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Assessment of Energy Efficiency Improvement and CO_2 Emission Reduction Potentials in India's Cement Industry

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Abstract

India's cement industry is the second largest in the world behind China with annual cement production of 168 Mt in 2010 which accounted for slightly greater than six percent of the world's annual cement production in the same year. To produce that amount of cement, the industry consumed roughly 700 PJ of fuel and 14.7 TWh of electricity. We identified and analyzed 22 energy efficiency technologies and measures applicable to the processes in the Indian cement industry. The Conservation Supply Curve (CSC) used in this study is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. Using a bottom-up electricity CSC model and compared to an electricity price forecast the cumulative cost-effective plant-level electricity savings potential for the Indian cement industry for 2010-2030 is estimated to be 83 TWh, and the cumulative plant-level technical electricity saving potential is 89 TWh during the same period. The grid-level CO_2 emissions reduction associated with cost-effective electricity savings is 82 Mt CO_2 and the electric grid-level CO_2 emission reduction associated with technical electricity saving potential is 88 Mt CO_2. Compared to a fuel price forecast, an estimated cumulative cost-effective fuel savings potential of 1,029 PJ with associated CO_2 emission reduction of 97 Mt CO_2 during 2010-2030 is possible. In addition, a sensitivity analysis with respect to the discount rate used is conducted to assess the effect of changes in this parameter on the results. The result of this study gives a comprehensive and easy to understand perspective to the Indian cement industry and policy makers about the energy efficiency potential and its associated cost over the next twenty years.

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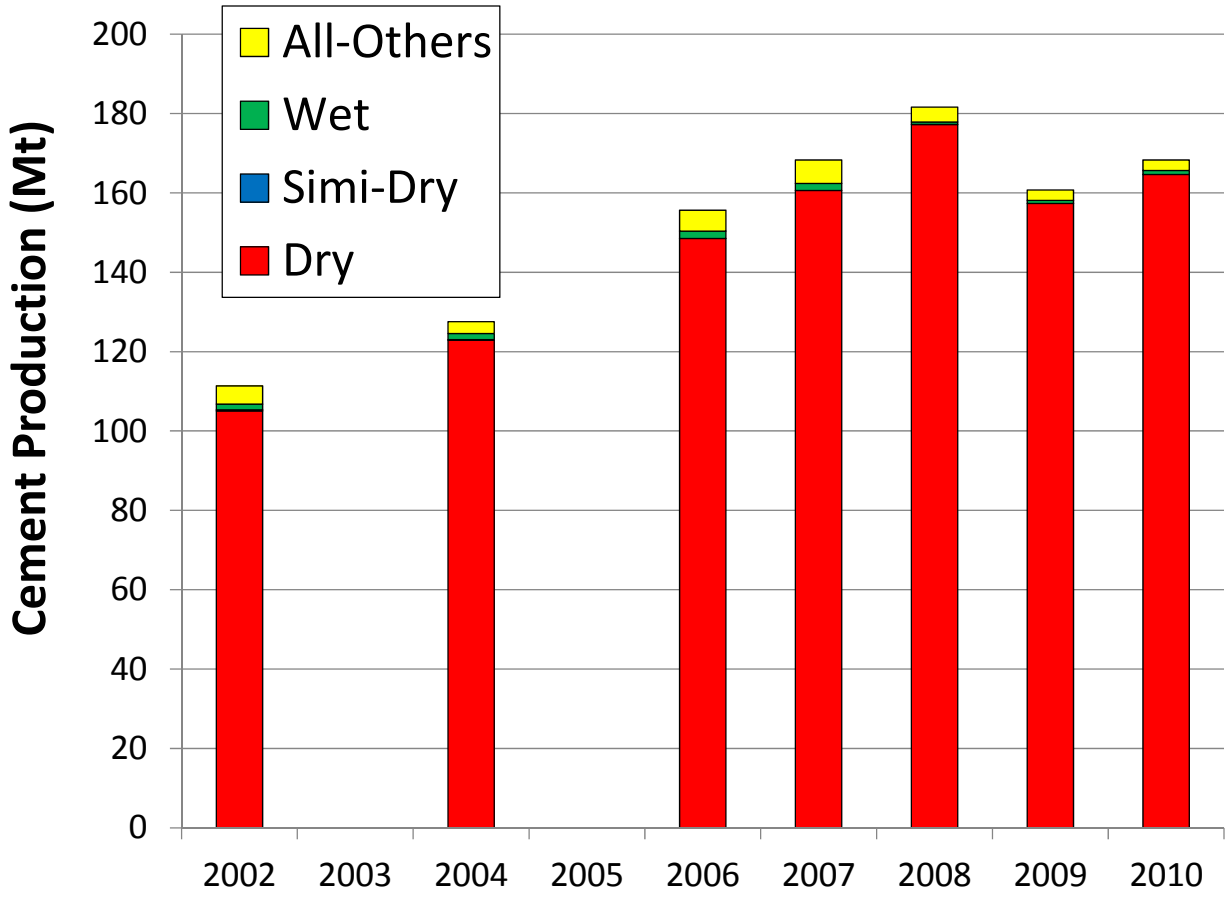
1. Introduction

1.1 Indian Cement Industry Overview

More than 6% of global cement output was produced in India in 2010 representing the second largest national cement industry in the world following China's (USGS, 2012). The 168 million metric tonnes (Mt) of cement production in India in 2010[1] was produce from a total capacity of 221 Mt spread across more than 500 cement plants (IndiaStat, 2012a). India also produced 132 Mt of clinker, the primary material used to make cement. India's cement industry has developed a primarily large-plant-capacity sector with 96 percent of the 2009 installed capacity in the 139 large cement plants (CMA, 2010). This has enabled economies of scale, which combined with India's rapid industry growth, has resulted in one of the most efficient cement sectors in the world. 98 percent of the cement production is produced in rotary dry kilns (IndiaStat, 2012b), which are more efficient than rotary wet or semi-dry kilns. Figure 1 shows processes-wise production output in recent years.



[1] India data is reported using the Hindu calendar which is March through February. For simplification, the dominant year (March through December) is the year used in this report.

Figure 1. Indian Cement Production by Kiln Type (IndiaStat 2012b)

The dry process is the most energy efficient technology available in the industry with energy requirements ranging between 2.9 GJ/t and 3.5 GJ/t clinker while the wet processes require significantly greater amounts of energy 5.9 GJ/t to 6.7GJ/t clinker (IEA, 2011a). As can been seen in figure 1, India's cement output is largely produced using dry processes. Variations in dry process energy intensity can largely be the results of how the raw materials are pretreated before entering the kiln. The more energy efficient process (known as "new suspension preheating, or NSP) preheats the raw materials through multi-stage cyclones using waste heat from the kiln and post-kiln coolers. To make the processes even more energy efficient, a precalciner is added between the preheaters and the kiln to precalcine the raw materials before they enter the kiln for full calcination (WBCSD, 2004). The lowest energy intensity process or "best of industry" utilizes a 6-stage cyclone pre-heater with the energy intensity increasing with decreasing stages of pre-heating (IEA, 2007). While India has seen some of the most efficient technologies deployed, the average fuel intensity of the industry was 3.07 GJ/t clinker and average electricity intensity was 89 kWh/t cement in 2005 (Krishnan, 2012). By comparison, China's cement sector consumed, on average, 4.2 GJ/t clinker, and the next largest cement producing country, the United States, consumed on average 4.5 GJ/t clinker in 2005 (IEA 2011a). India's cement industry total fuel energy consumption in 2010 was roughly 700 PJ (IndiaStat, 2012c) and the cements industries total electricity consumption was roughly 14.7 TWh (Krishnan, 2012).

India's cement sector is expected to expand by 2030, the timeframe of this analysis. By 2030 India's cement sector is anticipated to produce between 646 and 742 Mt cement per year (IEA 2011a). We use the lower growth assumption, but note that using the higher growth assumption simply increases the benefits, or energy savings potential, in proportion to the relative higher demand to lower demand but does not change the cost effectiveness of measures. See Appendix 2 for the demand forecast used in this analysis.

This report is unique for India as it provides a detailed analysis of energy efficiency improvement opportunities for the majority of Indian cement industry. However, wet kilns and mini cement plants are not addressed in this report because of their relatively small and dwindling production output. This report presents an assessment of the potential for energy saving in the Indian cement industry using a technology-level, bottom-up approach and estimates the cost associated with this potential. We use the concept of a "Conservation Supply Curve (CSC)" (Meier 1982) to construct a bottom-up model in order to capture the cost-effective potential as well as the technical potential for energy efficiency improvements and CO_2 emission reductions. These results can guide policy makers in designing better sector-specific energy efficiency policy programs.

1.2 Cement Production Overview

The primary energy consuming processes associated with cement production are the grinding of raw materials and coal, the pyro-processing or calcine process that produces clinker, clinker cooling, grinding clinker and other additives for mixing into cement, and lastly the remaining plant energy consumptions (conveyors, packaging, lighting, etc.). Each process is briefly described below with a specific focus on the unique properties of India's cement industry and production capacities. Included is an estimate of energy consumption of a sample cement plant in India (Krishnan, 2012).

Raw material and coal grinding

Grinding raw materials and coal is necessary to prepare for use in the pyro-processing unit of the cement plant. Typically raw materials are delivered and stored in small rocks or lump sizes and must be crushed to achieve powder-like (less than 90 μm) consistencies to enhance heat transfer surface area. Solid fuels such as coal, the primary fuel used in India's cement industry must also be crushed to enhance combustion properties and control for combustion regions within the pyro-processing unit. The Indian sample cement plant consumed around 20 kWh/t cement, or 24% of the total energy electrical consumption, in its grinding of raw mill, and coal mill equipment (Krishnan, 2012).

Pyro-processing & Clinker cooling

The pyro-processing transforms raw material inputs (primarily limestone) into clinker (lime) the basic component of cement, and releases CO_2 during the transformation. The majority of India's cement industry utilizes a rotary kiln designed to maximize the efficiency of heat transfer from fuel combustion to the raw material while maintaining quality through uniform mixing. Most new kilns have multi-stage suspension preheaters (typically cyclone vessels) or shaft preheater in which raw material is preheated by upward flowing kiln flue gas and released CO_2. Modern kilns are equipped with a pre-calciner, or a second combustion chamber, positioned between the kiln and preheater. Pre-calciners allow for partial calcination and greater fuel efficiency. The material then flows into the rotary kiln for complete calcination and sintering. Fully calcined and sintered clinker exits the pyro-processing unit at temperatures far in excess of 1,000°C (Ghosh, 2002). A balance exists between heat transfer from fuel combustion to materials, resident times at certain temperatures necessary for calcination, and flue gas pressure drops through the staged equipment.

Molten clinker exits the kiln and must immediately be cooled to ensure clinker quality and to allow for handling of down-stream equipment. This is done by passing ambient air through the clinker in the cooler. Modern clinker coolers route the heated air to the pre-calciner to serve as combustion air, or to the preheaters to preheat raw material prior to entering the kiln. Heated air can also be used to generate electricity through waste heat recovery processes. The primary

energy consumption in a clinker cooler is the electricity required to push cooling air through the clinker.

The Indian sample cement plant consumed 3.38 GJ/t clinker, or 100% of its total thermal energy consumption and 20 kWh/t cement, or 24% of the total electrical energy consumption, in its pyro-processing and clinker cooling equipment respectively (Krishnan, 2012). The report does not separate kiln drive, cooling fans, or flue gas fan electricity consumption.

Finish grinding & blending

Once the clinker has been cooled, it must be crushed and mixed with other materials to produce the finial cement product. If the blending material is not already in a powdered state, it too must be crushed prior to blending. Ordinary Portland cement is comprised of 95% clinker and 5% additives. "Blended cement" is the term applied to cement that made from clinker that has been inter-ground with a larger share of one or more additives. These additives can include such materials as fly ash from electric power plants, blast furnace slag from iron-making facilities, volcanic ash, and pozzolans. The Indian sample cement plant consumed around 39 kWh/t cement, or 47% of the total energy electrical consumption, in its finish grinding equipment (Krishnan, 2012).

Other energy consumptions at cement plants

The remaining energy consumption at cement plants is used for packaging finial product, lighting, and building services. This are typically minor electricity uses compared to the other major electricity and fuel consumption processes in cement plants. The Indian sample cement plant consumed around 4 kWh/t cement, or 5% of the total energy electrical consumption, for packaging and lighting (Krishnan, 2012).

2. Methodology

2.1. Data Collection

The data collection in this report draws upon work done by Lawrence Berkeley National Laboratory (LBNL) on the assessment of energy efficiency and CO_2 emission reduction potentials of the cement industry in the U.S. and in China (Worrell et al. 2000; Worrell et al. 2008; LBNL & ERI, 2008, Hasanbeigi 2012; Sathaye et al. 2010; Xu et al. 2013a), as well as other references. Many of the international energy-efficient technologies examined in LBNL publications and reports are used in this analysis because other studies on energy efficiency in the cement industry do not provide consistent and comprehensive data on energy savings, CO_2 emission reductions, or the cost of different technologies. Information on some of the technologies examined, however, is presented in other studies (e.g. CSI/ECRA, 2009). Furthermore, the methodology used for this analysis, i.e. construction of the energy CSC and

abatement cost curve, is also used by LBNL for other cement industry analysis and reports (Xu et al. 2013a, Sathaye 2010, Worrell 2000, Hasanbeigi 2010a&b).

The national level data for the production of different products for India's cement industry was obtained from IEA (IEA 2009). However, the penetration rates of energy efficient measures in India's current cement industry is an uncertain, but critical variable to the results of this type of analysis. We have worked closely with Indian industry expert of the CSTEP (Center for Study of Science, Technology, and Policy), to develop high-level estimates for the penetration rates of measures within India's current cement sector as a whole. CSTEP have worked closely with the Indian cement industry and the Indian government in the development of the PAT (Perform, Achieve and Trade) program designed to reduce energy consumption in key Indian industrial sectors, including the cement sector (Krishnan 2012).

2.2. Conversion Factors and Assumptions

Roughly 82% of India's electricity was generated from fossil fuels in 2011 (GOI 2012a). India's fossil fuel generation capacity is primarily domestically sourced coal based which has a lower average heat rate due to the poor energy density of India's coal than many non-domestic coals. India's national average net heat rate for fossil fuel-fired power generation was 10.5 MJ/kWh in 2011 (GOI, 2012b). India's 2009 national average electricity system transmission and distribution (T&D) losses of 25.4% (GOI 2012c) are used for the analysis. A conversion factor of 2.9 is used to convert electricity to primary fossil fuel. The conversion factor combines the percentage of fossil fueled power, the average heat rate of thermal plants, and the T&D losses. The CO_2 emission factor for grid electricity was 0.79 kg CO_2/kWh in 2012 (GOI, 2012b). Although the electricity savings are reported as finial electricity (electricity used by the cement sector), due to T&D losses, saving a kWh of electricity at the final use, or plant level, saves more than 0.79 kg of CO_2 from grid-level electricity generation. Thus, the primary energy related electricity CO_2 emissions factor used in this analysis is 0.99 kg CO_2/kWh which includes T&D losses of 25.4%. The CO_2 emission factor for grid electricity is held constant through 2030 as fossil-fueled thermal power plants are forecasted to remain the dominating power generation technology through this time period (GOI 2000) (see Appendix 2).

The CO_2 conversion factor for coal (94.6 tCO_2/TJ) taken from the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC 2006) is used for calculating CO_2 emissions from energy consumption. The emission factor is assumed to be unchanged during the study period because coal is assumed to be the primary source of fuel used in the Indian cement industry up to 2030.

The variation between state-based electricity prices averaged across all customer classes is quite substantial ranging from 52 – 103 US$/MWh in 2010 (GOI 2012a). The industrial sector's national average price was 114 US$/MWh in 2010 (GOI, 2012a). The national average industrial price is used as the electricity price in the base year. Since the majority of the fuel use in the Indian cement industry is coal, the historic (2000-2009) average steam coal for industry trend is

used to estimate the 2010 base year value of 1.66 US$/GJ (IEA 2012). Future price escalation rates, based on historic real energy price trends, are used to estimate future energy prices for the study period (3.8% real escalation rate between 2000 and 2010 is used for electricity, and 5.6% real escalation rate between 2000 and 2010 is used for coal (IEA 2012)). These prices are in constant dollars. The 2011 average exchange rate of 45.73 Rupees/US$ is used to convert reported costs in Indian Rupees to U.S. dollars (US$) (The World Bank 2012). Then, we used the same discount rate that we used to calculate the NPV of the future capital costs, to calculate the present value of the future energy prices in constant dollars in the base year. Finally, we calculated the discounted average unit price of electricity and coal used in electricity and fuel CSCs, respectively.

Future energy prices (i.e. prices in 2010-2030) determine the cost-effectiveness of energy efficiency measure implementations over the analysis period and are treated the same as future capital and operation and maintenance (O&M) non-energy costs over the study period by discounting them to a present value using the same discount rate as applied to future capital and non-energy O&M costs. This consistent treatment represents the benefit-cost decision from the cement industry perspective. If future energy prices are not treated the same as capital and O&M costs (i.e., not discounted to present value using the same discount rate), then the cost effective results could be misinterpreted.

2.3. Energy Conservation Supply Curve Modeling

A bottom-up model based on the CSC concept was developed in order to estimate the cost effectiveness and technical potential for efficiency improvements and CO_2 emission reduction in India's cement industry. The CSC approach, first introduced by Art Rosenfeld and his colleagues at LBNL, is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy and has been used in various studies to assess energy efficiency potentials in different economic sectors and industries (Sathaye et al. 2010, Xu et al. 2010, 2011, 2013a&b, Koomey et al. 1990, Levine and Meier 1999, Lutsey 2008, Hasanbeigi 2010a&b). Recently, McKinsey & Company (2008) also developed GHG abatement cost curves for different countries using the CSC concept. The CSC can be developed for a plant, a group of plants, an industry, or for the entire economic sector.

The work presented in this chapter is a unique study of India as it provides a detailed analysis of energy-efficiency improvement opportunities in the entire Indian cement industry.

The Cost of Conserved Energy (CCE) required for constructing the CSC can be calculated as shown in Equation 1:

$$\mathrm{CCE} = \frac{\sum_{n=1}^{N} \frac{(ACC + \Delta\, AO\&M)_n}{(1+d)^n}}{\sum_{n=1}^{N} (Annual\ Energy\ Saving)_n} = \frac{\text{NPV (Annual Costs)}}{\text{Sum (Annual Energy Saving)}} \quad \text{(Equation 1)}$$

Where:
CCE = Cost of Conserved Energy
ACC = Annualized Capital Costs
Δ AO&M = Change in Annual Operations and Maintenance Non-energy Cost
n= year – measure lifetime
N = time horizon of the analysis period
d = discount rate

The annualized capital cost can be calculated from Equation 2:

Annualized capital cost = Capital Cost*(d/ (1-(1+d)$^{-n}$) (Equation 2)

Where:
d = discount rate
n = lifetime of the energy efficiency measure

After calculating the Cost of Conserved Energy for all energy-efficiency measures separately, the measures were ranked in ascending order of their Cost of Conserved Energy to construct the Energy CSC, and measures were applied in cascading fashion to avoid "double counting" of savings between measures. In an Energy CSC, an energy price line is determined. The energy price line is the net present value of energy prices escalated through over the analysis period as shown in equation 3. All measures that fall below the energy price line are considered "cost-effective". Furthermore, the CSC also shows the total technical potential for electricity or fuel savings accumulated from all the applicable measures. On the curve, the width of each measure (plotted on the x-axis) represents the energy saved by that measure in a year or during the period for which the analysis is conducted. The height (plotted on the y-axis) shows the measure's CCE calculated as explained above.

Energy Price Line = $\sum_{t=1}^{T} \frac{P \times (1+E)^t}{(1+d)^t \times T}$ (Equation 3)

Where:
P = base year energy price
E = energy price escalation rate
d = discount rate
t = analysis time frame

The methodology used for the analysis consists of five main steps as follows:

1. Establish 2010 as the base year for energy, material use, and production in the cement industry. The base year is also used to calculate the costs in constant base year dollar. The study period for which the CSC was developed is 2010-2030. Thus, the implementation of the measures starts in 2010. This is different from some other studies such Sathaye et

al. (2010) where the application of energy efficiency technologies and the cost-effectiveness is assessed only for the base year.

2. Develop a list of commercially available energy-efficiency technologies and measures in the cement industry to include in the construction of the conservation supply curves. We assumed that the energy efficiency measures are mutually exclusive and there is no interaction between them. Twenty-two energy efficiency measures/technologies are used in this study based on their applicability to the Indian cement industry as well as the significant energy saving that can be achieved by implementing them.

3. Determine the potential application of energy-efficiency technologies and measures in the Indian cement industry in the base year based on an estimate of their current adoption in India's existing cement industry. Basing their current adoption on India's cement industry is simply a starting point for this analysis because detailed information on the Indian industry was not available. We assumed 70% of the existing potential for energy efficiency measures will be realized by the end of 2030 (3.5% per year in each year (starting after the 2010 base year between 2011 and 2030 for an additive total of 70% of the remaining potential by 2030) (except for a two measures which were treated differently: replacing a ball mill with vertical roller mill in finish grinding (assume 50% of reaming potential by 2030 because many plants will implement roller presses instead of vertical roller mills), and the use of alternative fuels (25% of reaming potential by 2030 reflecting limited alternative fuel supplies), with a linear deployment rate assumed between the start year (2010) and end year (2030).

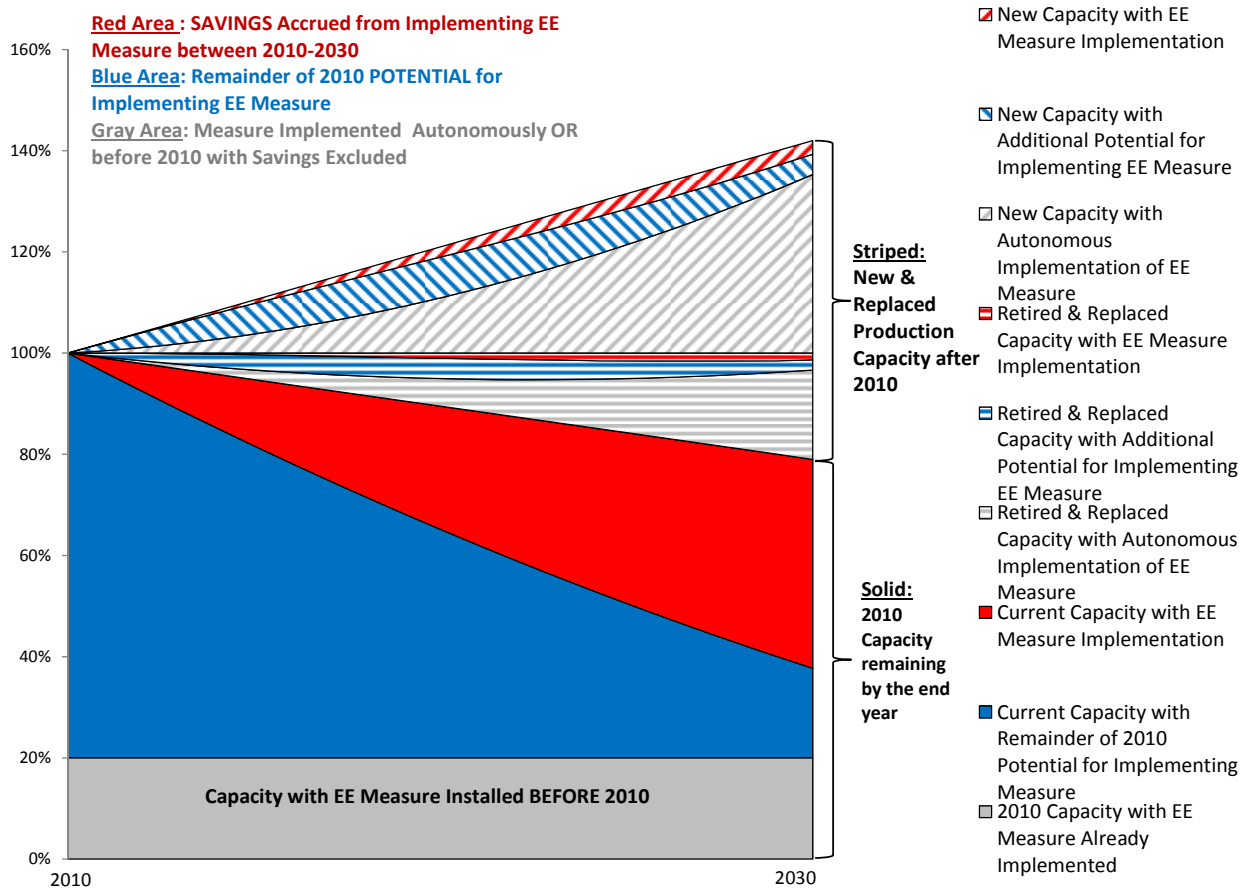
4. Obtain forecast data for clinker and cement demand up to 2030. The adoption rate explained in step 3 was based on the base year's production capacity. However, there will be new capacity installed by 2030 to meet increased demand. Additionally, there will be plant retirements in the existing capacity that will be replaced with new capacity. To define the potential application of the measures to the new production capacity, we used the "new capacity with EE implementation" indicator. By defining this indicator, we take into consideration how much of the new capacity will have already implemented the energy efficiency measures from the start and how much potential will still exist in each subsequent year. We apply the same adoption assumptions to the retired and replaced capacity as we do to the new capacity.

5. Construct an Electricity Conservation Supply Curve (ECSC) and a Fuel Conservation Supply Curve (FCSC) separately in order to capture the accumulated cost effective and total technical savings potential due to electricity and fuel efficiency improvements in the cement industry from 2010 to 2030. For this purpose, the Cost of Conserved Electricity (CCE) and Cost of Conserved Fuel (CCF) were calculated separately for respective technologies in order to construct the CSCs. After calculating the CCE or CCF for all energy-efficiency measures, we rank the measures in ascending order of CCE or CCF to construct an ECSC and a FCSC, respectively. Two separate curves for electricity and fuel

are constructed because the cost-effectiveness of each energy-efficiency measure is highly dependent on the price of energy. Since average electricity and fuel prices are different and because many technologies save either solely electricity or fuel, it is appropriate to separate electricity and fuel saving measures. Hence, the ECSC with discounted average unit price of electricity only plots technologies that save electrical energy while the FCSC with discounted average unit price of fuel only plots technologies that save fuel.

An important aspect of the CSCs is the methodology that was used to determine how energy efficiency measures are implemented. An illustrative graph is used below to explain the underlying basis for the implementation of each energy efficiency measure in the model (Figure 2).

Figure 2. Illustration of Methodology for Determining Implementation of Energy Efficiency Measures from 2010 to 2030



Note: This graph is only for illustrative purposes

Based on estimates of penetration rate of energy efficiency measures in the base year (i.e., 2010) as shown in Table 1, we can calculate the remaining potential for adoption of efficiency

measures in the existing capacity in the base year. We first estimate how much of the existing capacity should be retired and replaced with new capacity based on historic capacity expansions and the assumption that cement plants last 40 years (IEA 2011b). This is shown in the figure as "Retired and Replacement". For the remaining existing potential we assumed 70% adoption will be reached by 2030 (i.e., 70% / (2030-2010) = 3.5% per year) for almost all measures. We developed a linear line which serves as the slope for the new implementation of the measure in each year between 2010 and 2030. We can then calculate the proportion of current capacity where savings are achieved through the implementation of each efficiency measure after the end of 2010, i.e. beginning of 2011 through the end of 2030 (solid red area in Figure 2).

In addition, industrial production capacity is expected to grow between 2010 and 2030. To determine the implementation potential of efficiency measures in the new additional capacity, we did the following. First, we used estimated production capacity growth from (IEA, 2011a) and assumed that a certain proportion of the new capacity will adopt the efficiency measures autonomously each year. We assume that the new capacity within 2011 autonomously adopts measures to the same ratio that current capacity has adoption measures within 2010. Then we assume that new production capacity stock out to the end of 2030 autonomously adopts energy efficiency measures at the incremental rate of 4% of the remaining potential each year (reflecting a continuation of India's aggressive implementation of energy efficiency measures (gray angular striped area in Figure 2)). Since the autonomous implementation of the measure in some of the new capacity will occur regardless of new policies, the savings potential of the autonomous implementation is excluded from the supply curves calculation. Second, the new capacity with additional potential for implementing the efficiency measures (not captured in autonomous improvement) is determined for each year (blue angular striped area in Figure 2). We assumed that a certain portion of the new capacity with additional potential for implementing the efficiency measures adopts the measures each year (2% per year between 2010 and 2030, for a total of 40% implementation by 2030) (the red angular striped area in Figure 2). We treat the *retired and replacement* capacity the same as new capacity expansions by assuming the same rates for autonomous adoption of energy efficiency measures and adoption rates within the additional potential for implementing the efficiency measures (the horizontal striped area in Figure 2). Because the *new capacity* and *retired and replaced* capacity are both calculated as the product of growth rates and the adoption rates, the resulting wedges are not always straight lines (e.g., gray stripped areas – both horizontal and angular). To sum up, the red solid and red stripped areas in Figure 2 is the total source of energy saving potentials captured on the supply curves.

Although the CSC methodology is a good screening tool for evaluating the potentials of energy-efficiency measures, the actual energy savings potential and cost of each energy-efficiency measure and technology may vary and depend on various conditions such as raw material quality (e.g. moisture content of raw materials, hardness of the limestone, etc.), technology provider, production capacity, size of the kiln, fineness of the final product and byproducts, time of the

analysis, and other factors. Moreover, it should be noted that some energy efficiency measures also provide additional productivity and environmental benefits which are difficult and sometimes impossible to quantify. However, including quantified estimates of other non-energy benefits could further reduce the CCE values for the energy-efficiency measures (Worrell et al. 2003; Lung et al. 2005; Xu et al. 2010, 2011, 2013a; Sathaye et al. 2010). In this study, we include only O&M benefits when treating other non-energy benefits in the analysis.

It should be noted that there are other approaches for developing conservations supply curves. For a review of these, as well as a discussion of some of the key differences and driving components and variable of single-year versus time horizon (the approach used in this analysis) methodologies, see (Hasanbeigi 2012).

2.4. Discount Rate

In this study, a real discount rate of 15% was assumed for the analysis. However, the choice of the discount rate depends on the purpose and approach of the analysis (prescriptive versus descriptive) used. A prescriptive approach (also known as social perspective) uses lower discount rates (4% to 10%), especially for long-term issues like climate change or public sector projects (Worrell et al. 2004). Low discount rates have the advantage of treating future generations more equally to current generations; thus may less favor the relatively certain, near-term effects over more uncertain, long-term effects (NEPO/DANCED, 1998).

A descriptive approach (or private-sector or industry perspective), however, uses relatively high discount rates between 10% and 30% in order to reflect the existence of barriers to energy efficiency investments (Worrell et al. 2004; Sathaye et al. 2010; Xu et al. 2010; 2011, 2013a&b). These barriers include perceived risk, lack of information, management concerns about production and other issues, capital constraints, opportunity cost, and preference for short payback periods and high internal rates of return (Bernstein et al. 2007 and Worrell et al. 2000). Hence, the 15% discount rate used for these analyses is close to the higher end of discount rates from a social perspective and the lower end of the discount rates from private-sector or industry perspective.

3. Technologies and Measures to Reduce Energy and CO_2 Emissions for the Cement Industry

The initial list of energy efficiency measures considered for the cement industry in this analysis includes 22 measures/technologies, all of which were used in the development of the conservation supply curves. The descriptions of the measures are presented in Appendix 1. The reason for the choice of these 22 efficiency measures was that during an earlier study (Hasanbeigi et al. 2010c), we found that these measures are the most relevant to the cement industry in terms of applicability as well as the significance of the energy saving that can be achieved by implementing them. Table 1 presents data related to the production capacity in each

step of the cement production process in India. It also presents the energy savings, capital costs, and change in annual operation and maintenance (O&M) cost, and potential application share of the respective production for each energy-efficiency technology and measure when applied to India's cement industry. The potential application share of the respective production is based on expert estimates in collaboration with CSTEP (Krishnan 2012).

Table 1. Energy Savings and Costs for Energy-Efficient Technologies and Measures Applied to the Cement Industry

No.	Energy-Efficiency Measures / Technologies	Clinker Production Capacity in base year to which the measure is applied (Mt/year)	Fuel Saving (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Costs (2010 US$/t-cl)	Change in Annual O&M cost (2010 US$/t-cl)	Share of clinker production capacity in base year (2010) to which measure is applicable (%) *
	Fuel Preparation						
1	Replacing a ball mill with vertical roller mill for coal grinding	129	N.A.	1.47	1.59	0.00	75%
2	Installation of variable frequency drive & replacement of coal mill bag dust collector's fan with high efficiency fan	129	N.A.	0.16	0.04	0.00	70%
	Raw Materials Preparation						
3	High Efficiency classifiers/separators for raw material grinding	129	N.A.	5.08	6.10	0.00	20%
4	Replacing a ball mill with vertical roller mill /High pressure roller presses in raw material grinding	129	N.A.	11.00	15.26	0.00	50%
5	Efficient (mechanical) transport system for raw materials preparation	129	N.A.	3.13	7.13	0.00	40%
6	High efficiency fan for raw mill vent fan with inverter	129	N.A.	0.36	0.04	0.00	40%
	Clinker Making						
7	Kiln shell heat loss reduction (Improved refractories)	129	0.26	N.A.	0.33	0.00	50%

No.	Energy-Efficiency Measures / Technologies	Clinker Production Capacity in base year to which the measure is applied (Mt/year)	Fuel Saving (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Costs (2010 US$/t-cl)	Change in Annual O&M cost (2010 US$/t-cl)	Share of clinker production capacity in base year (2010) to which measure is applicable (%) *
8	Energy management and process control systems in clinker making	129	0.15	2.35	1.50	0.00	40%
9	Optimize heat recovery/upgrade clinker cooler	129	0.11	-2 **	0.25	0.00	45%
10	Low temperature Waste Heat Recovery power generation	129	N.A.	39.20	12.19	1.08	70%
11	Upgrading of a Preheater kiln to a Preheater/Precalciner Kiln	129	0.43	N.A.	22.91	-2.36	30%
12	Low pressure drop cyclones for suspension preheater	129	N.A.	2.60	3.40	0.00	46%
	Finish Grinding						
13	Energy management & process control in grinding	129	N.A.	4.00	0.60	0.00	30%
14	Replacing a ball mill with vertical roller mill in finish grinding	129	N.A.	25.93	13.87	0.00	90%
15	High pressure roller press as pre-grinding to ball mill in finish grinding	129	N.A.	24.41	13.87	0.00	70%
16	Improved grinding media for ball mills	129	N.A.	6.10	2.18	0.00	50%
17	High-Efficiency classifiers for finish grinding	129	N.A.	6.10	5.55	0.00	25%

No.	Energy-Efficiency Measures / Technologies	Clinker Production Capacity in base year to which the measure is applied (Mt/year)	Fuel Saving (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Costs (2010 US$/t-cl)	Change in Annual O&M cost (2010 US$/t-cl)	Share of clinker production capacity in base year (2010) to which measure is applicable (%) *
18	Replacement of cement mill vent fan with high efficiency fan	129	N.A.	0.13	0.01	0.00	50%
	General Measures						
19	High efficiency motors	129	N.A.	4.58	0.48	0.00	50%
20	Adjustable Speed Drives	129	N.A.	9.15	1.90	0.00	60%
21	Use of Alternative Fuels	129	0.60	N.A.	1.10	0.00	99%
	Product Change ***	**Cement Production Capacity in base year to which the measure is applied (Mt/year)**	**Fuel Saving (GJ/t-cem)**	**Electricity Savings (kWh/t-cem)**	**Capital Costs (2010 US$/t-cem)**	**Change in Annual O&M cost (2010 US$/t-cem)**	**Share of Cement Production Capacity in base year (2010) to which measure is applicable (%) ***
22	Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag)	165	1.77	-7.21 **	0.72	-0.08	30%

* The share of production capacity in base year (2010) to which the measure is **applicable** is different than the share of cement production capacity in the base year to which the measure is **applied**. The method for determining the application rates of the measures are described in detail in the methodology section with Figure 2 as an illustration.
** The negative value for electricity saving indicates that although the application of this measure saves fuel, it will increase electricity consumption. However, it should be noted that the total primary energy savings of these measures is positive.

*** Since the "Share of production to which the measure applied" for product change measures is based on the "Share from total Cement Production Capacity in 2010", the calculations were made based on production of cement in contrast to the other measures for which the calculations were based on the clinker production capacity.

Note: N.A.: Not Available; cem = cement; cl=clinker

4. Results and Discussions

Based on the methodology explained above and the information from Table 2, the FCSC and ECSC were constructed separately to estimate the cost-effective and total technical potential for electricity and fuel efficiency improvement in the Indian cement industry from 2010 to 2030. In addition, the CO_2 emission reduction potential from implementing efficiency measures was also calculated. Six of the 22 energy-efficiency measures are fuel-saving measures that are included in FCSC and 16 are electricity-saving measures used to derive the ECSC.

However, it should be noted that there are a few technologies such as energy management and process control systems in clinker making, optimize heat recovery/upgrade clinker cooler, and blended cement production that either save both electricity and fuels, or increase electricity consumption as a result of saving fuel. These technologies with fuel savings accounting for a significant portion of their total primary energy savings are included in the FCSC.

4.1. Fuel Conservation Supply Curve for the Cement Industry

Six energy-efficiency measures were used to construct the FCSC. Figure 3 shows that all six energy-efficiency measures fall below the discounted average unit price of fuel (coal) in the cement industry from 2010 to 2030 (0.7US$/GJ) (Equation 3), indicating that the CCF is less than the discounted average unit price of fuel for these measures. In other words, the cost of investing in these six energy-efficiency measures to save one GJ of energy in the period of 2010 - 2030 is less than purchasing one GJ of fuel at the given price. Figure 4 shows the annual cost-effective fuel and fuel-based CO_2 saving including the electricity grid generator-level fuels and CO_2 emissions from the measures that have both fuel and electricity savings identified in Table 2.

Table 2 presents the fuel efficiency measures applicable to the cement industry ranked by their CCF, including the fuel savings and CO_2 emission reduction achieved by each measure. Increased production of blended cement (additives: fly ash, pozzolans, limestone or/and blast furnace slag) and kiln shell heat loss reduction (improved refractories) are the two most cost effective measures. The highest fuel saving is achieved by increased production of blended cement during 2010-2030. The adoption of this measure might be limited by availability of additives in the future. We have not speculated if market conditions outside the cement industry will limit the cement industries' ability to increase additives. Table 3 shows the cumulative cost-effective and the total technical potential for energy savings and CO_2 emission reduction from 2010 to 2030.

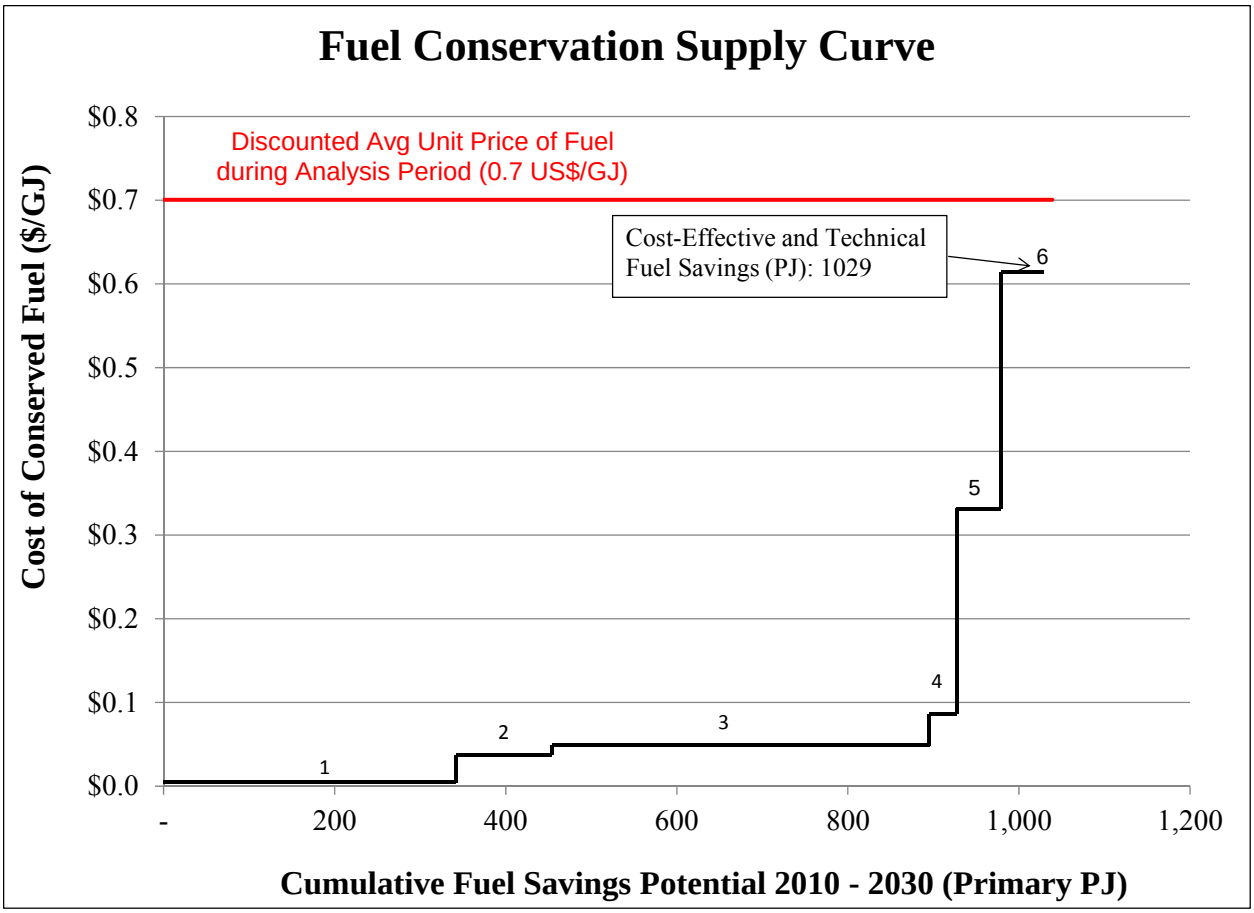


Figure 3. 2010-2030 FCSC for the Cement industry in India

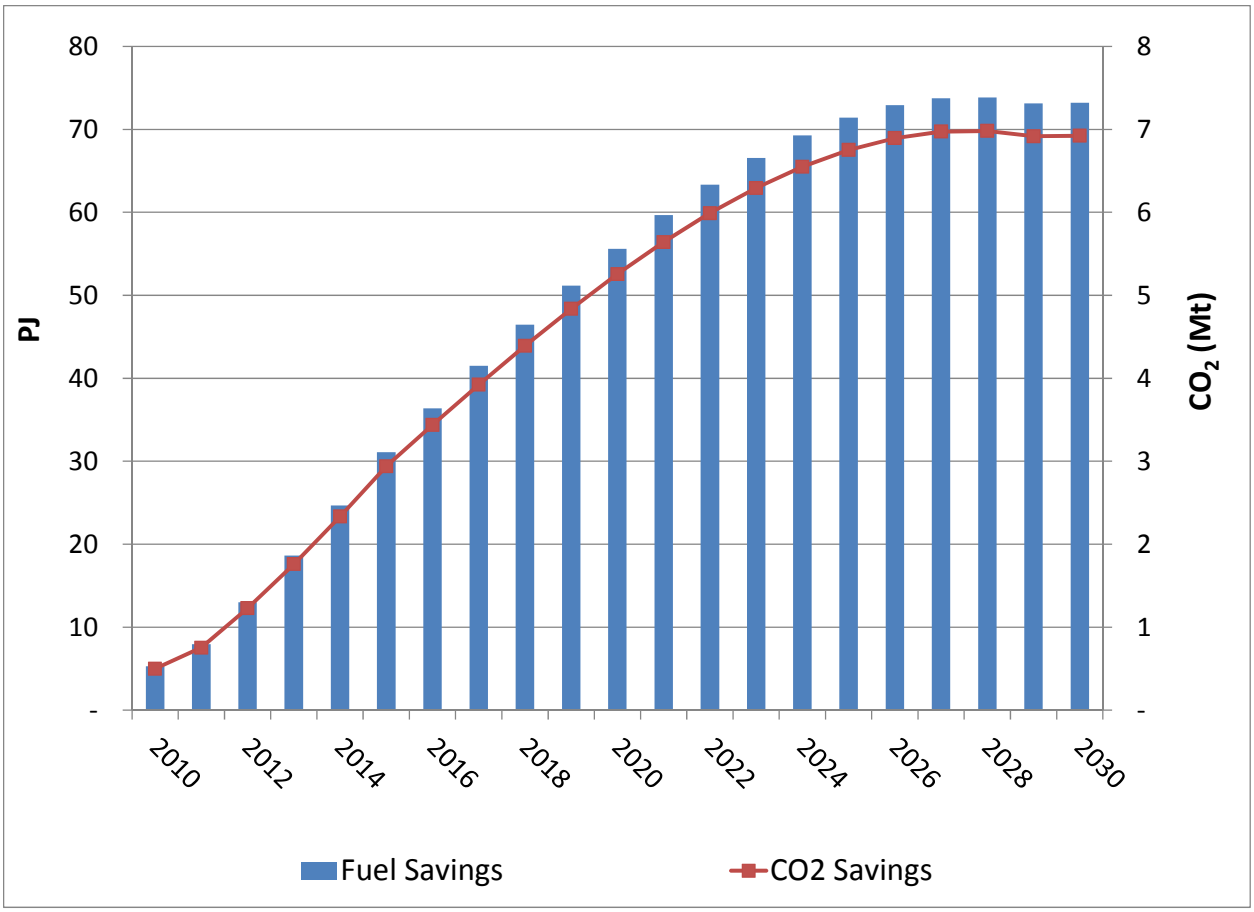


Figure 4. 2010-2030 Cost-Effective Fuel and Fuel-Base CO_2 Emissions Savings for the Cement industry in India for measures identified in Table 2

Table 2. Fuel Efficiency Measures for the Cement industry in India Ranked by Cost of Conserved Fuel (CCF)

CCF Rank	Energy-Efficiency Measures / Technologies *	Fuel Savings (PJ)	Cost of Conserved Fuel (US$/GJ-saved)	CO_2 Emissions Reduction (Mt CO_2)
1	Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag) **, ***	357.4	0.00	32.4
2	Kiln shell heat loss reduction (Improved refractories)	112.1	0.04	10.6
3	Use of Alternative Fuels	441.4	0.05	41.8
4	Optimize heat recovery/upgrade clinker cooler **	39.9	0.09	3.1
5	Energy management and process control systems in clinker making **	44.2	0.33	4.9

6	Upgrading of a Preheater kiln to a Preheater/Precalciner Kiln	49.8	0.61	4.7

* The descriptions of these measures can be found in Appendix 1.
** For this measure, primary energy saving was used to calculate CCF based on both the electricity and fuel savings. Since the share of fuel saving is more than that of electricity savings, this measure is included as a fuel saving measures. The national average power generation efficiency is used to convert electricity to fuel saving and the national electricity grid generator-level CO_2 emissions factor is used to calculate electric grid CO_2 savings.
*** CO_2 emission reduction from reduced energy use only. The CO_2 emission reduction as a result of reduced calcination in clinker making process is not counted here.

Table 3. Cost-Effective and Total Technical Potential for Fuel Savings and the Associated CO_2 Emission Reduction in the Cement Industry in India during 2010-2030

	Cumulative Fuel Savings Potential (PJ)		Cumulative CO_2 Emissions Reduction (Mt CO_2)	
	Cost-Effective	Technical	Cost-Effective	Technical
Cumulative Saving Potential During 2010-2030	1029	1029	97	97

Note: Numbers are rounded.

4.2. Electricity Conservation Supply Curve for the Cement Industry

For the cement industry, 16 energy-efficiency measures are included in the ECSC. Figure 5 and Table 4 shows that out of 16 energy-efficiency measures, 14 measures fall below the discounted average unit price of electricity during the period of 2010-2030 (43.10US$/MWh) (Equation 3). Therefore, the CCE is less than the discounted average electricity price during the study period for these measures. In other words, these measures can be considered cost-effective as the cost of investing in these 15 energy-efficiency measures to save one MWh of electricity is less than purchasing one MWh of electricity at the discounted average 2010-2030 unit price of electricity. The last two efficiency measures (grey area in Table 4) are technically applicable but are not cost-effective; thus, implementing these measures may require financial incentives beyond their energy savings alone. Figure 6 shows the annual cost-effective final electricity, or plant-level electricity, and electricity grid generator-level CO_2 emissions from the measures identified in Table 4.

The two most cost-effective measures are installation of high efficiency fan for raw mill vent fan with inverter and high efficiency motors. The largest electricity saving potential is from low temperature waste heat recovery power generation, which is saving in purchased electricity by generating electricity from the waste heat onsite (ranked 8 on the curve) and replacing a ball mill with vertical roller mill in finish grinding (ranked 9 on the curve). Table 5 shows the cumulative cost-effective and the total technical potential savings for plant-level electricity and electricity grid generator-level CO_2 emissions from the measures identified in Table 4 for 2010-2030.

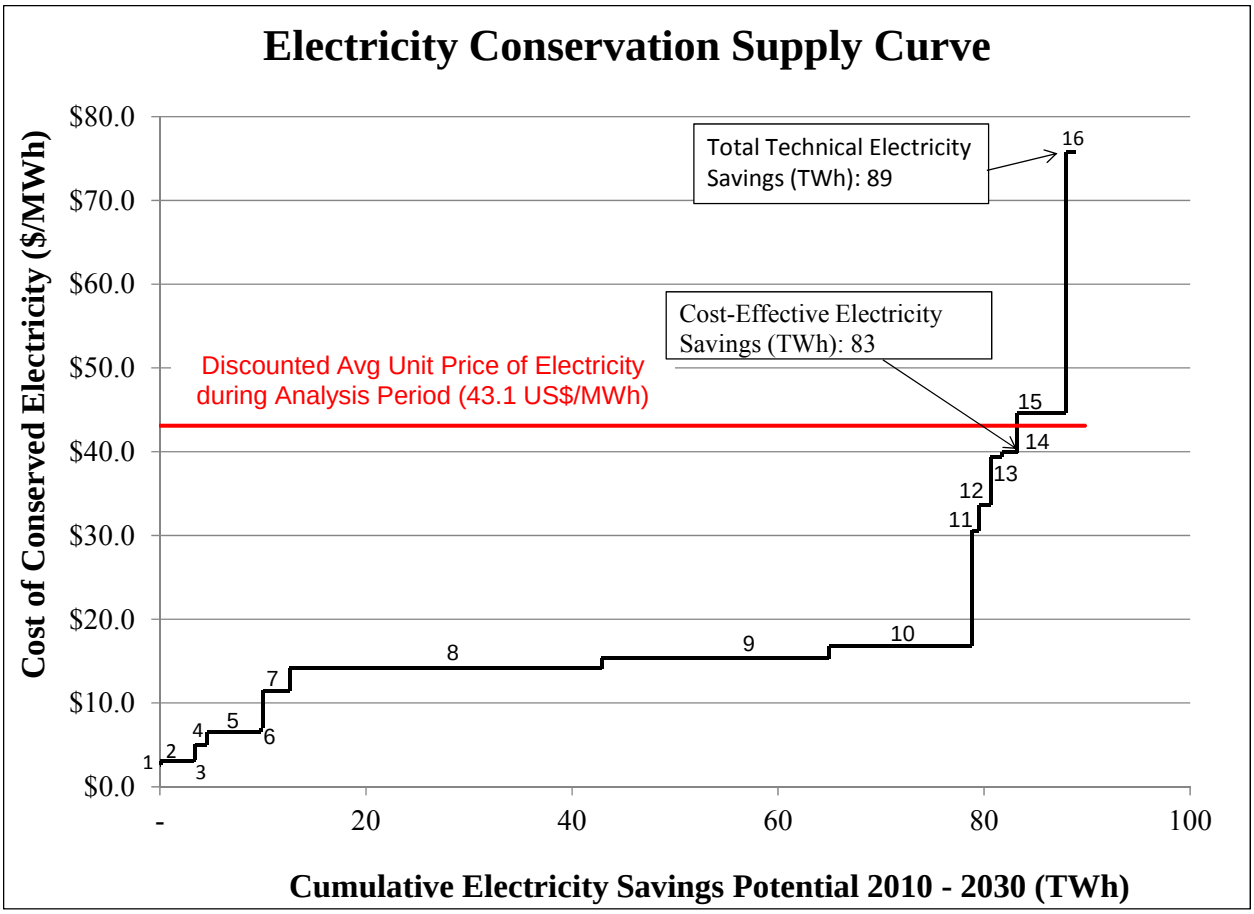


Figure 5. 2010-2030 ECSC for the Cement Industry in India (Final Electricity)

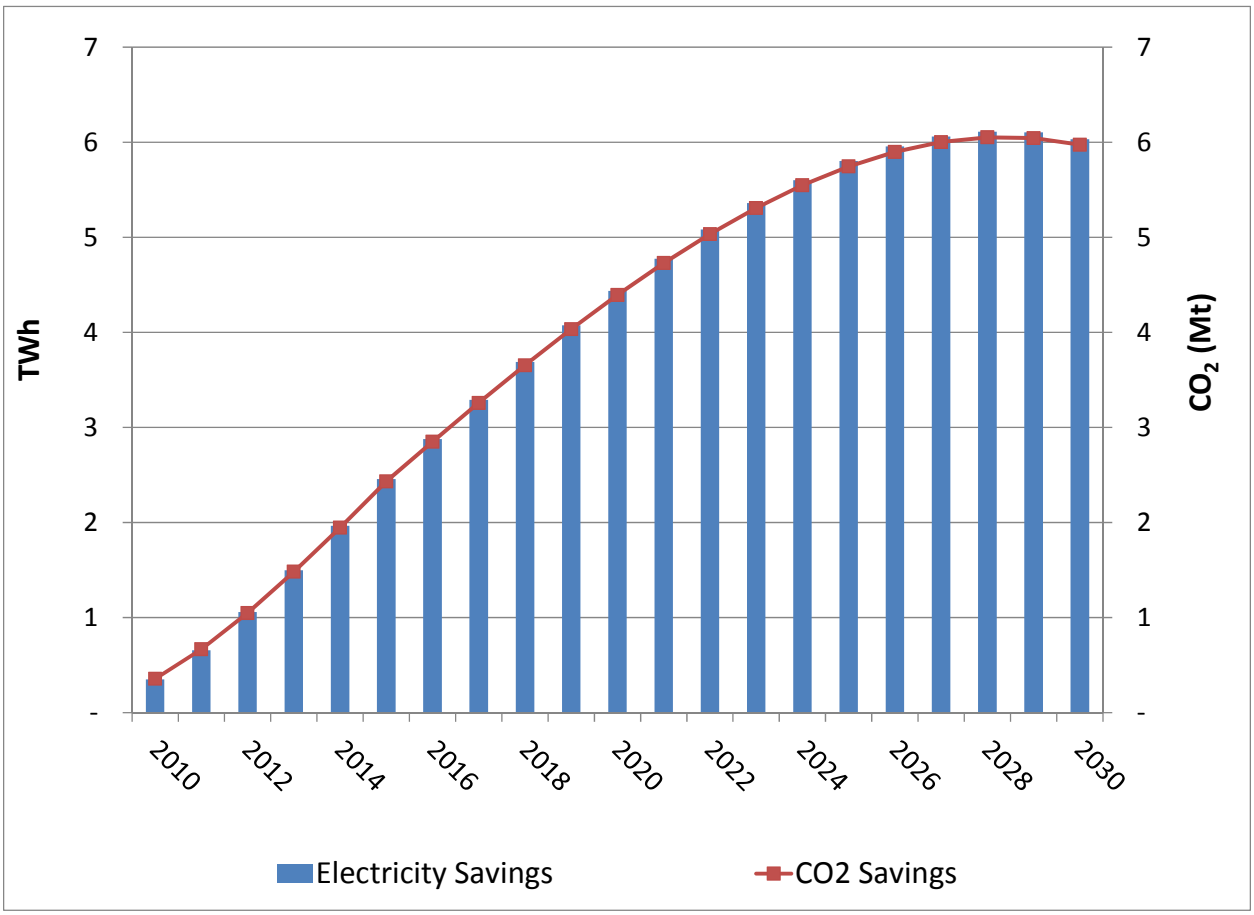


Figure 6. 2010-2030 Electricity and Electricity-Base CO_2 Emissions Savings for the Cement industry in India for the measures identified in Table 5

Table 4. Electricity Efficiency Measures for the Cement industry in India Ranked by Cost of Conserved Electricity (CCE)

CCE Rank	Energy-Efficiency Measures / Technologies *	Electricity Savings (TWh) **	Cost of Conserved Electricity (US$/kWh-saved)	CO_2 Emissions Reduction (Mt CO_2) ***
1	Replacement of cement mill vent fan with high efficiency fan	0.1	2.67	0.1
2	High efficiency motors	3.2	3.05	3.2
3	High efficiency fan for raw mill vent fan with inverter	0.2	3.22	0.2
4	Energy management & process control in grinding	1.2	5.01	1.2
5	Adjustable Speed Drives	5.2	6.56	5.2

CCE Rank	Energy-Efficiency Measures / Technologies *	Electricity Savings (TWh) **	Cost of Conserved Electricity (US$/kWh-saved)	CO_2 Emissions Reduction (Mt CO_2) ***
6	Installation of variable frequency drive & replacement of coal mill bag dust collector's fan with high efficiency fan	0.1	6.98	0.1
7	Improved grinding media for ball mills	2.6	11.47	2.6
8	Low temperature Waste Heat Recovery power generation	30.3	14.14	30
9	Replacing a ball mill with vertical roller mill in finish grinding	22.0	15.34	21.8
10	High pressure roller press as pre-grinding to ball mill in finish grinding	13.9	16.78	13.7
11	High-Efficiency classifiers for finish grinding	0.7	30.57	0.7
12	Replacing a ball mill with vertical roller mill for coal grinding	1.1	33.64	1.1
13	Low pressure drop cyclones for suspension preheater	1.1	39.35	1.1
14	High Efficiency classifiers/separators for raw material grinding	1.5	39.97	1.5
15	Replacing a ball mill with vertical roller mill /High pressure roller presses in raw material grinding	4.7	44.63	4.7
16	Efficient (mechanical) transport system for raw materials preparation	0.9	75.78	0.9

* The descriptions of these measures can be found in Appendix 1.
** Electricity results are final electricity, not primary electricity (electricity grid generator level), and therefor exclude transmission and distribution losses.
*** CO_2 results are primary energy related (electricity grid generator level) and therefor included transmission and distribution losses.

Table 5. Cost-Effective and Total Technical Potential for Electricity Saving and CO_2 Emission Reduction in the Cement Industry in India during 2010-2030

	Cumulative Electricity Savings Potential (TWh) *		Cumulative CO_2 Emissions Reduction (Mt CO_2) **	
	Cost-Effective	Technical	Cost-Effective	Technical
Cumulative Saving Potential During 2010-2030	83	89	82	88

Note: Numbers are rounded.
* Electricity results are final electricity, not primary electricity (electricity grid generator level), and therefor exclude transmission and distribution losses.
** CO_2 results are at the electricity grid generator-level and therefor included transmission and distribution losses.

4.2. Sensitivity Analysis

In the previous sections, the cost-effective and technical energy-efficiency improvement

potentials for India's cement industry were presented and discussed. Since the discount rate used in the analysis plays an important role in the analysis and results of energy-efficiency potentials, it is important and relevant to see how changes in this parameter can influence the cost effectiveness of the potentials. Hence, a discount rate sensitivity analysis is performed and the results are discussed below.

We conducted the sensitivity analysis for the discount rates of 5%, 13%, 17%, and 30%. As discussed previously in section 2.4. Discount Rate, A discount rate of 5% represents a societal perspective, while a discount rate of 30% represents an industry perspective capturing various non-monetary barriers to implementation. Discount rates of 13% and 17% are very close to the 15% discount rate used in the base case. Because some plants may use slightly different discount rate than 15% for their investment decision making, we assess the effect of the minor changes in the discount rate.

Table 6 shows how changes in the discount rate can affect the cost-effective energy-saving potentials and their associated CO_2 emission reduction potentials while keeping the other parameters constant (i.e. electricity and fuel prices, investment cost of the measures, and energy saving of the measures). It shows that, for this specific study, the increasing of the discount rate from 17% to 30% decrease the cost-effective fuel savings. The cost-effective fuel saving does not change with changes in the discount rates from 17% to 30% (i.e., 979 PJ) but does when the discount rate is 15% or lower (i.e., 1,029 PJ). The cost-effective electricity savings does not change with changes in the discount rates from 15% to 17% (i.e., 83 TWh), but does increase when the discount rate is lowered to 13% (i.e., 88 TWh) and decreases when the discount rate is raised to 30% (i.e., 79 TWh).

Table 6. Sensitivity Analysis for the Cost-Effective Electricity and Fuel Saving Potentials and CO_2 Emission Reduction in Indian Cement Industry during 2010-2030 with Different Discount Rates Keeping Other Parameters Constant

Discount Rate (%)	Electricity		Fuel	
	Cost-Effective Savings (TWh) **	Cost-effective CO_2 emission reduction ($MtCO_2$) ***	Cost-effective saving (PJ)	Cost-effective CO_2 emission reduction ($MtCO_2$)
D.R. = 5	88	87	1,029	97
D.R. = 13	88	87	1,029	97
D.R. = 15 *	83	82	1,029	97
D.R. = 17	83	82	979	93
D.R. = 30	79	78	979	93

*: The discount rate = 15% is the base scenario which is used in the main analysis presented in previous sections.

** Electricity results are final electricity, not primary electricity (electricity grid generator level), and therefor exclude transmission and distribution losses.

*** CO_2 results are at the electricity grid generator-level and therefor included transmission and distribution losses.

In general, for this specific study, results are not very sensitive to discount rates. The total technical energy saving and CO_2 emission potentials (the X axes) do not change with the variation of the discount rate. The discount rate is applied to both the measure investments and the unit price of energy that determines cost-effectiveness. Therefore, the effect that the discount rates has on the CSC tends to move the curve up or down along the Y axis (the cost axis) and it also moves the discounted unit price of energy up or down the Y axis. Thus, discount rate effect tends to cancel out leaving the analysis results largely insensitive to changes in the discount rates.

4.3. Barriers to the Adoption of Energy-Efficiency Technologies and Measures in the Cement Industry in India

There are various underlying factors behind why cement plants have not adopted the highly cost-effective measures identified in this study. Possible reasons include: the age of the plant (e.g., the plant was constructed earlier or the application of the measure was limited by the technical conditions at that time, and current plant designs offer limited space for new technology addition or replacements), overall technical knowledge of the staff, lack of knowledge about the energy-efficiency measure, uncertainty about the new technology, plant-specific operating conditions, and investor preferences. Furthermore, although some energy-efficient technologies have short payback periods, the high initial capital cost of the project often deters adoption and installation. For example, an efficient vertical mill system can cost close to 4 times as much as ball mill system. Hence, if plant owners lack sufficient capital in the initial stage of building the plant, they cannot purchase the more efficient equipment. Other barriers could be plant and raw material specific. For example, the hardness of some raw materials could limit the use of vertical roller mills for crushing and milling. Another example could be that by adopting one measure (e.g. installing waste heat recovery power generation) might limit the applicability of another measure (e.g., recovering heat to dry raw materials to meet vertical roller mill specifications).

Blending alternative materials into cement has the advantage of displacing clinker which is energy intensive to produce. Materials like fly-ash from coal-fired power plants or slag from the iron and steel sectors are currently considered waste by-product and have no economic value. Blending them in with cement provides a waste disposal option as long as the cement quality can be maintained. These wastes by-products are expected to grow as India's electric power and iron and steel sectors grow but incorporating them into cement could result in them becoming a valuable inputs that has a price or cost associated. Policies should be developed the limit the rent seeking opportunities that could arise in the future if fly-ash and slag use increases in India's cement industry.

The Indian cement industry's utilization of alternative fuels has progressed in recent years, but still faces key barriers. For instance, because the recycling and reprocessing of scrap tires in

India for other purposes than using as fuel in cement industry already result in resource utilization with higher economic benefits, scrap tires are less likely to be utilized by Indian cement kilns. An increased use of hazardous waste by India's cement industry is impeded by transportation regulations, capacity alliances between waste producers and cements plants, testing the cement quality impacts associated with introducing wastes that could contain metals or other materials, and lastly incorporating the additional emissions controls and monitoring when introducing a new combustion fuel. All of these can be addressed by policies that promote the benefits of waste material combustion in cement kilns. Similarly, more research, capacity building, and demonstration is still required for biomass applications in the cement industry.

A similar study that investigated barriers to the implementation of cost-effective, energy-efficiency technologies and measures in Thailand (Hasanbeigi, 2009) found the following key barriers:

- **Management concerns about the high investment costs of energy efficiency measures**: Even though the payback period of efficiency measures might be short, some cement plants still have difficulty acquiring the high initial investment needed to purchase energy efficiency measures.
- **Management considers production more important:** In many industrial production plants, upper management is focused solely on production output, final product quality and sales, with little or no attention to energy efficiency. This is also the case for some cement plants, although energy cost's high share of cement production cost makes it less of a barrier when compared to less energy-intensive industries .
- **Management concerns about time required to improve energy efficiency**: The high cost of disrupting industrial production may raise concerns about the time requirements for implementing energy efficiency measures.
- **Lack of coordination between external organizations**: The implementation of energy and environmental regulations lacks proper execution and enforcement as a result of the lack of coordination between different ministries and government institutions responsible for energy and environmental issues.
- **Current installations are already considered efficient**: This is especially true for newly-installed cement production lines, although they may not be as efficient as the best commercially available technologies.

In conclusion, it must be noted that progress is being made in India to continue to promote energy efficiency in the Cement industry. Programs such as PAT (Perform, Achieve and Trade) have been developed by the Bureau or Energy Efficiency, Ministry of Power, and the Government of India, to help facilitate energy efficiency adoption and to lower greenhouse gas emissions. Also, the ISO 50001 standard for Energy Management) helps cement plants develop energy management monitoring an improvement strategies (ISO, 2011). Both these programs

provide guidance and directives to support the adoption of energy efficient technologies in the Indian cement industry.

5. Conclusions

Given the importance of India's cement industry as one of the highest energy-consuming and CO_2-emitting industry, this study aims to understand the potential for energy-efficiency improvement and CO_2 emission reduction using a bottom-up model. Specifically, bottom-up Energy Conservation Supply Curves (i.e. ECSC and FCSC) were constructed for the Indian cement industry to estimate the savings potential and costs of energy-efficiency improvements by taking into account the costs and energy savings of different technologies.

We analyzed 22 energy efficiency technologies and measures for the cement industry. Using a bottom-up CSC models, the cumulative cost-effective and technical electricity and fuel savings as well as the CO_2 emissions reduction potentials for the Indian cement industry for 2010-2030 are estimated. The estimated energy and related CO2 emissions savings are significant. Between now and 2030, the cumulative fuels saving potential exceeds the current annual total cement sector fuel consumptions and the electricity savings potential is five and a half times the size of the industry's current annual electricity consumption.

When looking at CSCs and trying to interpret the results, one should pay attention to the method and formulas used in the development of the curves in addition to the assumptions used such as the discount rate, energy prices, period of the analysis, measure penetration rates, cost of technologies and their energy saving, etc. Finally, the approach used in this study and the model developed can be viewed as a screening tool to help policymakers understand the savings potential of energy-efficiency measures and design appropriate policies to capture the identified savings. However, energy-saving potentials and the cost of energy-efficiency measures and technologies will vary according to regional- and plant-specific conditions. This study shows that in India's case, an efficiency gap is relatively small as many of the identified cost-effective opportunities for energy efficiency improvement have already been adopted within the relatively new and efficient industry. The gap that does exist is a result of various obstacles to adoption, especially non-monetary barriers in the cement industry, and suggests that effective energy efficiency policies and programs are needed to realize cost-effective energy savings and emission reduction potential.

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Appendixes

Appendix 1. Description of Energy Efficiency Technologies/Measures for the Cement Industry Included in This Study[2]

Fuel Preparation

Replacing a ball mill with vertical roller mill for coal grinding:

Efficient vertical roller mills have been developed for on-site fuel preparation at cement plants. Fuel preparation may include crushing, grinding and drying of coal. Passing hot gases through the mill combines the grinding and drying.

Installation of variable frequency drive & replacement of coal mill bag dust collector's fan:

Variable frequency drives can be installed on coal mill bag dust collector fans to improve energy efficiency.

Raw Materials Preparation

High Efficiency classifiers/separators for raw material grinding:

High efficiency classifiers can be used in both the raw materials mill and in the finish grinding mill. Standard classifiers may have low separation efficiency, leading to the recycling of fine particles that causes additional power demands in the grinding mill. In high-efficiency classifiers, the material stays in the separator for a longer period of time, leading to sharper separation and thus reducing over-grinding.

Replacing a ball mill with vertical roller mill /High pressure roller presses:

Traditional ball mills used for grinding certain raw materials (mainly hard limestone) can be replaced by vertical roller mill or high-efficiency roller mills, by ball mills combined with high-pressure roller presses, or by horizontal roller mills. Adoption of these advanced mills saves energy without compromising product quality. An additional advantage of the inline vertical roller mills is that they can integrate raw material drying with the grinding process by using large quantities of low grade waste heat from the kilns or clinker coolers.

Efficient (mechanical) transport system for raw materials preparation:

Transport systems are required to move powdered materials such as kiln feed, kiln dust, and finished cement throughout the plant, with transport usually in the form of either pneumatic or mechanical conveyors. Mechanical conveyors use less power than pneumatic systems. Conversion to mechanical conveyors is cost-effective when conveyor systems are replaced to increase reliability and reduce downtime.

[2] Measure descriptions are taken from Hasanbeigi (2012)

Raw meal blending (homogenizing) systems:
Most plants use compressed air to agitate the powdered meal in so-called air-fluidized homogenizing silos. Older dry process plants use mechanical systems, which simultaneously withdraw material from six to eight different silos at variable rates. Modern plants use gravity-type homogenizing silos (or continuous blending and storage silos) that reduce power consumption. In these silos, material funnels down one of many discharge points, where it is mixed in an inverted cone. Silo retrofit options are cost-effective when the silo can be partitioned with air slides and divided into compartments which are sequentially agitated, as opposed to the construction of a whole new silo system.

High efficiency fan for raw mill vent fan with inverter: In the Birla Vikas Cement Works, Birla Corporation Limited, India, the raw mill vent fans were older generation, less-efficient, high energy-consuming fans. These fans were replaced with high efficiency fans, resulting in power consumption savings. Further, the air volume of these fans was controlled by controlling the damper, which consumes more energy; hence it was decided to provide suitable speed control system for AC drives for controlling the speed.

Clinker Making
Kiln shell heat loss reduction (Improved refractories):
There can be considerable heat losses through the shell of a cement kiln, especially in the burning zone. The use of better insulating refractories (for example Lytherm) can reduce heat losses. Extended lifetime of the higher quality refractories can offset their higher costs by extending operating periods and thereby lowering the lost production time between relining of the kiln. The use of improved kiln-refractories may also improve kiln reliability and reduce the downtime, which will lower production costs considerably and reduce energy needs during start-ups. Structural considerations may limit the use of new insulation materials.

Energy management and process control systems in clinker making:
Automated computer controls systems help optimize the combustion process and conditions. Improved process control will also improve product quality and grindability such as the reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding. A uniform feed allows for steadier kiln operation, reducing fuel requirements. Expert control systems simulate the best human operator, using information from various stages of the process. An alternative to expert systems or fuzzy logic is model-predictive control using dynamic models of the processes in the kiln. Additional process control systems include the use of on-line analyzers that permit operators to instantaneously determine the chemical composition of raw materials being processed, thereby allowing for immediate changes in the blend of raw materials. Process control of the clinker cooler can help improve heat recovery, material throughput, control of free lime content in the clinker and reduce NO_x emissions. Control technologies also exist for

controlling the air intake. Raw materials and fuel mix can be improved by a careful analysis of the chemical and physical characteristics of them, and by automating the weighing process, the pellet production (water content and raw feed mixtures), the blending process and kiln operation (optimizing air flow, temperature distribution, and the speed of feeding and discharging).

Optimize heat recovery/upgrade clinker cooler:
The clinker cooler lowers the clinker temperature from 1200°C to 100°C. The most common cooler designs are the planetary (or satellite), traveling and reciprocating grate type. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner. Reciprocating grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tpd). Grate coolers use electric fans and excess air. The portion of the remaining air with the highest temperature can be used as tertiary air for the precalciner. Rotary coolers (used for plants up to 2200 to 5000 tpd) and planetary coolers (used for plants up to 3300 to 4400 tpd) do not need combustion air fans and use little excess air, resulting in relatively lower heat losses. Heat recovery can be improved through reduction of excess air volume, control of clinker bed depth and new grates such as ring grate. Improving heat recovery efficiency in the cooler results in fuel savings, but may also influence product quality and emission levels. Controlling the cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. Additional heat recovery results in lowered energy use in the kiln and precalciner due to higher combustion air temperatures.

Low temperature Waste Heat Recovery power generation:
A large amount of energy consumption for cement production occurs in the calcination process. This involves passing raw materials through a preheater stack containing cyclone heaters to a long rotating kiln to create clinker and then cooling clinker in the clinker cooler. In the clinker production process, a significant amount of heat is typically vented to the atmosphere without being used, resulting in wasted heat that can lead to heat pollution. If the waste heat is captured and used for power generation, it can significantly improve energy efficiency and reduce the amount of power imported from the electric grid. A Waste Heat Recovery (WHR) system can effectively utilize the low temperature waste heat of the exit gases from Suspension Preheater (SP) and Air Quenching Chamber (AQC) in cement production. The WHR captive power plant consists of WHR boilers (SP boiler and AQC boiler), steam turbine generators, controlling system, water-circulation system and dust-removal system etc. The steam from SP boiler and AQC boiler is fed to the steam turbine generator to produce power.

Upgrading of a Preheater kiln to a Preheater/Precalciner Kiln:
An existing preheater kiln may be converted to a multi-stage preheater/precalciner kiln by adding a precalciner and an extra preheater when possible. The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption and reducing thermal NO_x emissions (due to lower combustion temperatures in the precalciner). Using as many

features of the existing plant and infrastructure as possible, special precalciners have been developed by various manufacturers to convert existing plants, for example Pyroclon®-RP by KHD in Germany. Generally, the kiln, foundation and towers are used in the new plant, while cooler and preheaters are replaced. Cooler replacement may be necessary in order to increase the cooling capacity for larger production volumes. Older precalciners can be retrofitted for energy efficiency improvement and NO_x emission reduction.

Low pressure drop cyclones for suspension preheater:
Cyclones are a basic component of plants with pre-heating systems. The installation of newer cyclones in a plant with lower pressure losses will reduce the power consumption of the kiln exhaust gas fan system. Installation of the cyclones can be expensive, since it may often entail the rebuilding or the modification of the preheater tower, and the costs are very site specific. New cyclone systems may increase overall dust loading and increase dust carryover from the preheater tower. However, the dust carryover problem is less severe if an inline raw mill follows it.

Finish Grinding

Energy management and process control in grinding:
Control systems for grinding operations are developed using the same approaches as for kilns. The systems control the flow in the mill and classifiers, attaining a stable and high quality product. Several systems are marketed by a number of manufacturers. Expert systems have been commercially available since the early 1990's. The systems result in electricity savings as well as other benefits such as reduced process and quality variability as well as improved throughput/production increases.

Replacing a ball mill with vertical roller mill:
Roller mills employ a mix of compression and shearing, using 2-4 grinding rollers carried on hinged arms riding on a horizontal grinding table. The raw material is grounded on a surface by rollers that are pressed down using spring or hydraulic pressure, with hot gas used for drying during the grinding process. A vertical roller mill can accept raw materials with up to 20% moisture content and there is less variability in product consistency.

High pressure roller press as pre-grinding to ball mill:
A high pressure roller press, in which two rollers pressurize the material up to 3,500 bar, can replace ball mills for finish grinding, improving the grinding efficiency dramatically.

Improved grinding media for ball mills:
Improved wear-resistant materials can be installed for grinding media, especially in ball mills. Grinding media are usually selected according to the wear characteristics of the material. Increasing the ball charge distribution and surface hardness of grinding media and wear-resistant mill linings have shown potential for reducing wear as well as energy consumption. Improved balls

and liners made of high chromium steel is one such material but other materials are also possible. Other improvements include the use of improved liner designs, such as grooved classifying liners.

High-Efficiency classifiers for finish grinding:
A recent development in efficient grinding technologies is the use of high-efficiency classifiers or separators. Classifiers separate the finely ground particles from the coarse particles. The large particles are then recycled back to the mill. Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, resulting in extra power use in the grinding mill. In high-efficiency classifiers, the material is more cleanly separated, thus reducing over-grinding. High efficiency classifiers or separators have had the greatest impact on improving product quality and reducing electricity consumption. Newer designs of high-efficiency separators aim to improve the separation efficiency further and reduce the required volume of air (hence reducing power use).

Replacement of cement mill vent fan with high efficiency fan: In the Birla Cement Works in Chittorgarh Company, India, the cement mill # 2 vent fan was an older generation, less-efficient, high energy-consumption fan. Therefore, it was replaced with a high-efficiency fan resulting in the power savings.

General measures
Use of Alternative Fuels:
Alternative fuels can be substituted for traditional commercial fuels in a cement kiln. A cement kiln is an efficient way to recover energy from waste. The CO_2 emission reduction depends on the carbon content of the waste-derived fuel, as well as the alternative use of the waste and efficiency of use (for example incineration with or without heat recovery). For biomass fuels that are considered carbon neutral, the CO_2 emission reduction is 100% compared to the commercial fossil fuels used in the cement industry. The high temperatures and long residence times in the kiln destroy virtually all organic compounds, while efficient dust filters may reduce some other potential emissions to safe levels. Alternative fuels include tires, carpet and plastic wastes, filter cake, paint residue and (dewatered) sewage sludge, and hazardous wastes.

High efficiency motors:
Motors and drives are used throughout the cement plant to move fans (preheater, cooler, alkali bypass), to rotate the kiln, to transport materials and, most importantly, for grinding. In a typical cement plant, 500-700 electric motors may be used, varying in size from a few kW to MW. Power use in the kiln (excluding grinding) is roughly estimated to be 40-50 kWh/tonne clinker. Variable speed drives, improved control strategies and high-efficiency motors can help reduce power use in cement kilns. If the replacement does not influence the process operation, motors may be replaced at any time. However, motors are often rewired rather than being replaced by new motors.

Adjustable Speed Drives:

Drives are the largest power consumers in cement making. The energy efficiency of a drive system can be improved by reducing energy losses or by increasing motor efficiency. Most motors are fixed speed AC models. However, motor systems are often operated at partial or variable load. Also, large variations in load can occur in cement plants. Within a plant, adjustable speed drives (ASDs) can mainly be applied for fans in the kiln, cooler, preheater, separator and mills, and for various drives. Decreasing throttling can reduce energy losses in the system and coupling losses through the installation of ASD. ASD equipment is used more and more in cement plants, but the application may vary widely depending on electricity costs. ASDs for clinker cooler fans have a low payback, even when energy savings are the only benefit to installing ASDs.

Product Change

Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag):

The production of blended cement involves the intergrinding of clinker with one or more additives (fly ash, pozzolans, blast furnace slag, volcanic ash) in various proportions. Blended cement demonstrates a higher long-term strength, as well as improved resistance to acids and sulfates, while using waste materials for high-value applications. Short-term strength (measured after less than 7 days) of blended cement may be lower, although cement containing less than 30% additives will generally have setting times comparable to concrete based on Portland cement. Blended cement has been used for many decades around the world. Blended cement are very common in Europe; blast furnace and pozzolanic cements account for about 12% of total cement production with Portland composite cement accounting for an additional 44%.

Appendix 2. Time Dependent Key Model Inputs

Time Dependent Key Model Inputs	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions Factors																					
CO2 Emission factor for grid electricity (tonne CO2/MWh)	1.02	1.02	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
CO2 Emission factor for fuel (tonne CO2/TJ)	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6	94.6
Industry Capacity (Mt)																					
Clinker Production	129	149	169	188	208	228	238	248	258	268	278	287	297	307	317	327	337	347	357	367	377
Cement Production	165	190	215	241	266	291	304	316	329	342	355	367	380	393	406	418	431	444	457	469	482

Source: IEA 2011a, GOI 2012b

Appendix 3. Annual Results

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fuel Savings (PJ)	5.29	7.97	13.01	18.62	24.68	31.10	36.36	41.50	46.45	51.17	55.59	59.67	63.35	66.57	69.27	71.40	72.91	73.74	73.84	73.14	73.21
Fuel Related CO_2 Savings (Mt)	0.50	0.75	1.23	1.76	2.33	2.94	3.44	3.92	4.39	4.84	5.26	5.64	5.99	6.29	6.55	6.75	6.89	6.97	6.98	6.92	6.92
Electricity Savings (TWh)	0.35	0.66	1.06	1.50	1.97	2.46	2.88	3.29	3.69	4.07	4.44	4.78	5.08	5.36	5.60	5.80	5.96	6.06	6.11	6.10	6.03
Electricity Related CO_2 Savings (Mt)	0.36	0.67	1.05	1.48	1.95	2.43	2.85	3.26	3.65	4.03	4.39	4.73	5.04	5.31	5.55	5.75	5.90	6.00	6.05	6.04	5.97