Temperature change and mitigation potential of Indian cement industry

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ABSTRACT
Cement is one of the highest energy-consuming and emission generating industries around the world. To reduce greenhouse emissions, several mitigation measures have been proposed, and their effectiveness is estimated. However, estimates of the global temperature change potential of the cement industry have seldom been performed. Hence, in this study, we propose a new framework that estimates CO₂ emissions and other seven pollutants to estimate temperature change potential from the cement industry. The underlying framework uses system dynamics, where the effectiveness of four mitigation measures, i.e., a shift in demand, newer methodologies to produce clinker, use of energy efficiency improvements, and implementation of renewable energy, are explored. The results indicate that renewable sources of energy show highest mitigation potential. The cement industry has contributed to an increase in 2 mK temperature since 1990, which is likely to grow up to 14.8 mK by 2050 if no mitigation measures are applied. Energy efficiency improvements by extensions of perform achieve and trade scheme can reduce 0.33 mK from the Indian cement industry. This paper provides a unique opportunity for estimating temperature influence of the cement industry, which can be further implemented for other countries.

KEYWORDS
Cement industry; temperature change potential; climate change mitigation; system dynamics

Introduction
The production of cement is one of the highest energy-consuming and emission-producing industries in the world [1, 2]. Two significant sources of greenhouse gas (GHG) emissions from the cement industry are (i) the use of fossil fuels and (ii) the calcination process (wherein limestone (CaCO₃) is converted into CaO and CO₂ at high temperatures) [3–5]. Cement production is expected to increase in developing countries such as India, whereas it is expected to stay constant in developed economies [6, 7]. Several mitigation strategies are proposed here, along with different methodologies to evaluate emissions from the cement industry, to reduce emissions effectively and efficiently.

To estimate carbon emissions, the Intergovernmental Panel on Climate Change (IPCC) has suggested three methods, i.e. Tier 1, Tier 2, and Tier 3, which are based on data availability [8]. Tier 1 employs the emission factors of the fuel used in the cement industry. Additional data on clinker production at the national level is required to implement Tier 2 methodology. Tier 3 uses the plant-wise specific emission factor, along with the proportion of CaO in the clinker. The accuracy of the methods is highly dependent on the granularity of data. Thus, it is suggested to use country-level data to achieve accurate estimates [8, 9].

Several other methodologies have been developed for cement emission estimation. The integrated assessment model (IAM), physical production index (PPI), and cost-based analysis have been applied to the world cement production, in the present and for future scenarios [5, 10, 11]. The mitigation analysis performed mainly focused on energy efficiency improvements in a global cement industry analysis, along with technology shifts and fuel mix shifts. On the other hand, country-specific models have been developed using various methodologies. One such method includes the conserved cost of energy that determines air pollution and CO₂ emission mitigation for the cement industry in China [12] and India [13]. The Indian study identified individual energy efficiency improvement retrofits along with their costs. The study suggested that despite...
the high cost of improvements resulting in higher mitigation, low to no-cost mitigation may be able to achieve up to 5% emission reductions in the future [13].

Other methods include the MARKAL and Long-range Energy Alternative Planning (LEAP) models, which have been adopted to estimate energy conservation [14] and emission mitigation [15–17]. These models have optimized the system cost to be minimum, using demand, production, energy consumption, and emission parameters. An analysis of the Canadian cement industry using the LEAP model showed that it is possible to achieve significant emission mitigations with negative costs [17]. However, optimization of demand and supply does not ensure that demand as a mitigation option, as well as energy optimization, will not miss out on the opportunity of technology shifts. Moreover, renewable energy use has seldom been discussed in studies on cement industry mitigation.

Demand as a mitigation option has been understood using the IPAT equation and its modification [18]. Ruijven et al. [19] have attempted to integrate various demands with gross domestic product (GDP) and their future implications for emissions from the sector, which suggested a linear integration of GDP and demand. Factorial assessment of demand and supply dynamics suggested GDP as the main influencing factor [20]. The feedback loops of mitigation are highlighted in the models; however, they lack to represent the cumulative effect. The present study looks at each of the mitigation strategies separately and in combination.

Methods

System dynamics is one of the methodologies incorporated to understand the policy implications of emission mitigation. Demand and supply dynamics have been integrated along with technological details Anand et al. [21] and Jokar and Mokhtar [22] using system dynamics. Although the representation of demand–supply dynamics was incorporated, future alternatives were not explored from a material efficiency perspective. Furthermore, mitigation studies thus far are limited to CO₂ and SO₂ emissions for limited technological improvements. Hence, in this study, we attempt to build a framework to address all the mitigation options for nine climate pollutants of the cement industry and their global temperature change potential.

The study is divided into four sections; the second section describes the methods used in the development of the system dynamics framework. Here, assumptions to develop scenarios for the Indian cement industry and their respective methodologies are also discussed in detail. Next, the third section outlines the results of emissions from 1990 to 2050 of the Indian cement industry, where all the scenarios are outlined. Finally, the fourth section presents a discussion on the Indian cement industry, the mitigation measures, and the future scope, along with a conclusion.

Causal loop diagram

First, a causal loop diagram was developed to understand the interactions between variables of concern, which is given in Figure 1. The GDP drives the demand for cement, along with the population. Interactions between GDP and cement demand are externally established. An increase in imports in a country results in reduced domestic production, whereas exports encourage domestic production. Two sources of pollution identified from the system are energy consumption and clinker proportion [21, 22, 28]. The feedback loops of mitigation are highlighted in the models; however, they lack to represent the cumulative effect. The present study looks at each of the mitigation strategies separately and in combination.
been identified as an M1 balancing loop. On the other hand, advancement in production technology and the use of blended materials result in a shift in the production of clinker, creating the second balancing loop (M2). Lastly, energy efficiency improvements and implementation of renewable energy affect the energy use of the industry, creating the two feedback loops M3 and M4, respectively.

**Stock and flow diagram**

The stock and flow system dynamics diagram represents the numerical flow of information in the system. Three types of variables are illustrated in Figure 2: (a) levels or stocks, (b) rate or flow and (c) auxiliary. The levels accumulate over time. The input and output from the levels are rates; levels can change their value only when the rates inflow the information or outflow the same. Auxiliaries are used to add to the existing information in the system.

In this study, we develop a stock and flow diagram where population, production and emissions are the stocks of the system, which can only be changed by the rates of population growth, production and emissions over a year. The policy variables represent each policy intervention adapted in the study: the first is demand changes; the second and fifth represent energy efficiency in terms of electricity and thermal energy, respectively; the third is technology changes; and the fourth represents the implementation of renewables. The flow of the system is similar to that of the causal loop diagram, where population along with cement demand drives production. Production of cement requires the production of clinker to burn in the kiln using thermal energy. Each energy source and clinker production results in emissions with interactions of energy and emission factors. Interactions between variables are given in Table S1 (Supplementary material).

**Temperature change potential**

Absolute global temperature change potential (AGTP) has been used for temperature estimation. AGTP is estimated by IPCC using radiative forcing ($A_x$) of pollutant $x$, the heat capacity of the system ($C$) and the residence time of pollutants in the atmosphere ($\tau_x$) [29]. The interaction of the variable is expressed in Equation (1) in K/kg emission. The AGTPs adopted for the pollutants considered in the study are listed in Table 1 [29]; although the uncertainty of these parameters is high, they provide a good measure of the temperature change potential [30, 31].

$$AGTP_x(t) = \frac{A_x t}{C} \exp \left( -\frac{t}{\tau_x} \right)$$

(1)

**Scenario assumptions**

Four mitigation measures are explored in the study to understand the implications for future emissions. The Indian cement industry has been assessed using the proposed framework through 1990–2050. The mitigation scenarios comprise two demand scenarios, three technology scenarios, two energy efficiency scenarios, and two renewable implementation scenarios. Each mitigation measure refers to specific assumptions discussed here.

**Demand assumptions**

Material demand is proportionally related to per capita GDP [6, 19], linearly or non-linearly. The
The historical trend between per capita cement production and per capita GDP has been developed from 1990 to 2015 (data acquired from CMIE [32]). As shown in Figure 3, two types of future trends are expected for cement demand. One shows an exponential increase in the demand (D1); on the other hand, the demand for cement may become saturated and stabilize after reaching a peak (D2). The exponential curve adopts the log–log inverse relation, as shown in Equation (2) [19].

\[
\ln Y = a + \frac{b}{X} + d \ln X \tag{2}
\]

\[
Y = \frac{Y_{\text{max}}}{1 + e^{(a-bx)}} \tag{3}
\]

**Clinker production scenarios**

As clinkerization is one of the highest energy-consuming and emission-producing processes, a separate optimization has been developed for it. Currently, only one type of clinker exists in the market, which makes up about 70–95% of the cement along with the additives like gypsum. However, research is underway to reduce \(\text{CO}_2\) emissions from clinker production. One such option is carbonatable calcium silicate cement (CCSC), which requires less clinker to harden the blend [34]. Moreover, during curing, CCSC absorbs \(\text{CO}_2\), resulting in a 30% reduction in \(\text{CO}_2\) emissions. Currently, there are three major types of cement produced in India including, ordinary portland cement (OPC), pozzolana portland cement (PPC) and portland slag cement (PSC).

Estimations of the future share of each type of cement is undertaken using an optimization (genetic algorithm) between cost and emission, which are assessed to reach a theoretical optimum value. For this purpose, each technology production is considered for separate investments and emissions. carbonatable calcium silicate clinker (CCSC) is a new type of clinker, which is in the research phase; however, its cost of implementation is expected to be similar to that of ordinary portland cement (OPC) [35]. To estimate the best practices that optimize cost and emissions, the genetic algorithm was used. The results of this optimization formed the basis of the technology share for each cement type. Optimization results are shown in Figure 4, with cost optimization on the x-axis and emission optimization on the y-axis. The initial values on each axis represent the highest optimization of that parameter, i.e. cost (T1) or emission (T2). The third scenario (T3) represents the
optimization of both cost and emissions, represented by the middle section of the graph. The shares of each technology based on the type of cement are shown in Table 2.

Energy efficiency improvements

The Indian cement industry is one of the most energy-efficient industries compared to the world average [14]. Two types of energies are required for cement manufacturing; one is the thermal energy required in the kiln to reach high temperatures during clinker production, whereas electricity is required for other processes. In the early 2000s, the primary fuel for the industry was coal and lignite, with less than 10% coming from petroleum [36]. However, the share of petcoke has been increasing and accounted for about 39% of fuel use in the cement industry as of 2015 [37]. In the future, the share of petcoke is expected to increase up to 50% with a concomitant reduction in coal use. In this study, two energy efficiency scenarios are considered with the constant fuel share in the future. The energy efficiency improvements have been assumed from the current state to the best available technology (BAT), derived from Worrell et al. [38] (Table 3). Business as usual (BAU) of the energy efficiency (E1) is assumed to reach the upper bound of the BAT by 2050, whereas E2 reaches similar levels by 2030 (Table 3). The energy efficiency scenario (E2) goes beyond the upper

Table 2. Technology share for three scenarios assumed based on the optimization algorithm.

| Scenario       | OPC | PPC | PSC | CCSC | Clinker (share) |
|----------------|-----|-----|-----|------|----------------|
| 2015           | 42  | 46  | 12  | 0    | 84.5           |
| T1 – 2050 Low cost | 10.75 | 4.41 | 74.93 | 9.96 | 71.91          |
| T2 – 2050 Low emissions | 3.76 | 4.01 | 61.21 | 30.99 | 76.01          |
| T3 – 2050 Optimization | 12.89 | 4.48 | 76.57 | 6.14 | 71.43          |
bound during the 2030–2050 period to reach the lower bound by 2050.

Renewable energy and waste heat recovery

The thermal energy used for clinker production can be recovered and reused in various stages of pre-heating processes. Currently, only 5% heat is recovered [37]; hence, the BAU is assumed to continue with a similar share. The alternate scenario assumes that the share of Waste Heat Recovery (WHR) will increase to 30% throughout the industry by 2050. Second, the electricity is supplied from the grid at present; therefore, the BAU scenario continues with the same. However, the plants can install a solar power supply to ensure electricity supply off the grid. As a result, the second renewable scenario (R1) assumes that by 2050, the use of renewable energy for electricity production will account for up to 30%. The share of renewable energy in the cement industry is expected at around 1% per annum, which is similar to the present growth rate for electricity production [39].

Cost analysis

Emissions and mitigation measures assessed here have been ranked by their cost of mitigation. The mitigation cost is calculated using Equation (4), where \( C_{\text{scenario}, t} \) is the cost incorporated to implement scenario mitigation measures in a given year, and \( C_{\text{BAU}, t} \) is the cost for the BAU scenario. The difference in cost is divided by the emission differences in the same year. Here, only \( \text{CO}_2 \) emissions are considered, where the BAU is expected to emit a higher amount of \( \text{CO}_2 \) compared to the other scenarios. For cost estimation (Equation 5), three costs are considered: capital costs converted into annualized form (net present value (NPV_{(CC,t)}) of capital cost), fuel costs among the maintenance costs (FCt), and, lastly, the cost of renewable energy and WHR installations (RCt). Other maintenance costs are not considered in the study, as they are not expected to differ among the scenarios. The cost assumed for the study is shown in

\[
\text{Mitigation Cost}_t = \frac{C_{\text{scenario}, t} - C_{\text{BAU}, t}}{E_{\text{scenario}, t} - E_{\text{BAU}, t}} \quad (4)
\]

\[
C = \text{NPV}_{(CC,t)} + FC_t + RC_t \quad (5)
\]

Results

The framework developed for the Indian cement industry was assessed from 1990 to 2015, and future mitigation was estimated from 2015 to 2050. Historical data from the cement industry show that the highest emissions are contributed during clinkerization (70%), followed by thermal energy use for clinker production (25%). The total emissions from the cement production are estimated at 220 MT \( \text{CO}_2 \) in 2015 using the presented framework (Figure 5). The temperature change increased to 2.03 mK from 1990 to 2015, accounting for \( \text{CO}_2 \), black carbon (BC), organic carbon (OC), sulfur dioxide (SO2), nitrogen oxides (NOX), non-metal volatile organic compounds (NMVOC), methane (CH4), nitrous oxide (N2O), and carbon monoxide (CO).

The future emissions from the cement industry are expected to increase to 475 and 980 MT \( \text{CO}_2 \) by 2030 and 2050, respectively, for the BAU scenario (Figure 6). A shift in demand toward saturation (D2) would result in a reduction of emissions by 2030 and 2050, to 327 and 365 MT \( \text{CO}_2 \), respectively. An increase in temperature can be seen in both scenarios, where the exponential demand (D1) results in a 14.9 mK temperature increase by 2050. The saturation demand (D2), on the other hand, shows a reduced increase in temperature at 7.3 mK in 2050.

The low-cost approach (T1) for D1 and D2 shows that the emissions spike to 978 and 365 MT \( \text{CO}_2 \), respectively, in 2050. Implementation of the low-emission approach (T2) leads to an increase in emissions of 270 MT \( \text{CO}_2 \), resulting in emissions of 1250 MT \( \text{CO}_2 \) in 2050 for D1. The increase in

| Table 3. Energy efficiency and thermal efficiency assumptions for the two scenarios. |
|-------------------------------------------|----------|----------|------------|
| Unit | Energy efficiency kWh/t cement | Thermal efficiency GJ/t clinker | Fuel share Percentage |
| Scenario | E1 | E2 | E1 | E2 | Coal | PetCoke | TSR |
| 2015 | 80a | 80a | 3.07b | 3.07b | 57 | 39 | 4 |
| 2030 | 76 | 74 | 2.4 | 2.1 | 56 | 40 | 4 |
| 2050 | 74 | 70 | 2.1 | 1.8 | 46 | 50 | 4 |

a Dutta and Mukherjee [14].
b WBCSD [50].

| Table 4. Cost assumptions for the Indian cement industry, with details on capital cost, fuel cost and renewable energy cost. |
|-------------------------------------------------------------|
| Capital cost NPV at 12% discount rate (2015) | 393.21 Crore Rs/t clinker |
| Fuel costb |  |
| Coal | Rs/t |
| 2015 | 1716 |
| 2030 | 2445 |
| 2050 | 4006 |
| Renewable costc | 2.43 |
| 2.43 | Rs/kWh |

a Ministry of Environment, Forest and Climate Change [40].
b Bharat Coking Coal Ltd [41] and Coal India Ltd [42–45].
c Solar Energy Corporation of India Ltd [46].

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emissions can be attributed to the 30% share of CCSC, which produces high emissions during production, with carbon sequestration during curing that has not been considered here. Similarly, emissions increase for the D2 scenario up to 101 MT CO₂. The third shift toward optimization technology (T3) results in mitigation of 17 and 7 MT CO₂ for D1 and D2, respectively. However, the temperature change shows an increase for T3 at 0.1 mK for D1 and 0.07 mK for D2 in 2050. It is important to move toward the optimization scenario to achieve mitigation of emissions and temperature increase.

Emission mitigation can achieve a reduction of up to 7 MT CO₂ by 2050 for the exponential demand (D1) and cost optimization (T1) scenarios by improving the energy efficiency of cement production. Energy efficiency improvement for the saturation demand (D2) scenario with the same technological options (T1) results in an emissions reduction of 3 MT CO₂ by 2050. Temperature change due to energy efficiency improvements shows a reduction of up to 0.33 mK and 0.17 mK by 2050 for the D1 and D2 demand scenarios, respectively, with T1.

Lastly, emission mitigation of up to 46 MT CO₂ is achieved by implementing renewable energy sources for electricity production and waste heat recovery by 2050 for the D1 demand scenario. Similarly, for D2 demand, renewable energy and WHR bring a mitigation of 17 MT CO₂ by 2050. Reductions in temperature change by 2050 are 5.4 and 2.6 mK for D1 and D2, respectively, when renewables are implemented with other parameters held constant. A temperature reduction is observed due to a reduction in CO₂ emissions along with reductions in SO₂, NOₓ, N₂O, and CH₄.

Combined mitigation measures of energy efficiency and renewable energy lead to a mitigation potential of 68 and 25 MT CO₂ compared to BAU for demands under D1 and D2, respectively. The lowest emissions and temperature change can be achieved when technology is shifted toward T3
along with energy efficiency improvements and renewable energy. The emissions are recorded at 893 and 333 MT CO₂ for D1 and D2, respectively, by 2050. The temperature change is expected to be 9.2 mK for D1 demand and 4.5 mK for D2 demand, both with T3 technology, energy efficiency enhancements and renewable energy implementation by 2050.

The cost of emissions and mitigation has been assessed for all mitigation measures considered in the study. Energy efficiency improvements result in negative costs per emission, as the cost of implementation reduces energy costs. On the other hand, implementation of renewable energy results in high costs of mitigation, as capital costs for the renewable energy are high initially; however, they drop to near zero once the payback period is completed (illustrated in Figure 7). Negative costs can be due to increased emissions or reduced costs. Here, the negative costs are mainly due to increased emissions when shifting away from BAU technologies (T1) to optimization scenario T2. It is evident from Figure 7 that despite low costs of mitigation, the resulting emissions have increased for technology shifts. Hence, energy efficiency improvements and renewable energy should be the focus. Energy efficiency improvements for the D1 and T1 scenario results in −1 Rs/kg CO₂ for 2050. However, for saturation demand (D2), energy efficiency improvements result in −12.6 Rs/kg CO₂ by 2050 with a reduction in cost over time. Renewable energy implementation results in mitigation costs of 0.18 and 1.17 Rs/kg CO₂ for D1 and D2, respectively.

Discussion

The study estimates emissions from the Indian cement industry between 1990 to 2050. Historical CO₂ emissions for 2005, taken from Akashi et al. [47], Anand et al. [21], Bhushan [36] and Shakti Sustainable Energy Foundation et al. [48], show a range from 120 to 135 MT CO₂, while the Ministry of Environment, Forest and Climate Change [40] and Dhar et al. [18] estimated 40–80 MT CO₂ (for 2010), compared to the framework estimates presented here of 157 MT CO₂. In contrast to 2005, the present study estimates emissions in 2015 to be 217 MT CO₂, while Rue du Can et al. [16] estimated emissions from non-metal mineral products at 200 MT CO₂, and Bhushan [36] projected emissions from the cement industry to be 174–184 MT CO₂. The future emissions up to 2020 and 2050 are only comparable to the BAU scenario with the D2 demand of the present study [16, 18, 19, 21, 36, 48]. However, temperature change estimates have not been attempted in the literature, so no comparison can be made here.

Mitigation opportunities from the Indian cement industry include energy efficiency improvements [21], increase in blending material [36], technology shifts [19], waste heat recovery [21, 36], carbon capture and storage (CCS) [19], and a shift in material intensity [18]. Results from various studies suggest a similar mitigation capacity to that in the present study. The maximum mitigation in the previous studies were observed by Ruijven et al. [19], at 200 MT in 2050, that incorporated CCS and technology shift. In comparison, demand shift results in higher mitigation potential for 2050. The per capita material shift in the present study shows a steep reduction of 600 MT CO₂, which is higher than the estimate of 180 MT CO₂ by Dhar et al. [18]. The resulting shift in temperature is 7.6 mK less than in the BAU scenario.

Lastly, the estimated mitigation costs range from −10 USD/tonne CO₂ to +18 USD/tonne CO₂. Comparing the cost of mitigation with other
studies shows that the negative costs estimated in the present study are the lowest, suggesting energy efficiency improvements as a viable mitigation strategy. Implementation of solar rooftops for electricity production is lower compared to the Canadian cement industry mitigation costs of 146.9 USD/tonne CO₂ [17]. The social cost of mitigation within China’s overall mitigation effort is comparable to the cost of the renewable energy efforts in the present study (17 USD/tonne CO₂) [49,50].

The study suggests that newer technologies of production for clinker may require more research as an alternative for climate change mitigation. However, it is recommended to implement the energy efficiency measures along with the existing policies such as perform, achieve and trade (PAT) schemes in India to encourage meeting and exceeding BAT standards. The use of renewable energy for electricity production throughout the industry would also result in CO₂ emission mitigation. All the measures mentioned above may be limited to CO₂ mitigation and may not be reflected in the temperature change effect (the cumulative effect of all the pollutants over 20 years). Hence, further research is required to estimate the temperature change potential of the cement industry for India.

Conclusion

The present study has addressed the pressing issue of cement industry emissions in India, with a focus on innovative estimation of temperature change. The study has also demonstrated the use of system dynamics for cement industry emissions and possible policy pathways for the future. The system dynamics model adds a policy dimension to the emission projections with the use of logical and numerical flow. The four policy interventions identified in the study are demand change, technology advancements, energy efficiency improvements, and use of renewable energy. Each intervention was discussed in detail, along with the methodology used for its future projections.

First, demand change is identified based on an analysis of the past trend between per capita cement demand and per capita GDP from 1990 to 2015. The future demand estimates use two statistical models, one where the demand increases exponentially and the other with saturation predefined at 400 kg per capita. The past trends extended into the future for these demands show an increase in total production, which also drives the overall emissions and temperature increase. The resulting CO₂ emissions for exponential demand (D1) and saturation demand (D2) are 978 and 365 MT, respectively. The difference between the two emission levels suggests that lower demand results in lower emissions as well as lower temperature change potential.

The second mitigation option considered in the study is technology changes, with a unique cost–emission optimization algorithm. The results of this analysis indicate that for all future prospects, the share of PSC needs to be higher than 50%, with variations in other types of cement. The second scenario (T2), with 30% share of CCSC along with 61% PSC, results in increased emissions in the production phase; however, sequestration of CO₂ emissions during the use phase have not been considered for CCSC here. The technology scenarios recommend an increased use of PSC relative to any other type of cement for highest mitigation.

Energy efficiency improvement is the third mitigation option considered, where improvements toward the best practices result in emission reductions and less temperature change. The opportunity to improve the efficiency by retrofitting is a low-hanging fruit for the industry. The use of renewable energy for electricity production in the cement industry has also been shown to reduce emissions. Implementation of this policy requires the availability of rooftop and capital investments. Lack of motivation and status quo may pose issues in tapping these low-cost opportunities.

The present study suggests that mitigation of emissions from a shift in clinker production is lowest compared with the other mitigation measures. Despite the use of the lower emission-generating clinker CCSC, the emissions tend to increase. The most cost-effective mitigation strategy is proven to be the use of renewable energy for electricity production and waste heat recovery. Combining the efforts toward energy efficiency improvements and renewable energy use would lead to the highest mitigation with the least cost. Thermal substitution rate (TSR) is an emerging carbon mitigation option that focuses on alternate fuels, raw materials, and waste management. The study considers alternate clinker production technologies and energy efficiency mitigation options that are a part of TSR.
Here, we provide three mitigation strategies for the cement industry. Energy efficiency improvements along with solar rooftop provide a low-cost solution for the Indian cement industry. Moreover, alternate technology adoption requires investments in research and development to promote it in the future. Adopting renewable energy along with a low-demand route will align with India’s commitment to the carbon reduction targets by 2050.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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