in the cost. This essentially means that the cement manufacturer can implement these decarbonisation measures without increasing the price of cement per unit. However, reducing emissions beyond this would require the manufacturer to bear a significant cost, which, in turn, will be passed on to the consumer. The cost of near net-zero cement per tonne would be approximately 107 per cent higher than the current prices. In a scenario where only CCS is implemented as a carbon management mechanism, its cost would reduce from USD 90 to 50 per tonne of CO2. Consequently, the cost of near net-zero cement will increase by 19 per cent instead of 34 per cent due to CCS implementation.

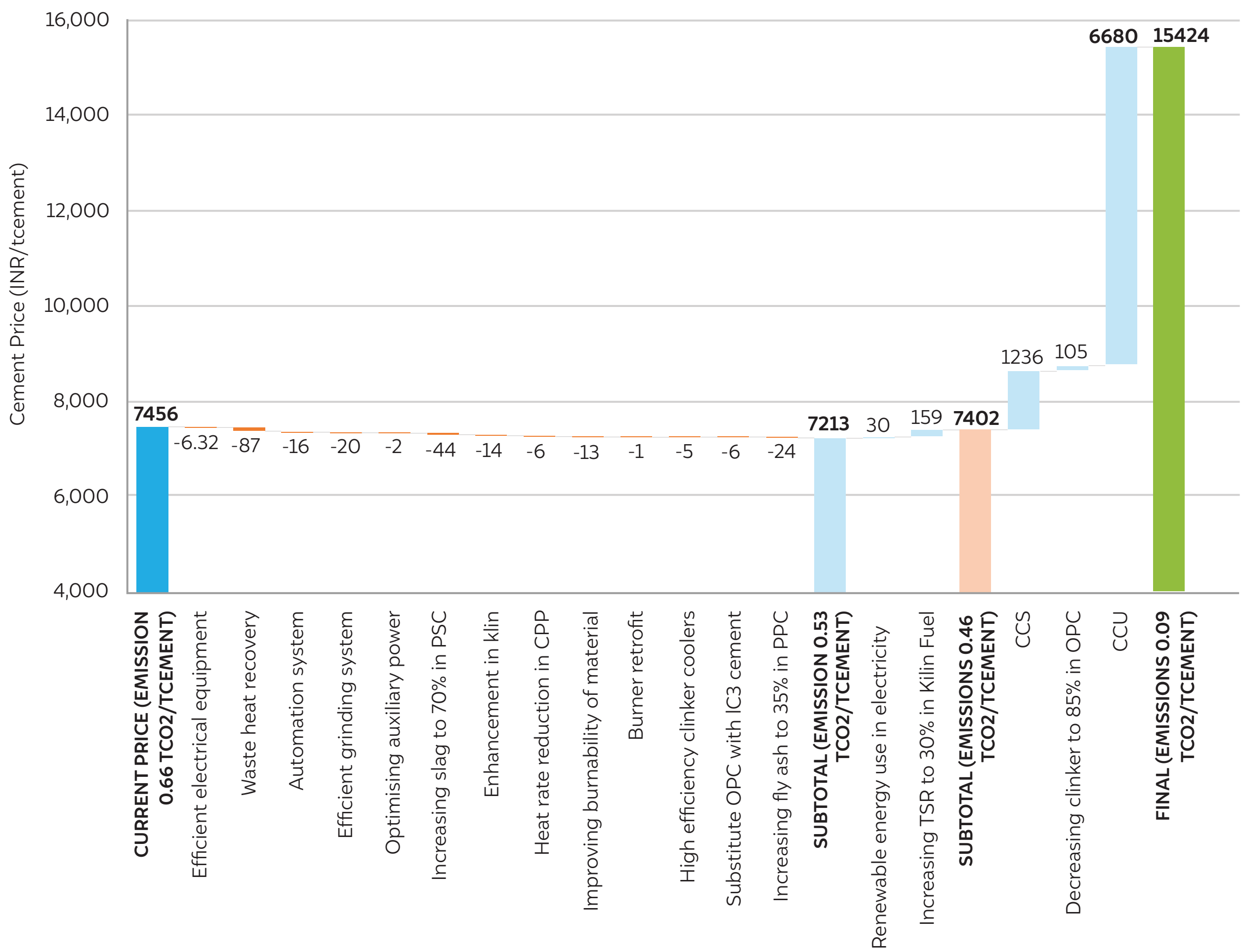
Figure 29 The emissions intensity of cement can be reduced by 32% without increasing the cost of cement



(b) Cost of cement in a net-zero scenario



(c) Trajectory of cement cost increase



Source: Authors' analysis; IBEF 2023; communication with industry experts

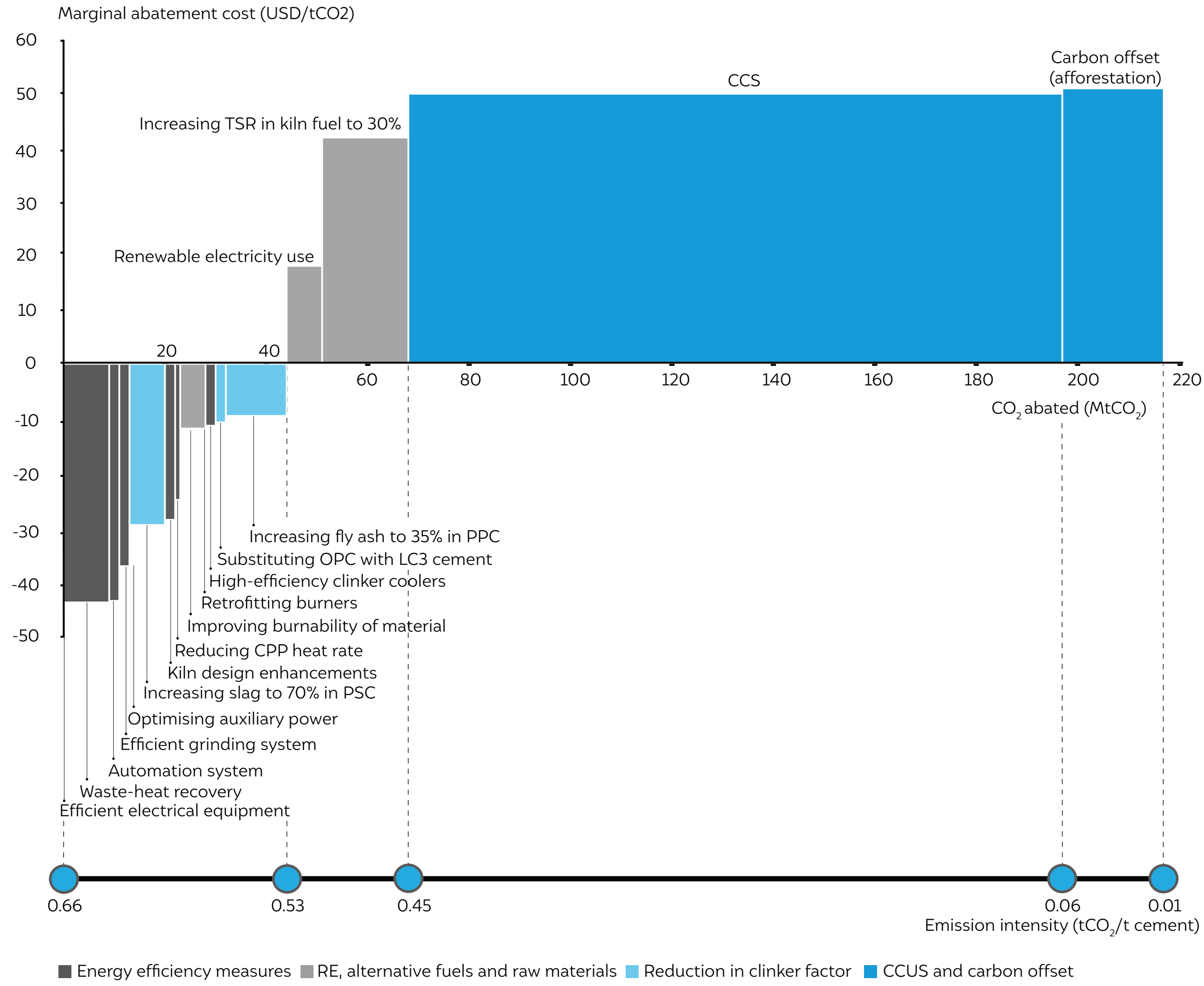
4.4 Sensitivity analysis

A sensitivity analysis gauges the changes in target variables when the input variables of a model are changed. In our study, the MAC of various decarbonisation measures and their subsequent CO2 abatement potential would be the target variables, and variables such as fuel and raw material costs and calorific values are input parameters.

Currently, if the distance from the cement plant to the natural gas pipeline is more than 100 km, CCU is assumed to be the only solution for the industry to reach net-zero. If the cost of capture per tonne of CO2 in CCS decreases to USD 50 from the current USD 90, and installation of dedicated pipelines to transport CO2 becomes possible, then all decarbonisation measures (except switching to RE), such as increasing TSR to 30 per cent, adopting CCS, and afforestation will have a negative MAC (Figure 30). In this scenario, OPC manufacturers could opt for CCS as a decarbonisation measure over the reduction of clinker factor.

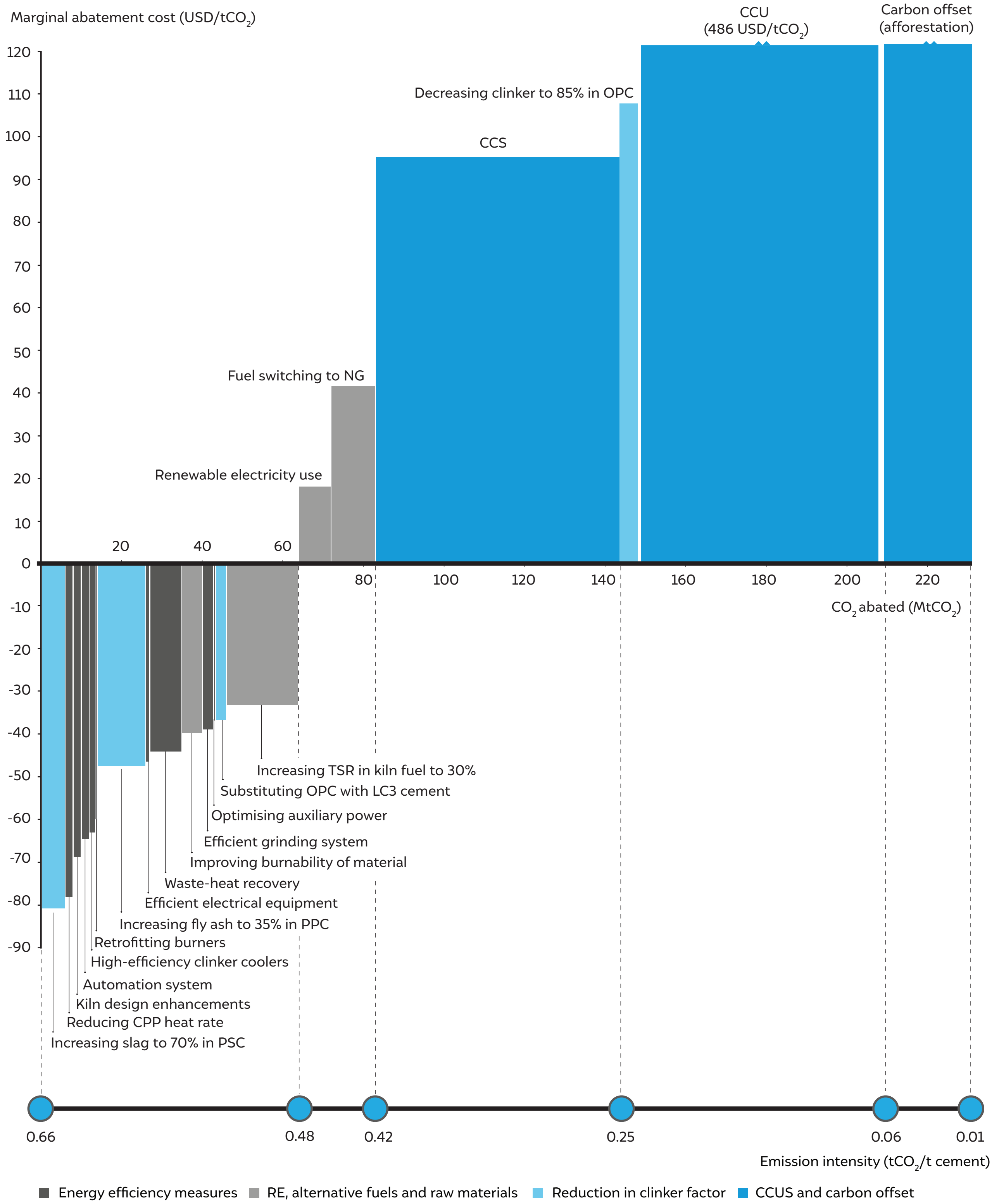
Figure 31 shows the sensitivity of the MAC curve for the financial year 2021-22 and therefore consider different values for cement production, fuel prices and share of electricity used from the grid, captive power plant, and RE power. In the financial year 2022, cement production increased by 6 per cent to 356 MTPA, the cost of petcoke rose to INR 23,100 per metric tonne, and the natural gas price surged to USD 14 per GJ. If the cost of captive power is taken to be constant at INR 3.72 per kWh, the share of captive power is taken as 18 per cent, grid power as 72 per cent, electricity generated through waste heat recovery at 6 per cent, and RE power at 4 per cent; then, as a consequence, the MAC curve changes. These estimations are based on interactions with industry experts, plant level managers and values as reported in literature. As seen in the MAC curve, the reduction in clinker factor to 85 per cent in OPC, switching to RE power, CCS, CCU, and afforestation continue to have positive abatement costs, while all other decarbonisation measures have negative abatement costs, making them financially attractive to adopt.

Figure 30 **MAC curve if the cost of CCS decreases to USD 50/tCO_2**



Source: Authors' analysis

Figure 31 **Barring a few, most decarbonisation measures have negative abatement costs, making them financially attractive to adopt**

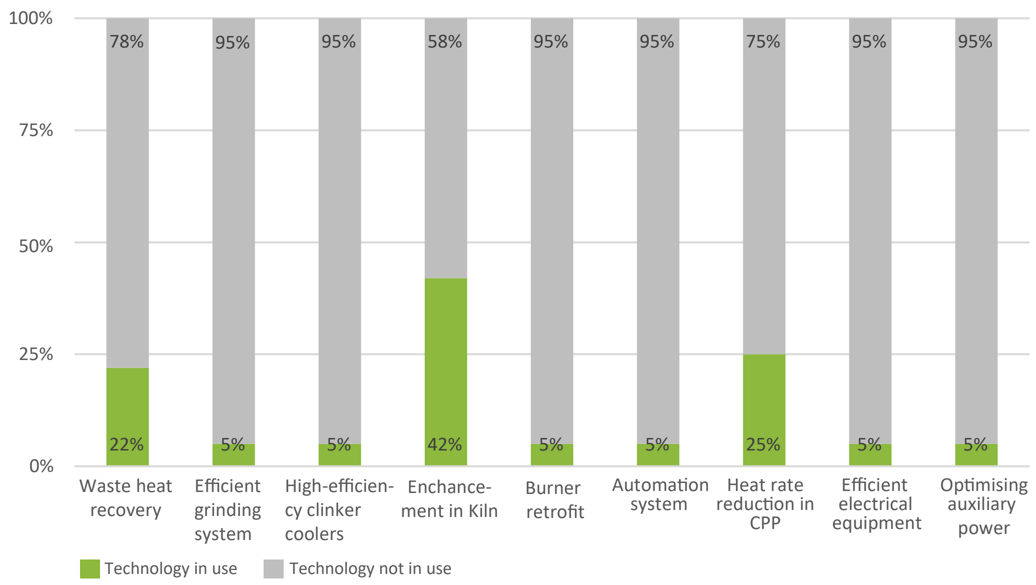


Source: Authors' analysis

4.5 Uncertainties in the analysis

The data relating to plant-level material consumption, emissions, and efficiency technologies currently in use were not available. The penetration level of energy efficiency measures was obtained from the sustainability reports of the top 13 cement manufacturers in the country, who contribute to approximately 59 per cent of the cement production (Figure 2). The assumed penetration levels for energy efficiency technologies considered in this study are graphically represented in Figure 32. In addition, some of the data points chosen were national or global averages and, therefore, may not reflect the Indian scenario adequately. This is of particular consequence for the CAPEX and OPEX of mitigation measures. Further, plant-level prices of fuels used in the cement plant and captive units were unavailable, and an overarching assumption was made for these parameters. Regardless, the MAC curve can be updated based on the availability of plant-level data and can be used to develop a strategy for the decarbonisation of the cement industry in India.

Figure 32 Penetration of energy efficiency technologies



Source: Authors' compilation

5. Policy recommendations and conclusions


Image: iStock

Our study concludes that the cement industry can reduce the emissions intensity by 20 per cent (0.66 to 0.53 tCO_2/t cement) while also achieving a 3 per cent reduction in cement cost. Furthermore, we found that 32 per cent of emissions per tonne of cement (0.66 to 0.45 tCO_2/t cement) can be reduced without any increase in the cost of cement. This essentially means that the cement manufacturers can implement these decarbonisation measures without increasing the price of cement per unit and continue to obtain a profit from it. However, reducing emissions beyond this to reach near net-zero cement production would increase costs by 107 per cent higher than current prices. In addition, we also found that the use of natural gas as an alternative fuel is not financially viable. In order to manufacture net-zero cement while still maintaining economic viability, certain policy interventions are key. These are described as recommendations following.

- **Set targets for the use of the best available energy efficiency technologies under the Indian Carbon Market scheme:** Energy efficiency as a decarbonisation measure is a low-hanging fruit. All energy efficiency technologies discussed in this study have a high level of readiness (TRL 11). A survey of energy efficiency technologies currently deployed in Indian cement manufacturing units must be conducted to estimate the potential for rapid adoption of energy efficiency technologies. This survey should include an accounting of vintages of inefficient incumbent equipment and processes. These plants with inefficient old technologies should be incentivised to replace incumbent equipment with new, more efficient alternatives. The recently announced scheme on the Indian Carbon Market (ICM) should set targets on energy intensity such that the targets are higher than the reductions that can be achieved through energy efficiency technologies in each of the sectors. Further, greenfield investments should be mandated to adopt all energy efficiency technologies for getting environmental clearances.

The *Indian Carbon Market* scheme should set targets on energy intensity so that all industries adopt and install all energy efficiency technologies

- **Evaluate the suitability of EAF/IF slag as an additive and build a supply chain for them:** Clinker factor reduction through the addition of alternative materials is another important decarbonisation measure that will not only reduce the cost of cement production, but also mitigate GHG emissions. The cement industry is already using fly ash and BF-BoF slag as clinker substitution materials. The feasibility of using bottom ash as a clinker substitution material should be explored further. Similarly, research is needed to increase the use of EAF/IF slag (and other slags that are not used today) to test for their suitability to act as clinker substitution material. As the steel industry transitions from blast furnaces to hydrogen-based DRI technology, this research will become crucial. The effect of these additives and alternative materials on the strength of cement and build quality should also be assessed. Based on the findings, the existing building codes and construction protocols should be modified to incorporate these low-carbon building materials.

- **Develop efficient logistics for transport of clinker substitution material and alternative fuels:** Affordable logistics will be a key factor for increasing the uptake of clinker substitution material and alternative fuels such as biomass and MSW. Indian Railways should enable seamless transportation of fly ash by prioritising the movement of slag and other clinker-reducing material. It should also provide end-to-end connectivity between steel/power plants to cement mills where possible and enable intermodal transport to reduce logistic costs. Waste management mechanisms should be put in place at municipal levels to ensure access to MSW and facilitate its transportation by rail, if possible.

- **Develop a robust MRV framework to estimate GHG emissions at process, equipment, and plant levels:** The government should prioritise robust measurement, reporting, and verification (MRV) of emissions as industries decarbonise; this is critical given the advent of carbon pricing. The challenges related to MRV have become more important, especially for the use of alternative fuels such as biomass and MSW. It is also important to assess the net CO_2 reduction from the use of various kinds of biomass in cement skills.

- **Incentivise RE as it will play a pivotal role in decarbonisation:** According to our estimate, cement plants need 1.3 GW of round-the-clock RE to meet their power demand even after the adoption of all energy efficiency technologies, which comprises both wind and solar power capacities. Most cement plants are located in states having access to both wind and solar power potential. Although inter-state transmission charges for electricity generated from RE projects commissioned till 2025 are waived, the government should extend this incentive beyond 2025. In addition, RTC RE will only materialise if state governments also provide a top-up on existing government incentives.

- **Develop a CCS ecosystem in India for full decarbonisation:** A sizable share of process CO_2 can be mitigated only through the CCUS pathway. Therefore, infrastructure and technologies related to CCS have to be actively developed and deployed. The government should formulate a policy for CCS that will eventually lead to the development of the CCS ecosystem in India.

- **Formulate favourable policies to build a CCU ecosystem in the country:** CCU will be critical for the cement industry to achieve net-zero. However, CCU applications require green hydrogen. Therefore, the next phase of the National Green Hydrogen Mission (NGHM) should focus on creating a CCU ecosystem in India by developing favourable policies that incentivise industries to adopt CCU measures.

- **Build an R&D ecosystem for the cement industry:** A robust R&D ecosystem, including pilot projects for CCUS across all geographies (depleted oil and gas wells and saline and basalt rock formations) and utilisation pathways, must be carried out. Further, pilots on electrification and utilisation of green hydrogen should be planned and executed. There is also a need for deploying a pilot project using low-carbon LC3 and assessing the end-to-end viability of this pathway for producing cement.

India should formulate a CCUS policy for developing an ecosystem to decarbonise the cement industry

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Acronyms

EE	energy efficiency
EF	emission factor
AF	alternative fuel
MTPA	million tonnes per annum
MSW	municipal solid waste
MRV	measurement, reporting and verification
MMBtu	million metric British thermal units
NDC	nationally determined contributions
NG	natural gas
R&D	research and development
RTC RE	round-the-clock renewable energy
CCUS	carbon capture, utilisation and sequestration
TRL	technology readiness level
TSR	thermal substitution rate
CAPEX	capital expenditure
OPEX	operating expenditure
OPC	ordinary Portland Cement (OPC)
PPC	pozzolana Portland Cement (PPC)
PSC	portland Slag Cement (PSC)

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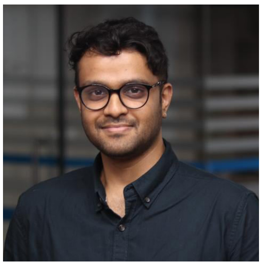

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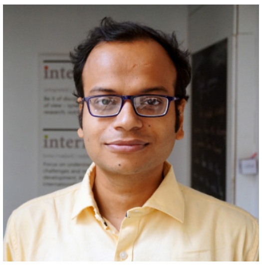

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Cement is an essential binding material used in concrete for construction.

Image: iStock

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