"CO2 EMISSION REDUCTION IN THE CEMENT INDUSTRY"

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Abstract

Cement industries are the largest contributors to greenhouse gas emissions, accounting for about 7% of global CO_2 emissions. As global cement demand continues to rise exponentially, the industry is taking numerous effective steps to meet net-zero emission targets by limiting global warming to 1.5 °C by the end of the century and improving the ecological system. Worldwide, about 2.9 billion tons of CO_2 were emitted in 2021 from cement production and the industries are expected to achieve the net-zero target by 2050. The reduction of CO_2 emission remains a major challenge for the cement industry as the manufacturing processes and the current infrastructure allow little margin for the reduction in CO_2 emission, considering the age-old and conventional Portland cement chemistry. To achieve a net-zero emission target, several effective measures are being explored to mitigate CO_2 emissions from cement industries, viz., use of alternative fuels, reducing clinker-to-cement ratio, improving energy efficiency, carbon capture, utilization, and storage (CCUS) techniques etc. Apart from this, production of low-carbon cement different from Portland clinker chemistry has the potential to make a big difference in mitigating CO_2 emission. Carbonatable calcium silicate-based cement, is found to be a promising alternative to OPC and reduces about 70% of total CO_2 emission from cement production. This paper thoroughly reviews the different low-carbon emission approaches (both direct and indirect) such as reducing clinker factor, lowering the clinkerization temperature by using fluxes and mineralizers (such as CaF_2, BaO, SnO_2, P_2O_5, Na_2O, NiO, ZnO etc), producing low temperature clinker, use of supplementary cementitious materials (SCMs) in concrete and capturing the emitted CO_2 through mineral carbonation, direct air capture (DAC) etc for future alternative low-carbon cements. Various commercialized technologies for reducing CO_2 emissions.

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).
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.
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, CO2 emissions are inherent to the production process (termed process emissions) due to limestone processing which cannot be eliminated by using alternative sources of energy.

2. Materials & Methods

The technological options for the decarbonization 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.

2.1 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.

2.1.1 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.

2.1.2 Renewable power

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.

2.1.3 Alternative fuels and raw materials

Increase in thermal substitution rate (TSR).

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.

2.2 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.

2.3 Post-combusting emission 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 CO2 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 CO2 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 CO2 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.

2.4 Clinker efficiency (reducing specific thermal energy consumption)

About 99% of the installed capacity of Indian cement industry uses energy efficient dry kiln process in the production. The Indian cement industry has successfully adopted a range of Energy Efficient (EE) technologies, e.g., process optimization, latest generation of clinker coolers, efficient grinding systems, digitalization, etc. The adoption of EE technologies and practices has enabled the Indian cement industry to improve the energy performance substantially. Although some of the cement plants in India have Specific Energy Consumption (SEC) levels that can be considered to be globally the best, there exists a potential in other plants and with advancement in technology, it is expected that further reduction would be possible in the future. The average thermal Specific Energy Consumption (SEC-thermal) of Indian cement industry was estimated to be 731 kcal per kg clinker in 2020-21 (Figure 1). The cement industry aims to achieve average SEC-thermal of about 705 kcal per kg of clinker in 2070 which is about 3.6% reduction with respect to 2020 level (Source: stakeholder discussions). This is by taking into consideration the increase in energy consumption due to deployment of CCUS technologies. In addition, there is a need to put in more efforts to identify potential biomass sources, establish biomass supply chain and use them in substantial quantities in the short to medium term with government.

2.5 Increased use of Supplementary Cementitious Materials (SCMs)

The use of SCMs is considered as one of the recognized strategies to reduce environmental impacts of cement industry. The Indian cement industry produced about 73% of blended cement, a combination of fly ash-based PPC, GGBS-based PSC and composite cements in 2021. Fly ash accounts for maximum use in cement industry as compared to other SCMs. About 25% of fly ash produced (~ 60 million tonnes) in India was utilized by the cement industry in 2021-22. Enhanced use of SCMs will help in reducing clinker factor, thereby reducing thermal energy requirements for a given volume of cement production. With continued increase in cement production over the next few decades, there will be a need to look out for newer and viable SCMs in future.

2.5.1 Fly ash utilization

The cement industry will continue to produce PPC based on availability while gradually replacing it with other blended cements such as composite cements, LC3 and PLC. The present level of usage of fly ash in PPC production is 20-32% and can be enhanced upto 35% as per Indian standards3 for PPC. The roadmap assumes that fly ash generation would continue upto 2047 and perhaps even beyond in 2070 with a few coal-based thermal power plants continuing to operate with CCUS (PSA, 2024). The share of PPC is expected to decline substantially by 2070 from the present level of 64%.

2.5.2 Maximizing slag utilization

The generation of blast furnace slag in India was estimated to be 34 million tonnes during 2021-22. The slag generation will continue to increase with the expansion of Indian steel industry through Blast Furnace-Basic Oxygen Furnace (BF-BOF) route in the coming decades. The National Steel Policy (NSP) 2017 projects the crude steel production of 255 million tonnes by 2030, of which, 60% production is envisaged through BF-BOF route. The recently released green steel report by the Ministry of Steel also envisages continued use of BF-BOF route for steel production in the coming decades. As a result, slag is likely to remain available for blended cement production. However, the share of PSC is expected to reduce marginally by 2070 from the present level of 7%.

2.5.3 Promote composite cements

The Indian cement industry produced a marginal 2% composite cement (which uses a combination of fly ash and slag as per BIS standards) in 2020. With continued availability of SCMs (flyash and slag), the share of composite cement is expected to increase substantially by 2070.

2.5.4 Enhanced use of calcined clay for LC3 cement production

Calcined clay has been identified as one of the potential SCM options to produce LC3 cement, a blended cement which has lower clinker factor.

Some of the features of LC3 cement include the following:

2.5.4.1 The clinker content of LC3 cement is lower at about 50%.

2.5.4.2 CO2 emissions from LC3 production are expected to be 30% lower than OPC and 11% lower than PPC based on current rates of fly ash use.

2.5.5 Use of limestone for PLC production

Portland Limestone Cement (PLC) is a new type of blended cement which may be explored by the Indian cement industry. PLC is presently being produced in countries like Sri Lanka and Bangladesh. PLC uses about 15% of limestone along with gypsum and clinker (Cement Association of Canada, (2023). Suitable standards for PLC production may be introduced, which would help Indian cement industry to explore and produce new blended cements. PLC might also play an important role in 2070 based on its acceptance and utilization in the construction sector.

2.6 Decarbonization of electricity

At present, about 10% of the cement industry's carbon footprint can be attributed to its electricity consumption in the production process. The cement industry meets its electricity requirements through captive power, waste heat recovery (WHR) system and grid electricity, including, a marginal share of renewable energy; the share of each depends on individual cement plants. The following decarbonization options would help the Indian cement industry move towards decarbonization of electricity.

2.6.1 Electrical efficiency improvements

The average Specific Electricity Consumption (SECelectrical) of cement plants was estimated to be 73 kWh per tonne cement in the 2020-21 period, which is lower than the global average. However, there is a potential to further improve the overall SEC-electrical performance of cement industry by adopting additional energy efficiency measures, e.g., vertical roller mills (VRMs), high pressure grinding rolls (HPGRs), variable frequency drives (VFDs), high efficiency separators, conveyors, etc., wherever applicable. This would help in reducing overall SEC-electrical to about 65 kWh per tonne cement by 2070. This is in spite of adopting CCUS and use of green hydrogen as a fuel in the cement industry by 2070.

2.6.2 Enhancing WHR-based power generation

In a cement plant, nearly 35% heat is lost primarily from clinker production process. In a waste heat recovery (WHR) system, the waste heat is utilized to generate power. In the past few years, the Indian cement industry has made efforts at adopting WHR system to improve energy efficiency and reduce carbon emissions. Many cement plants utilize WHR systems to generate electricity through high pressure steam route. The WHR-based electricity represents about 15% of electricity requirements in Indian cement plants (Industry data analysis, TERI, 2022).

2.7 New binders

There are possibilities of utilizing new binders such as geopolymers, carbosilicate and calcium hydrosilicate binders. Other examples of new binders include construction and demolition wastes, Reactive Belite-rich Portland Cement (RBPC), Belite Calcium Sulfoaluminate (BCSA) Cement, wollastonite-based cement4, prehydrated calcium silicate cement, magnesium silicate cement, alkali activated binders, bio-mineralization, etc. (GCCA). Globally, these new binders are under different stages of development. While some have a long history, spanning decades and are already utilized commercially, though not extensively, others are recent innovations or necessitate more extensive research before their actual potential can be gauged.
CO2 Reduction Potential with New Binders by 2070: 0.2%

2.8 Carbon Capture, Utilization and Storage (CCUS)

Carbon Capture, Utilization and Storage (CCUS) is a key lever to tackle process emissions from cement industry and achieve net-zero emissions. However, the Carbon Capture and Storage (CCS) technology options are still under nascent stages of development and not implemented so far in any of the cement industries in India. A set of carbon capture options are available or being tested globally and only a handful of cement companies in India have initiated actions to explore CCUS as an option. A number of carbon capture technologies are under development globally. Given the early stages of their commercial development and high capex, adoption of CCUS technologies by Indian cement industries will be possible only with substantial financial support from the government or through international climate finance options. It is equally important to plan, develop and establish suitable CO2 transport and storage infrastructure facilities to effectively handle CO2 storage and utilization.

2.8.1 Nature-based solutions

The Indian cement industry considers nature-based solutions (NbS) as an additional/complementary lever along with CCUS that can help supplement the ongoing carbon capture efforts. The United Nations Environment Assembly (UNEP, 2022) outlines NbS as a cost effective, sustainable, and long- term solution to mitigate and adapt to climate change. It defines NbS as ‘actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, fresh water, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services and resilience and biodiversity benefits.’ In this context, India is working towards developing an ecosystem-based approach or ecosystembased adaptation (EbA). The EbA, a subset of NbS, harnesses biodiversity and ecosystem services to reduce vulnerability and build resilience to climate change. NbS is closely linked to India’s commitments and targets, including Nationally Determined Contributions (NDCs).

2.9 Re-carbonation (Carbon Uptake)

Re-carbonation is a natural process of CO2 uptake by concrete. It has been considered in carbon accounting in the IPCC 6th Assessment Report (August, 2021). This roadmap uses Tier-1 of IVL methodology which permits 20% of theoretical maximum carbonation value of 525 kg CO2 per tonne clinker for re-carbonation. Therefore, the Indian cement roadmap considers a reduction of 105 kg CO2 per tonne clinker due to the natural re-carbonation. It may be noted that any modification in assessment methodology for natural re-carbonation would have impact on CO2 reduction potential. The forecast suggested in this document is intentionally kept conservative as work is still in progress on more detailed evaluation of the re-carbonation process.

CO2 Reduction Potential with Re-carbonation By 2070: 5.9%

2.10 Cement-use efficiency

In 2020, about 79% of cement dispatched from cement companies was bagged cement. It is projected that there will be a shift from bagged cement to bulk cement (ready-mix segment) with the advancement in the construction practices. Based on industry estimates, about 65% of the cement production is used in concrete making for structural applications of which 29% is consumed by ready mix plants while 36% is mixed at site. The balance 35% of cement produced is used for non-structural applications. The potential areas of improvements in cement end-use efficiency would include the following:

- Increased use of precast materials
- Shift from bricks to Autoclaved Aerated Concrete (AAC) blocks
- Replace cement mortar by adhesives in tiles and block adhesives
- Shift from volumetric method to weighing type at project sites for mixing of cement, sand, and aggregates to prepare concrete
- Waste reduction at construction sites
- Promote suitable Construction and Demolition (C&D) waste management for reuse of corecycled aggregates without compromising on performance of building structures
- Use of 3-D printing to address complicated structures
- Optimize of concrete floor slab geometry, concrete column spacing, etc.
- Amending specifications and standards of blended cement for non-structural applications, e.g., flooring and plastering
- Pre-engineered buildings, composite structures, pre-stressed structures, and pre-cast construction
- Increased weightage of embodied emission of a building under green building certification. CO2 Reduction Potential with Cement Use Efficiency by 2070: 30.2%.

3 Results and discussion

This section presents typical results from an attempt to evaluate the potential of concentrated solar energy in the Indian cement sector and the accompanying potential for CO_2 emission reduction using the methodology described in Section 3. Based on conventional and suggested (solar) systems, Table 1 estimates the annual thermal energy needs of clinker production for each state.

The estimated quantity of CO_2 emissions that can be mitigated by installing solar industrial process heating systems in clusters of cement plants in India. The Conventional cement plants with existing thermal energy produce 21.498 MT of CO_2 per annum whereas the use of SIPH system in conventional cement plants reduces the CO_2 emission to 16.979 MT per annum. As a result, the potential for reducing CO_2 emissions annually is relatively greater. Additionally, 100 % replacement of fossil fuel with concentrated solar energy could save 45.193 MT of CO_2 emission annually.

Table 1

Cement production and thermal energy requirement at preferred locations with clusters of cement plants in Indian.

Indian State/ UT	Annual Installed Capacity (MT)	Annual actual Production (MT)	ATEDCP Based on Conventional System (PJ)	ATEDCP Based on Proposed System (PJ)
Odisha	10.45	0	0	0
Jharkhand	13.47	2.05	6.6215	0.42845
Maharashtra	37.83	14.64	47.2872	3.05976
West Bengal	21.99	3.34	10.7882	0.69806
Himachal Pradesh	20.39	11.48	37.0804	2.39932
Chhattisgarh	27.55	18.11	58.4953	3.78499
Karnataka	32.98	15.96	51.5508	3.33564
Madhya Pradesh	46.92	20.27	65.4721	4.23643
Rajasthan	85.32	49.82	160.9186	10.41238
Tamil Nadu	42.99	20.25	65.4075	4.23225
Karnataka	24.76	10.43	33.6889	2.17987
Uttar Pradesh	25.62	7.13	23.0299	1.49017
Andhra Pradesh	80.67	31.43	101.5189	6.56887
Assam	6.74	1.1	3.553	0.2299
Gujarat	46.28	20.37	65.7951	4.25733
Punjab	7.45	2.63	8.4949	0.54967
Uttarakhand	5.2	0.84	2.7132	0.17556
Meghalaya	10.14	2.28	7.3644	0.47652
Telangana	37.07	17.29	55.8467	3.61361
Bihar	10.7	3.56	11.4988	0.74404
Andaman Nicobar Islands	1.65	0.81	2.6163	0.16929
J & K	0.83	0	0	0
Haryana	7.2	1.14	3.6822	0.23826
Kerala	0.86	0.4	1.292	0.0836
Total	**605.06**	**255.33**	**824.7159**	**53.36397**

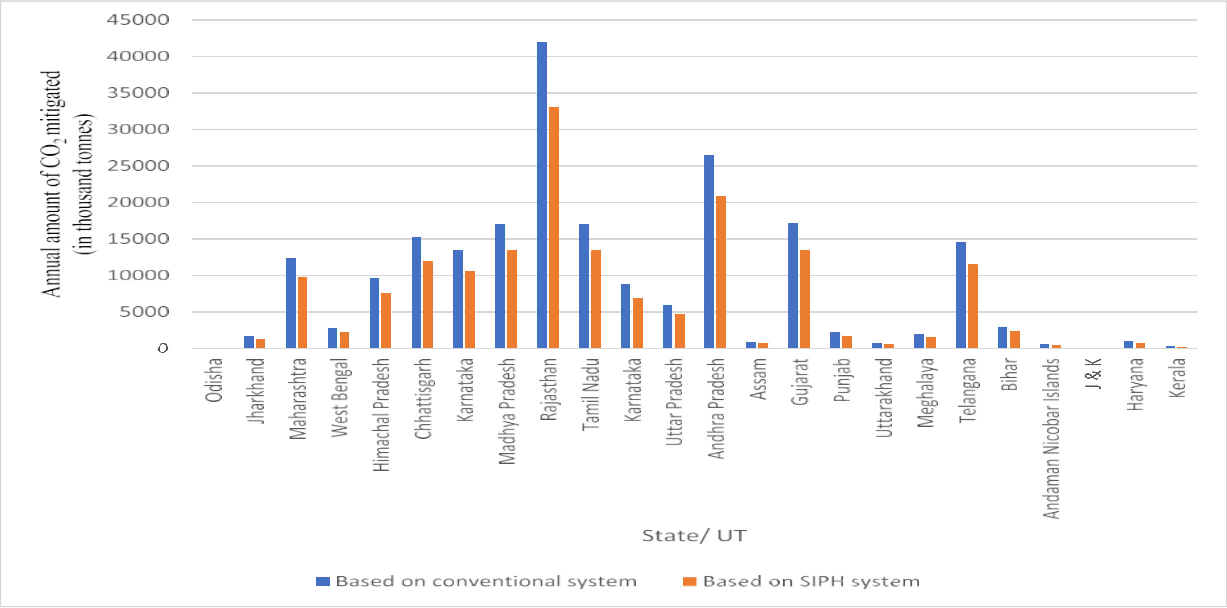

Fig.1 State-wise reduction of CO_2 emissions at Indian cement plants implementing SIPH system.

4 Conclusion

This paper presented a preliminary analysis to explore SIPH technology in the cement industry. The potential of SIPH system for the clink erization process in cement manufacturing has been analyzed. The annual thermal energy savings by the use of solar calciner reactors was found to be 771.35 PJ. Furthermore, CO_2 emission reduction potential was also evaluated. When all of the calciner's required thermal energy is replaced by solar energy, a maximum of 21 % of the total CO_2 emission may be prevented. The usage of concentrated solar energy can prevent an estimated 45.193 MT of CO_2 emissions. It's important to keep in mind that the estimations in this study are predicated on the premise that there is sufficient space (roofs and/or open land) for the construction of solar reactors. Our study concludes that the cement industry can reduce the emissions intensity by 20 per cent (0.66 to 0.53 tCO2/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 tCO2/t cement) can be reduced without any increase in the cost of cement. This essentially means that the cement manufacturers can implement these decarbonization 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.

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