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Assessment of Energy Efficiency Improvement and CO_2 Emission Reduction Potentials in the Cement Industry in China

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Abstract

China's annual cement production (i.e., 1,868 Mt) in 2010 accounted for nearly half of the world's annual cement production in the same year. We identified and analyzed 23 energy efficiency technologies and measures applicable to the processes in the 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, the cumulative cost-effective electricity savings potential for the Chinese cement industry for 2010-2030 is estimated to be 251 TWh, and the total technical electricity saving potential is 279 TWh. The CO_2 emissions reduction associated with cost-effective electricity savings is 144 Mt CO_2 and the CO_2 emission reduction associated with technical electricity saving potential is 161 Mt CO_2. The fuel CSC model for the cement industry suggests cumulative cost-effective fuel savings potential of 4,326 PJ which is equivalent to the total technical potential with associated CO_2 emission reductions of 406 Mt CO_2. 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. We also developed a scenario in which instead of only implementing the international technologies in 2010-2030, we implement both international and Chinese domestic technologies during the analysis period and calculate the saving and cost of conserved energy accordingly. The result of this study gives a comprehensive and easy to understand perspective to the Chinese cement industry and policy makers about the energy efficiency potential and its associated cost.

Contents

1. Introduction

China's cement industry, which produced 1,868 million metric tons (Mt) of cement in 2010, accounts for nearly half of the world's total cement production (MIIT, 2011). Nearly 20% of China's current cement production is from relatively obsolete vertical shaft kiln (VSK) cement plants, with the remainder from modern rotary kiln cement plants, including plants equipped with new suspension pre-heater and pre-calciner (NSP) kilns. To accelerate kiln technology switch, official Chinese government policy calls for the phase-out and replacement of all VSK cement plants with more modern kilns (NDRC, 2006). Figure 1 shows that cement production from rotary kilns has grown rapidly in recent years, jumping from 116 Mt in 2000 to 1,494 Mt in 2010 (ITIBMIC, 2004; MIIT, 2011).

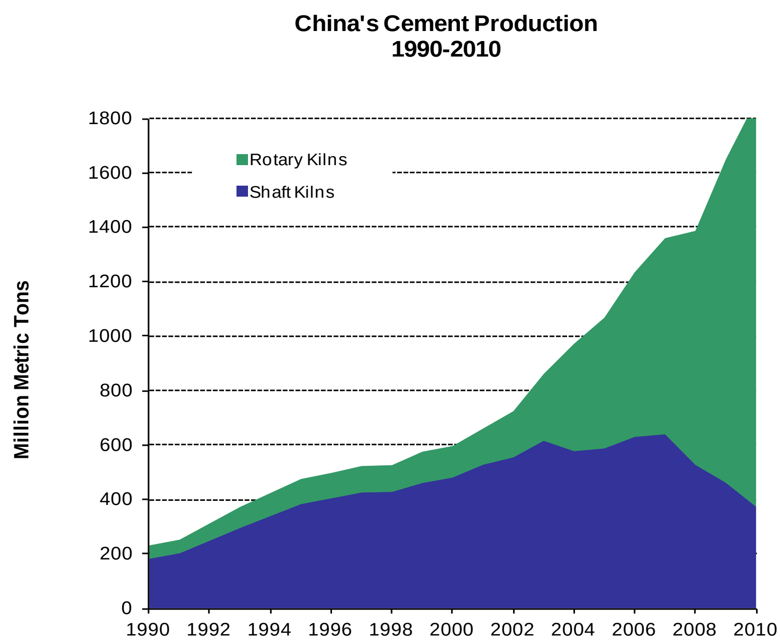


Figure 1. Cement Production in China by Major Kiln Type, 1990-2010 (ITIBMIC 2004; Kong, 2009; CCA, 2010; MIIT, 2011)

VSKs are basically a large drum that is oriented vertically with a packed mixture of raw material and fuel traveling down through it using gravity. A rotary kiln consists of a longer and wider drum oriented horizontally and at a slight incline on bearings, with raw material entering at the higher end and traveling as the kiln rotates towards the lower end, where fuel is blown into the kiln.

Since the 1970s, intensive domestic VSK technology research and development in China improved the kilns considerably. VSKs are much smaller, simpler and can be constructed much more rapidly than rotary kilns, making them attractive given the system of distributed production that arose in China due to lack of sufficient infrastructure as well as political, economic, and other factors. Simultaneous evolution of VSK technology with the more complex dry process rotary kilns resulted in a diverse mix of pyro-processing technologies in China's cement industry (Galitsky and Price, 2007).

There are three basic types of VSKs: ordinary, mechanized, and improved. In ordinary VSKs, high-ash anthracite coal and raw materials are layered in the kiln, consuming high amounts of energy while producing cement of inferior quality and severe environmental pollution. Mechanized VSKs use a manually operated feed chute to deliver mixed raw materials and fuel to the top of the kiln. Improved VSKs been upgraded and produce higher quality cement with lower environmental impacts (Sinton, 1996; ITIBMIC, 2004).

Rotary kilns can be either wet or dry process kilns. Wet process rotary kilns are more energy-intensive. Energy-efficient dry process rotary kilns can be equipped with grate or suspension pre-heaters to heat the raw materials using kiln exhaust gases prior to their entry into the kiln. In addition, the most efficient dry process rotary kilns use precalciner to calcine the raw materials after they have passed through the pre-heater but before they enter the rotary kiln (WBCSD, 2004). Construction of these modern NSP kilns has been growing rapidly in China since about 2000. Large and medium sized NSP kilns produced 56 Mt (10%) of cement in China in 2000, increasing to 623 Mt (50%) by 2006 (ITIBMIC, 2004; CCATC, 2008).

Globally, coal is the primary fuel burned in cement kilns, but petroleum coke, natural gas, and oil can also be combusted in the kiln. Waste fuels, such as hazardous wastes from painting operations, metal cleaning fluids, electronic industry solvents, as well as tires, are often used as fuels in cement kilns as a replacement for more traditional fossil fuels. In China, coal is used almost exclusively as the fuel for the cement kilns, while electricity – both provided by the grid and through the generation of electricity on-site using waste heat – is used to power the various grinding mills, conveyers, and other auxiliary equipment. In 2007, Chinese cement kilns used 174 Mt of mostly raw coal and 119 terawatt-hours (TWh) of electricity (CCA, 2009). There is very little use of alternative fuels (defined as waste materials with heat value more than 4000kcal/kg for cement clinker burning) or co-processing of waste materials (defined as the incineration of wastes for disposal purposes even if the calorific value of the waste can be used as a fuel) in cement production in China (Wang, L., 2008). Less than 20 cement facilities either burn alternative fuels or co-process waste materials as demonstration or pilot projects, but Chinese laws and industrial policies now encourage the use of alternative fuels and the National Development and Reform Commission (NDRC) has begun efforts to develop a Cement Kiln Alternative Fuel Program that will expand the demonstration projects, prepare regulations, develop a permitting-type system, and establish financing mechanisms (Wang, S., 2007).

Once clinker has been produced in either a shaft or rotary kiln, it is inter-ground with additives to form cement. Common 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. Blended cements may have a lower short-term strength (measures after less than 7 days), but have a higher long-term strength, as well as improved resistance to acids and sulfates. In 2007, 5.4% of the cement produced in China was Pure Portland Cement, which is defined as either being comprised of 100% clinker and gypsum or >95% clinker and gypsum with <5% of either granulated blast furnace slag (GGBS) or limestone. Common Portland Cement, comprised of >80% and <95% of clinker and gypsum combined with >5% and <20% of additives (GGBS, pozzolana, fly ash, or limestone), made up 54% of the cement produced in China that year. Slag Portland Cement, that blends anywhere from >20% to <70% GGBS with clinker and gypsum, constituted 36% of 2007 cement production. The remaining 5% of cement was Pozzolana (>20% to <40% pozzolan additives), fly ash (>20% to <40% fly ash), or other blended cement (>20% to <50% other additives) (Wang, L., 2009).

Given its large size, complexity, and global importance in terms of both energy consumption and greenhouse gas (GHG) emissions, the cement sector in China is receiving increasing attention among analysts, policy-makers, and others around the world. Early analyses of the industry in the 1990s focused on improvements that could be made to VSKs as well as scenarios exploring the energy savings possible with increased adoption of more modern pre-calciner kilns (Liu et al., 1995) and developments related to mechanized VSKs which at the time were less energy-intensive than both non-mechanized VSKs and the currently-used rotary kilns (Sinton, 1996). However, future efforts and studies focused more on the NSP rotary kilns as the structure of the Chinese cement industry changes towards this type of kiln (Hasanbeigi et al. 2010c, Ziwei Mao, 2009, and Liu et al. 2007).

The study presented in this report is unique for China as it provides a detailed analysis of energy efficiency improvement opportunities for the entire cement industry in China. In addition, compared with other international studies, the potential application of a larger number of energy-efficiency technologies is assessed. The objective of this study is to assess the potential for energy saving in the Chinese cement industry using a technology-level, bottom-up approach and to estimate the cost associated with this potential. These results can guide policy makers in designing better sector-specific energy efficiency policy programs.

In this report, we first briefly present an overview of the cement industry in China. In the next section, the methodology will be presented. After that, we present the technologies and measures available for energy-efficiency improvement and greenhouse gas (GHG) emission reduction in the cement industry, and conduct the technical and cost assessment for implementing those measures in China. 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 improvement and CO_2 emission reduction. Finally, we illustrate the results of the analysis and some of the barriers to the implementation of the efficiency measures in the cement industry.

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. (Worrell et al. 2000; Worrell et al., 2008; LBNL & ERI, 2008) and in Shandong province of China (Hasanbeigi et al. 2010), as well as other references. In this report, we have included two categories of the technologies:

1) International Technologies

International technologies are defined in our study as technologies that are manufactured outside of China. The data on the energy saving, cost, lifetime, and other details on each technology were obtained from these LBNL reports, which are based on case-studies around the world.

2) Chinese Domestic Technologies

In addition to international technologies, we also obtained data on the energy saving, costs, penetration rate of Chinese domestic technologies for the cement industry.

Because we could not obtain Chinese domestic technology information for all the energy efficiency measures/technologies in our list, the base case analysis in this report is done based on international technologies only. Then, we developed an alternative scenario in which we applied the penetration of Chinese domestic technologies which is further explained in Section 4.2.

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, and the cost of different technologies. Information on some of the technologies examined, however, was 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 the cement industry (Sathaye et al. 2010, Worrell et al., 2000, Hasanbeigi et al. 2010d).

The national level data for the production of different products for China's cement industry was obtained from China Cement Almanac (China Cement Association, 2009) and from the China Cement Association. For the penetration rate of the energy efficient measures, a questionnaire was developed and sent to individual experts in China (see Appendix 4 for a copy of the questionnaire used). In addition, we also benefited from the penetration rates published in Hasanbeigi et al. (2010c) which is based on the detailed survey of sixteen NSP kilns cement plants in Shandong province in China. Finally, we obtained some data from the "National Key Energy Conservation Technologies Promotion Catalogue" published by National Development and Reform Council (NDRC, 2008, 2009, 2010).

2.2. Conversion Factors and Assumptions

To convert electricity to primary energy, the conversion factor of 2.94 is used which is equivalent to China's national average net heat rate of fossil fuel-fired power generation of 0.337 kgce/kWh in 2009 plus national average transmission and distribution losses of around 6.5%[1] (SERC, 2011). The Lower Heating Value (LHV) of the fuel is used in the analysis. The 2009 monthly average exchange rate of 6.8 RMB/US$ is used to convert reported costs in Chinese Renminbi (RMB) to U.S. dollars (US$) (BOC 2009).

The carbon conversion factors for fuels used for calculating CO_2 emissions from energy consumption are taken from the 2006 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The emission factor for grid electricity is assumed to be 0.82 kg CO_2/kWh in 2009 and forecasted emission factors through 2030 were from the factors used in LBNL's China LEAP model (see Appendix A.3) (Fridley et al. 2011). The emission factor of the fuel is assumed to be unchanged during the study period because coal is assumed to be the primary source of fuel used in the Chinese cement industry up to 2030.

The average unit price of electricity paid by the cement industry in 2009 is used as the electricity price in the base year. Since more than 99% of the fuel use in the Chinese cement industry is coal, the average unit price of coal consumed in the cement industry in 2009 is used as the fuel price in the base year. Using energy prices in the base year and real electricity and fuel price escalation rates which are estimated based on Ni (2009), we calculated the energy prices in the future years during the study period. These prices are in constant dollars. 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) govern the future benefits from energy cost savings and are treated the same as future capital and operation and maintenance (O&M) costs over the study period by discounting them to a present value using the same discount rate as applied to future capital and 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 results could be misinterpreted as indicating that measures are cost effective to implement by overestimating the benefits (energy cost savings) relative to costs of measures.

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 China'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

[1] It should be noted that this value was the average net heat rate for those units larger than 6MW.

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, 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 China as it provides a detailed analysis of energy-efficiency improvement opportunities in the entire Chinese cement industry.

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

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

Where:
CCE = Cost of Conserved Energy
ACC = Annualized Capital Costs
Δ AO&M = Change in Annual Operations and Maintenance Cost
n= year
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

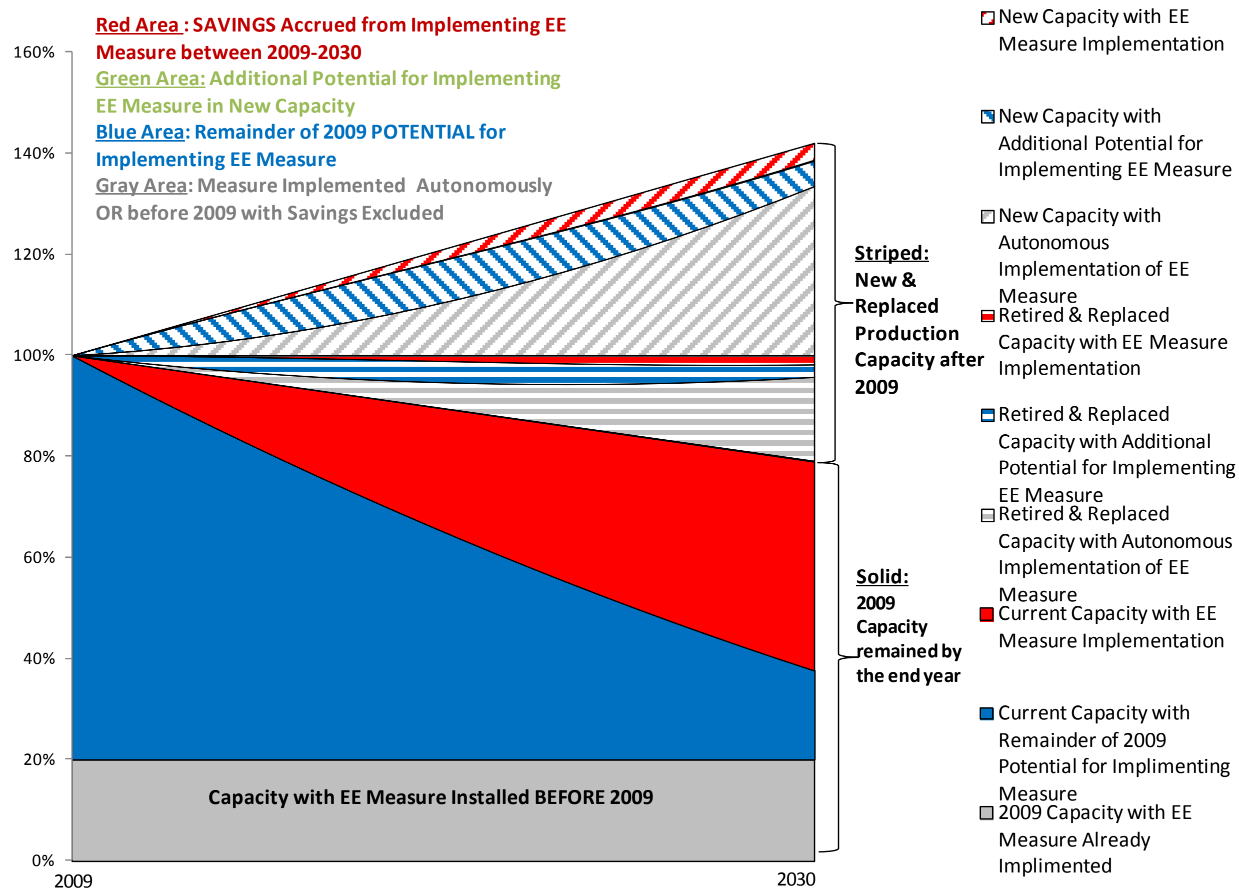
After calculating the Cost of Conserved Energy for all energy-efficiency measures separately, the measures were ranked in ascending order of their Cost of Conserved Energy to construct the Energy CSC, and measures were applied in cascading fashion to avoid “double counting” of savings between measures. In an Energy CSC, an energy price line is determined. All measures that fall below the energy price line are considered “cost-effective”. Furthermore, the CSC can show us 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.

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

1. Establish 2009 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 measure 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. The 23 energy efficiency measures/technologies are used in this study based on their applicability to the Chinese cement industry as well as the significant energy saving that can be achieved by the implementation of them. This information was obtained from previous LBNL study for a group of 16 cement plants in China (Hasanbeigi et al. 2010c).
3. Determine the potential application of energy-efficiency technologies and measures in the Chinese cement industry in the base year based on information collected from several sources. We assumed 70% of the potential for energy efficiency measures will be realized by the end of 2030 (3.5% per year) (except for a two measures, replacing a ball mill with vertical roller mill in finish grinding and the use of alternative fuels, which were treated differently), with a linear deployment rate assumed between the start year (2010) and end year (2030).
4. Obtain the annual 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 between 2010 and 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-effectiveness and total technical potential for 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, 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 energy-efficiency measures 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 measures in the model (Figure 2).



Note: This graph is only for illustrative purposes

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

Based on data received from the Chinese experts and our previous study (Hasanbeigi et al. 2010c) on actual penetration rate of energy efficiency measures in the base year (i.e. 2009), 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 2011). This is shown in the figure as "Retired and Replacement". For the remaining existing potential we assumed 70% adoption will be reached by 2030 (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 the efficiency measure after 2009, i.e. beginning of 2010 (solid red area in Figure 2).

In addition, industrial production capacity may 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 (Ke et al. 2012) and assumed that a certain proportion of the new capacity will adopt the efficiency measures autonomously each year (4% per year between 2010 and 2030) as a result of the installation of new efficient technology in the new stock (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) (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.

In forecasted years when the demand for cement declines either relative to the previous year or even relative to the base year, which is the case for the Chinese cement demand forecast, we assumed that *new capacity* added after 2009 remains in production. Thus, we assumed that reduced demand results in a reduced production at inefficient plants. However, we first estimated energy efficiency adoptions in the existing capacity regardless of reduced demand. Therefore, if the demand decline between 2010 and 2030 is large enough, the entire inefficient capacity can reach the decommissioning or zero production point within this period. This results in saturated adoption in the remaining existing capacity and no additional adoptions are possible since the entire existing capacity has either adopted the measures or been decommissioned by the saturation year. This represents one approach to deal with the sharp decreased cement demand in the future. An extreme case in the opposite direction is that production never falls despite domestic demand reductions and instead excess production is exported resulting in the same energy consumption, emissions, and energy efficiency adoption potential as would be the case if demand kept rising. Because of the transportation costs, exporting cement is not a highly profitable trade and Chinese companies are not exporting a high volume of cement either. However, a large domestic demand reduction could put considerable downward pricing pressure on the cement industry and could result in significant exports in the future. Another case could be the export of old yet not retired equipment to another country when Chinese domestic demands fall considerably and exporting cement would not be attractive. We have no way of modeling exported equipment and therefore made a conservative assumption that inefficient capacity will no longer be available within China to adopt energy conservation measures.

Although the CSC model developed 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 benefits could significantly reduce the CCE for the energy-efficiency measures (Worrell et al., 2003; Lung et al., 2005).

2.4. Different Approaches for Developing Conservation Supply Curves

It should be noted that there are different approaches for developing energy conservation supply curves and CO_2 abatement cost curves. These approaches may use different mathematical formulae as well as time horizons for constructing the energy conservation supply curve. The method used for the development of the curve can significantly influence the results and the interpretation of them (Fleiter et al. 2009). The CSC approach we used in this study for the Chinese cement industry is presented above. In this approach we calculated the cost of conserved energy by dividing the net present value (NPV) of annual costs (in constant 2009 US$) over the study period (2010-2030) by the simple sum of annual energy saving (in TWh or PJ) over the same period. We did not discount the energy saving values. Then, we presented the calculated cost of conserved energy on the CSC along with the cumulative energy saving over the same period. In addition, we projected the energy prices (for electricity and coal) in the future years up to 2030 and then discounted the forecasted energy price to the present value (2009 value). After that we calculated the average of these discounted energy prices to come with a single number (for electricity and coal, separately) used on the supply curve. Finally, we compared the cost of conserved energy with the average discounted energy price on the supply curves.

In some other studies such as McKinsey&Company (2009a), in addition to discounting the cash-flow of the annual costs, they also discounted the future annual energy savings to the present value and then sum these discounted present values to calculate the total energy saving in the present value over the time period. This is different from what we did in our study. The reason that we did not discount the energy saving is that energy savings in the future years are physical values presented in energy units (TWh or PJ). We believe that only monetary values should be discounted to represent the time value of the money, but the physical values (like energy saving) should not be discounted. Discounting the physical values will be misleading, as it will not represent the actual magnitude of the energy saving potential (in TWh or PJ) that can be achieved in the future.

The other approach commonly used in the construction of a CSC is to develop the curve only for one year (usually the base year). In this method, the cost of conserved energy is calculated by dividing the annual cost in the base year, which is the sum of annualized capital cost and the annual change in the O&M costs, by the annual energy saving in the base year. This approach is used in various studies such as Worrell et al. (2000) and Hasanbeigi et al. (2010c). Since this approach only shows the energy saving potential in the base year, the magnitude of saving shown on the supply curve is much lower than the cumulative, multi-year CSC shown on the supply curve developed using the methodology in our study. To sum up, when looking at a CSC and trying to interpret the results, one should pay attention to the method and formulae used in the development of the curve in addition to the assumptions used such as the discount rate, energy prices, period of the analysis, cost of technologies and their energy saving, etc. To make this important point clearer we present an illustrative example with the detailed explanation below.

2.4.1. Single-year Cost of conserved energy (CCE) Vs. discounted CCE over time horizon

The cost of conserved energy (CCE) is a calculation used within the energy analysis community to evaluate the cost-effectiveness of energy efficiency investments as compared to alternative investments such as producing more electricity or providing more fuel (Meier 1982). Sometimes, it is defined as the annualized costs, including the cost of capital investments with a time value of money using a discount rate plus variable costs, divided by the annual energy savings. This cost per unit of energy savings, or "cost of conserved energy" can then be directly compared to the annualized cost of energy supply, typically calculated using the same formula (i.e., annualized cost divided by annual energy output). This comparison allows for a quick and basic evaluation to determine if an energy efficiency investment is less costly than purchasing (or supplying) the equivalent amount of energy.

In the aforementioned approach, both the cost of conserved energy and the cost of energy supply are on an annualized basis comparing a single year snapshot. This does not provide an accurate evaluation in a forward looking analysis (like the one conducted in this report) where technology adoptions are modeled over a time period. Thus, an alternative methodology is needed to evaluate multiple technologies that have specific penetration rates, deployed at unique points within the analysis time period, each with individual accrued energy savings valued at escalating energy prices. We, therefore, adapted a methodology that discounts a series of annualized cash flow costs to a net present value and then divides by the cumulative energy savings, which is not discounted, over the time period. This is then compared to the average present value of the unit price of energy over the same time period.

Because this latter methodology uses several accounting steps (annualized capital costs, net present value of a cash flow series, undiscounted cumulative energy savings, and average present value of the unit price of energy) a simplified example is presented in order to demonstrate the effects each accounting step has on the comparison of cost effectiveness. For this example, assume a single technology's capital cost is $50 with no variable annual costs. Also, assume it has a lifetime of 10 years and accrues 10 GJ of energy savings per year. Table 1 shows the traditional single year annualized costs and CCE as a function of discount rates.

Table 1. Single-year CCE calculated with different discount rate - an illustrative example

Discount Rate	Annualized Costs	CCE (Annualized Costs/Annual Saving) in ($/GJ)
0%	$5.00	0.50
5%	$6.48	0.65
10%	$8.14	0.81
15%	$9.96	1.00
20%	$11.93	1.19
25%	$14.00	1.40
30%	$16.17	1.62

We now assume that an additional unit of this technology is deployed each year over a ten year time period resulting in an increasing cash flow of costs and energy savings. If the cash flow of cost and energy savings are discounted using the same discount rate, then the CCE would remain the same as presented in Table 1. However, as explained in the preceding section, we believe that it is misleading to discount the physical energy savings (electricity or fuel) and therefore the cash flow of costs is discounted to a net present value but the energy savings are not.

Discounting the cash flow of costs to a net present value while not discounting the energy savings effectively lowers the CCE because as more years are included in the time period the costs towards the end of the time period are discounted resulting in a lower present value, whereas the energy savings are not discounted and have the same value over the time period. As shown in the table above, the increasing discount rate tends to push the single-year CCE higher, but it pushes a "discounted CCE" downward as more years are included in the time period. In this example as shown in Figure 3, after approximately nine years, all discount rates greater than zero result in a lower "discounted CCE" than having no (zero) discount rate would.

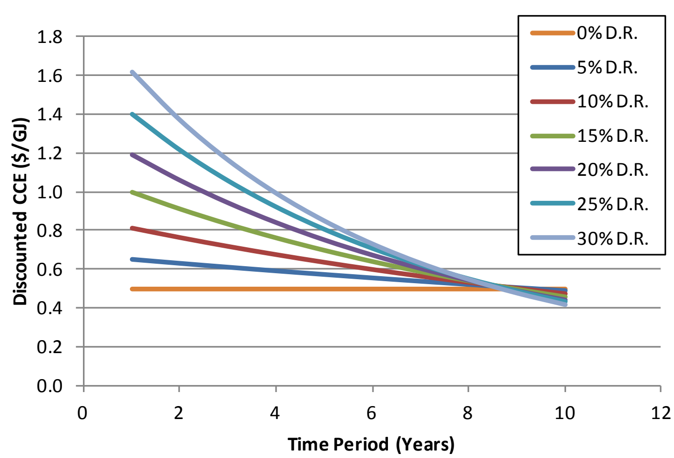


Figure 3. Discounted CCE over a time period- an illustrative example

Because the CCE is designed to facilitate an evaluation of an energy efficiency measure's cost-effectiveness when compared to purchasing the energy that would otherwise be consumed, the unit price of energy must also be treated from the same perspective as a cash flow series. Therefore, the unit price of energy over the time period should be discounted to a present value using the same discount rates and then the average of the discounted values can be calculated to be shown on the conservation supply curve. For this example, we assumed that the unit price of energy is $1.00 per unit with zero real price escalation. Increasing discount rates lower the unit discounted average unit price of energy over the time period as shown in figure 4.

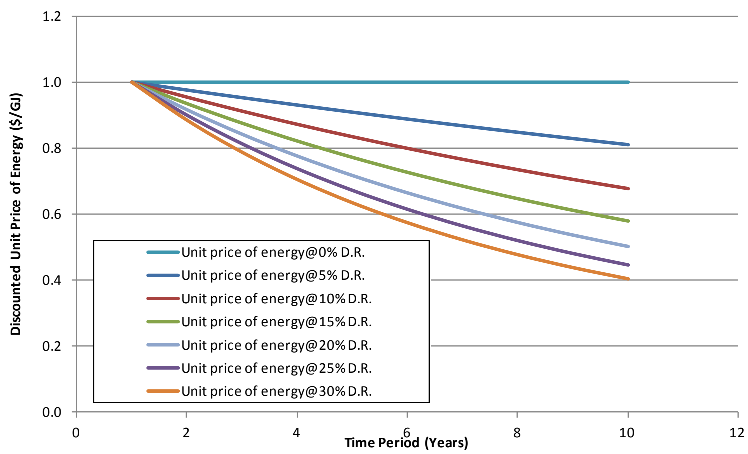


Figure 4. Unit price of energy over a time period Vs. discount rates - an illustrative example

The final step in the analysis is to compare the discounted CCE to the discounted average unit price of energy over the time period using consistent discount rates. Figure 5 shows the resulting comparison assuming a ten year time horizon. As the discount rate increases, the discounted average unit price of energy (the red line) declines at a greater rate than the discounted CCE (the blue line). This is expected as the discounted CCE is based on an annualized capital cost that includes the time value of money as shown in table 1. The cumulative effect of the annualized capital costs and a time series of cash flow costs results in discounted CCE that drops slower than the discounted average unit price of energy.

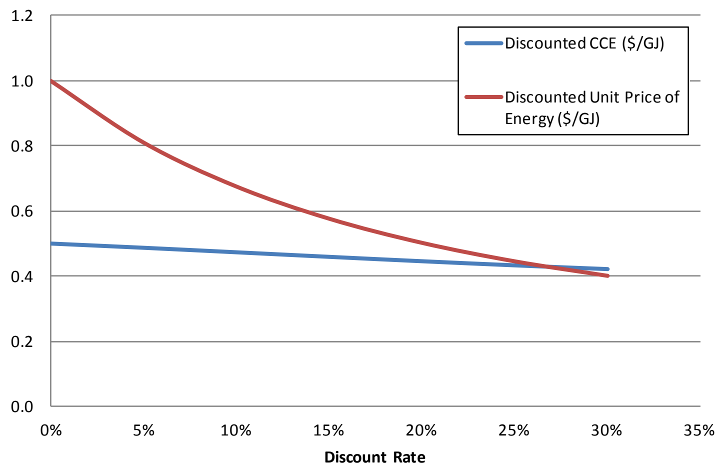


Figure 5. Discounted CCE and unit price of energy over a ten year time horizon vs. discount rates

In this example, the single year snapshot CCE indicates that below a discount rate of roughly 15%, saving a unit price of energy by implementing the energy efficiency measure is more cost-effective than purchasing the equivalent amount of energy (compare Figures 3 and 4 for a single year time period, i.e. year 1). Figure 5 shows that using the forward looking methodology, saving a unit price of energy by implementing the efficiency measure is more cost-effective than purchasing the equivalent amount of energy up to a discount rate of approximately 28% in this example. The cost-effectiveness of energy efficiency measures is improved by including the time series of investments.

2.5. Discount Rate

In this study, a real discount rate of 15% was assumed for the analysis. However, it should be noted that 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). 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.

Other industrial sector analyses use varying real discount rates. Carlos (2006) used a range of 10% to 16% discount rate in the financial analysis for cogeneration projects in Thailand. Garcia et al. (2007) used three discount rates of 12%, 15%, and 22% in three different investment scenarios for high efficiency motors in Brazil. Sathaye et al. (2010) used the discount rates of 10%, 20%, and 30% for different scenarios in their bottom-up modeling analysis for the U.S. cement industry. McKinsey & Company used a 7% social discount rate for developing Conservation Supply Curves and GHG abatement cost curve for the US (McKinsey & Company, 2007 and 2009a) and a 4% social discount rate for developing a GHG abatement cost curve for China (McKinsey & Company, 2009b). ICF developed an abatement cost curve for the cement industry in Brazil and Mexico in 2015 using a 10% discount rate (ICF International, 2009a, b). In the Asia Least-cost Greenhouse Gas Abatement Strategy (ALGAS) project, a 10% real discount rate is assumed for the calculation of GHG emissions abatement scenarios for various economic sectors including industry in Thailand (ADB/GEF, 1998).

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 23 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 23 efficiency measures was that during the earlier study (Hasanbeigi et al. 2010c), we found that these measures are the most relevant to the Chinese cement industry in terms of applicability as well as the significance of the energy saving that can be achieved by implementing them. Table 2 presents data related to the production capacity in each step of the cement production process in China. It also presents the energy savings, capital costs, and change in annual operation and maintenance (O&M) cost, and potential application share for each energy-efficiency technology and measure when applied to China’s cement industry.

Table 2. Energy Savings and Costs for Energy-Efficient Technologies and Measures Applied to the Cement Industry

No.	Technology/Measure	Clinker Production Capacity in base year to which the measure is applied (Mt/year)	Typical International Technology			Typical Chinese Domestic Technology			Change in annual O&M cost (2009 US$/t-cl)	Share of clinker production capacity in base year (2009) to which measure is applicable (%) *
			Fuel Savings (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Cost (2009 US$/t-cl)	Fuel Savings (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Cost (2009 US$/t-cl)		
	Fuel Preparation									
1	Replacing a ball mill with vertical roller mill for coal grinding	788.35		1.47	1.59		1.2	0.41	0.00	60%
2	Installation of variable frequency drive & replacement of coal mill bag dust collector's fan with high efficiency fan	788.35		0.16	0.04		N.A.	N.A.	0.00	20%
	Raw Materials Preparation									
3	High Efficiency classifiers/separators for raw material grinding	788.35		5.08	6.10		N.A.	N.A.	0.00	90%
4	Replacing a ball mill with vertical roller mill /High pressure roller presses in raw material grinding	788.35		11.00	15.26		11.0	2.57	0.00	50%
5	Efficient (mechanical) transport system for raw materials preparation	788.35		3.13	7.12		1.2	0.40	0.00	80%
6	Raw meal blending (homogenizing) systems	788.35		2.66	7.86		0.4	1.33	0.00	90%
7	High efficiency fan for raw mill vent fan with inverter	788.35		0.36	0.04		N.A.	N.A.	0.00	30%
	Clinker Making									
8	Kiln shell heat loss reduction (Improved refractories)	788.35	0.26		0.33	N.A.		N.A.	0.00	10%
9	Energy management and process control systems in clinker making	788.35	0.15	2.35	1.46	N.A.	N.A.	N.A.	0.00	5%
10	Optimize heat recovery/upgrade clinker cooler	788.35	0.11	-2.00 **	0.25	N.A.	N.A.	1.15	0.00	50%
11	Low temperature Waste Heat Recovery power generation	788.35		39.20	12.19		35.00	5.97	0.89	60%
12	Upgrading of a Preheater kiln to a Preheater/Precalciner Kiln	788.35	0.43		22.71	N.A.		N.A.	-1.44	100%
13	Low pressure drop cyclones for suspension preheater	788.35		2.60	3.38		N.A.	N.A.	0.00	60%
	Finish Grinding									
14	Energy management & process control in grinding	788.35		4.00	0.58		N.A.	N.A.	0.00	10%

No.	Technology/Measure	Clinker Production Capacity in base year to which the measure is applied (Mt/year)	Typical **International** Technology			Typical **Chinese Domestic** Technology			Change in annual O&M cost (2009 US$/t-cl)	Share of clinker production capacity in base year (2009) to which measure is applicable (%) *
			Fuel Savings (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Cost (2009 US$/t-cl)	Fuel Savings (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Capital Cost (2009 US$/t-cl)		
15	Replacing a ball mill with vertical roller mill in finish grinding	788.35		25.93	13.87		N.A.	N.A.	0.00	3%
16	High pressure roller press as pre-grinding to ball mill in finish grinding	788.35		24.41	13.87		8.00	2.67	0.00	60%
17	Improved grinding media for ball mills	788.35		6.10	2.18		N.A.	N.A.	0.00	80%
18	High-Efficiency classifiers for finish grinding	788.35		6.10	5.55		1.0	0.51	0.00	70%
19	Replacement of cement mill vent fan with high efficiency fan	788.35		0.13	0.01		N.A.	N.A.	0.00	50%
	General Measures									
20	High efficiency motors	788.35		4.58	0.47		N.A.	N.A.	0.00	10%
21	Adjustable Speed Drives	788.35		9.15	1.86		2.50	0.25	0.00	30%
22	Use of Alternative Fuels	788.35	0.6		1.10		N.A.	N.A.	0.00	0%
	Product Change ***	**Cement Production Capacity to which the measure is applied (Mt/year)**	**Fuel Savings (GJ/t-cem)**	**Electricity Savings (kWh/t-cem)**	**Capital Cost (US$/t-Cem)**	**Fuel Savings (GJ/t-Cem)**	**Electricity Savings (kWh/t- Cem)**	**Capital Cost (2009 US$/t-Cem)**	**Change in annual O&M cost (RMB/t-cem)**	**Share of cement production capacity in base year to which measure is applicable ***
23	Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag)	1187.28	1.77	-7.21 **	0.72	N.A.	N.A.	N.A.	-0.05	90%

* The share of production capacity in base year (2009) 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 2009", 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 Chinese cement industry from 2010 to 2030. In addition, the CO_2 emission reduction potential from implementing efficiency measures was also calculated. Out of 23 energy-efficiency measures that were included in our questionnaire, 22 measures were applicable to the cement industry in China, 17 of which are electricity-saving measures that are included in ECSC and 5 of which are fuel-saving measures used to derive the FCSC.

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

Five energy-efficiency measures were used to construct the FCSC. Figure 6 shows that all five energy-efficiency measures fall below the discounted average unit price of fuel (coal) in the cement industry from 2010 to 2030 (1.4US$/GJ), 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 five 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.

Table 3 presents the fuel efficiency measures applicable to the cement industry ranked by their CCF. The fuel savings and CO_2 emission reduction achieved by each measure is also shown. 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. Table 4 shows the cumulative cost-effective and the total technical potential for energy saving and CO_2 emission reduction from 2010 to 2030 as calculated by the model.

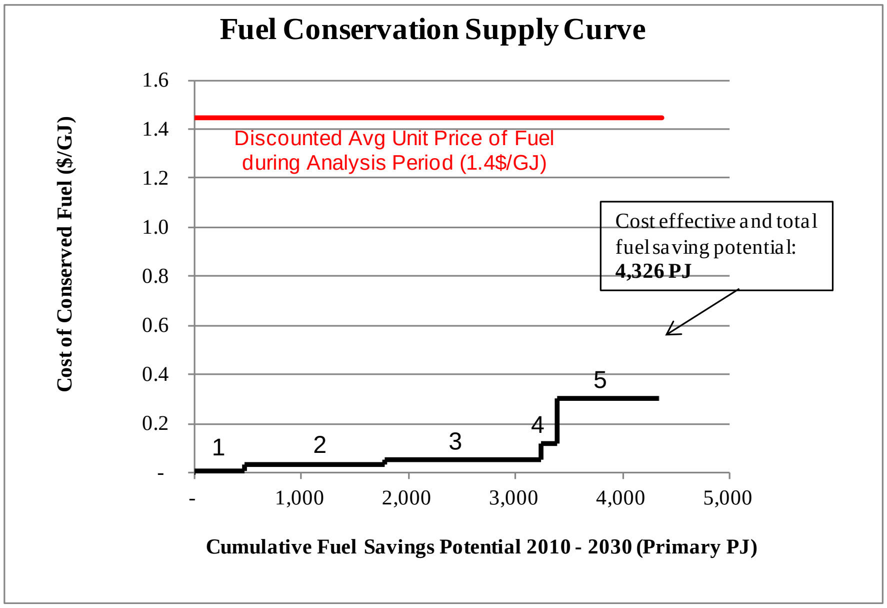


Figure 6. 2010-2030 FCSC for the Cement industry in China

Table 3. Fuel Efficiency Measures for the Cement industry in China Ranked by Cost of Conserved Fuel (CCF)

CCF Rank	Efficiency Measure ***	Fuel Savings (PJ)	Cost of Conserved Fuel (US$/GJ-saved)	CO_2 Emission Reduction (Mton CO_2)
1	Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag) **	458	0.01	44.1*
2	Kiln shell heat loss reduction (Improved refractories)	1,311	0.04	124.0
3	Use of Alternative Fuels	1,467	0.05	138.8
4	Optimize heat recovery/upgrade clinker cooler **	141	0.12	14.6
5	Energy management and process control systems in clinker making **	949	0.30	84.1

* 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.

** 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 saving, this measure is included between fuel saving measures.

*** The descriptions of these measures can be found in Appendix 1.

Table 4. Cost-Effective and Total Technical Potential for Fuel Saving and CO_2 Emission Reduction in the Cement Industry in China during 2010-2030

	Cumulative Fuel Saving Potential (PJ)		Cumulative Carbon Dioxide Emission Reduction ($MtCO_2$)	
	Cost-Effective	Technical	Cost-Effective	Technical
Cumulative saving potentials during 2010-2030	4,326	4,326	406	406

4.2. Electricity Conservation Supply Curve for the Cement Industry

For the cement industry, 17 energy-efficiency measures are included in the ECSC. Figure 7 and Table 5 shows that out of 17 energy-efficiency measures, 10 measures fall below the discounted average unit price of electricity in studied plants during the period of 2010-2030 (29US$/ megawatt-hour, MWh). 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 10 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 other 7 efficiency measures (grey area in Table 5) are technically applicable but they are not cost-effective; thus, their implementation may require financial incentives beyond energy savings alone.

The two most cost-effective measures are installation of high efficiency motors and High efficiency fan for raw mill vent fan with inverter. The largest electricity saving potential is from replacing a ball mill with vertical roller mill in finish grinding (ranked 7 on the curve) and low temperature waste heat recovery power generation, which is saving in purchased electricity by generating electricity from the waste heat onsite (ranked 9 on the curve). Table 6 shows the cumulative cost effective and the total technical potential for electricity saving and CO_2 emission reduction from 2010 to 2030.

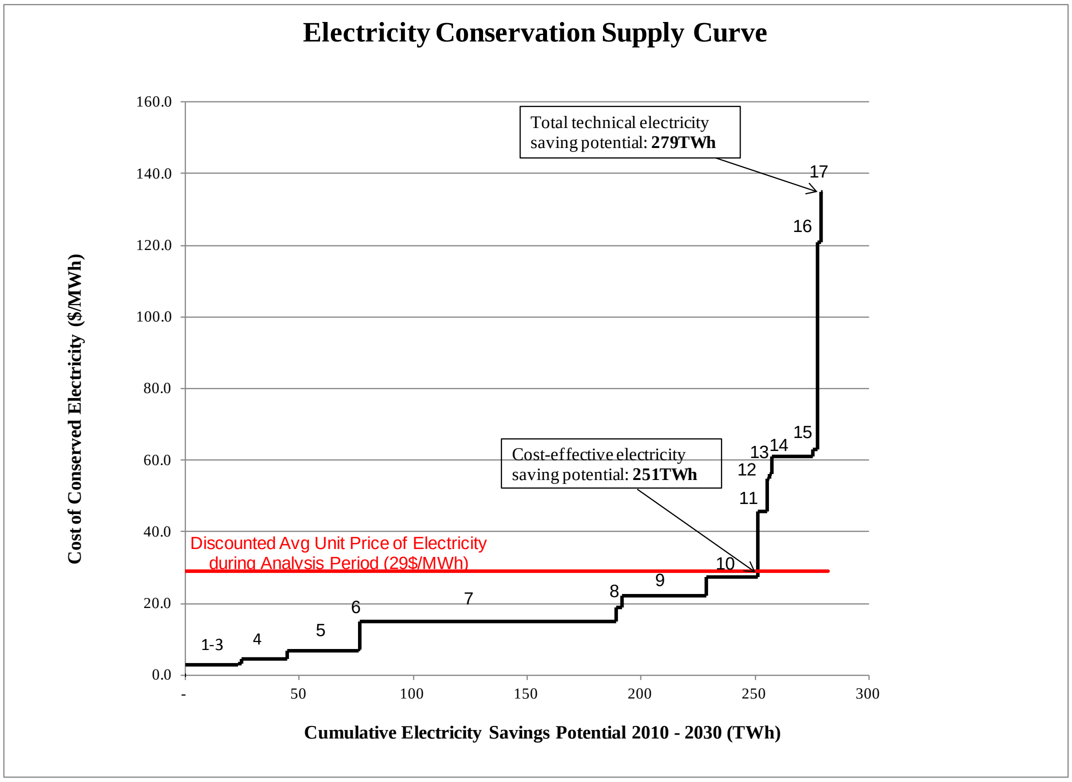


Figure 7. 2010-2030 ECSC for the Cement Industry in China

Table 5. Electricity Efficiency Measures for the Cement industry in China Ranked by Cost of Conserved Electricity (CCE)

CCE Rank	Efficiency Measure*	Electricity Savings (TWh)	Cost of Conserved Electricity (US$/MWh-saved)	CO_2 Emission Reduction (Mton CO_2)
1	Replacement of cement mill vent fan with high efficiency fan	23.1	3.03	12.9
2	High efficiency motors	1.2	3.38	0.7
3	High efficiency fan for raw mill vent fan with inverter	0.2	3.60	0.1
4	Energy management & process control in grinding	20.2	4.63	11.2
5	Adjustable Speed Drives	31.1	7.00	17.7
6	Installation of variable frequency drive & replacement of coal mill bag dust collector’s fan with high efficiency fan	0.7	7.22	0.4
7	Improved grinding media for ball mills	112.5	15.00	61.9
8	Low temperature Waste Heat Recovery power generation	2.4	18.98	1.5
9	Replacing a ball mill with vertical roller mill in finish grinding	36.8	22.14	23.0
10	High pressure roller press as pre-grinding to ball mill in finish grinding	22.9	27.65	14.3
11	High-Efficiency classifiers for finish grinding	3.9	45.69	2.4
12	Replacing a ball mill with vertical roller mill for coal grinding	0.9	54.99	0.5
13	High Efficiency classifiers/separators for raw material grinding	1.4	56.27	0.9
14	Low pressure drop cyclones for suspension preheater	17.5	61.27	10.5
15	Replacing a ball mill with vertical roller mill /High pressure roller presses in raw material grinding	2.4	63.16	1.5
16	Efficient (mechanical) transport system for raw materials preparation	1.2	121.09	0.8
17	Raw meal blending (homogenizing) systems	0.5	135.13	0.3

* The descriptions of these measures can be found in Appendix 1.

Table 6. Cost-Effective and Total Technical Potential for Electricity Saving and CO_2 Emission Reduction in the Cement Industry in China during 2010-2030

	Cumulative Electricity Saving Potential (TWh)		Cumulative Carbon Dioxide Emission Reduction (MtCO2)	
	Cost-effective	Technical	Cost-effective	Technical
Cumulative saving potentials during 2010-2030	251	279	144	161

4.3. Sensitivity Analysis

In the previous sections, the cost-effective and technical energy-efficiency improvement potentials for the cement industry in China were presented and discussed. Since the discount rate used in the analysis in among the parameters that play 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 sensitivity analysis was performed for discount rate and the results are discussed below.

We conducted the sensitivity analysis for the discount rates of 13% and 17% which are very close to the 15% discount rate used in the base case analysis. This was because some plants may use slightly different discount rate than 15% for their investment decision making. Thus, we assess the effect of the minor changes in the discount rate from the base case on the cost-effectiveness of savings. In addition, we conducted the sensitivity analysis for a low discount rate of 5% which represent more societal perspective to see how the cost-effectiveness will change by using a low societal discount rate. Finally, we used a 30% discount rate for the sensitivity analysis which is at the higher end of industry perspective for the discount rate. Because of the various non-monetary barriers such as lack of information, uncertainty about energy efficiency technologies, lower priority, etc. industry often tend to use a higher discount rate which less favor the energy efficiency projects. Conducting the sensitivity analysis using 30% discount rate, we assess the effect of high discount rate on the cost-effectiveness of savings.

Table 7 shows how changes in the discount rate can affect the cost-effective energy-saving potentials and their associated CO_2 emission reduction potentials, keeping constant the other parameters (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 reduction of the discount rate from 15% to 13% will not change the estimated cost-effective electricity and fuel savings. The cost-effective fuel saving will not change by changes in the discount rate in the range of 5 to 30% and it will remains equal to 4,326 PJ. The reason for this is that the total fuel saving potential in Fuel CSC is by far cost-effective and changes in the discount rate in the range of 5 to 30% will not affect its cost effectiveness. The decrease in the discount rate from 15% to 5% increase the cost-effective electricity saving from 251 TWh to 255 TWh, whereas the increase in the discount rate from 15% to 17% and 30% will have the reverse effect and decreases the cost-effective electricity saving.

In general, it should be noted that the cost-effectiveness of the savings may not change by the variation in the discount rate, as the discounted unit price of energy also plays a role in cost-effectiveness. Because in the calculation of discounted unit price of energy (electricity and fuel) used in the CSCs the discount rate plays an important role, changes in the discount rate will affect the discounted unit price of energy. The magnitude of the changes in the cost of conserved energy and the discounted unit price of energy by changing the discount rate will define the change in the cost-effectiveness of the savings. The total technical energy saving and CO_2 emission potentials do not change with the variation of the discount rate.

Table 7. Sensitivity Analysis for the Cost-Effective Electricity and Fuel Saving Potentials and CO_2 Emission Reductions in Chinese Cement Industry during 2010-2030 with Different Discount Rates Keeping Other Parameters Constant

Discount Rate (%)	Electricity		Fuel	
	Cost-effective saving (TWh)	Cost-effective CO_2 emission reduction ($MtCO_2$)	Cost-effective saving (PJ)	Cost-effective CO_2 emission reduction ($MtCO_2$)
d.r. = 5	255	146	4,326	406
d.r. = 13	251	144	4,326	406
d.r. = 15 *	251	144	4,326	406
d.r. = 17	228	129	4,326	406
d.r. = 30	189	105	4,326	406

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

4.4. Scenario Analysis

The above analysis and results are based on the implementation of what we called "international technologies." However, we also obtained information for 8 domestically produced technologies with regards to their energy saving, cost, and the share of implemented technology in Chinese cement plants in the base year (2009) that is domestically produced (see Table 2). Having this information, we developed a scenario in which instead of only implementing the international technologies in 2010-2030, we implement both international and Chinese domestic technologies during the analysis period and calculate the saving and cost of conserved energy accordingly. We used the fix rate for the future implementation of Chinese domestic technologies equal to the share of implemented technology in Chinese cement plants in the base year (2009) that is domestically produced. The rest of application that is not domestically produced is provided by the international technologies.

Table 8 shows the results of the scenario explained above as well as the base case analysis. As can be seen, both cost-effective and technical the energy saving and CO_2 emission reduction achieved in scenario is lower than the ones achieved in the base case analysis. The cumulative CCE and CCF (sum of all measures cost of conserved energy in supply curves) are given in Table 9 as an indicator to show that under the scenario analysis where part of the technologies implemented are Chinese domestic technologies although the capital cost of Chinese technologies are lower than international technologies, the cumulative CCF for the scenario analysis is higher than the base case analysis. This confirms the fact that when making the decision on the choice of technologies, the capital cost should not be the only factor to look, but the amount of energy saving and other factors should also be considered. For the electricity efficiency measures, the cumulative CCE for the scenario analysis is lower than that of in the base case analysis.

Table 8. Cost-Effective and Total Technical Potential for Electricity and Fuel Saving as well as CO_2 Emission Reduction in the Cement Industry in China during 2010-2030 using base case and scenario analysis (discount rate = 15%)

	Cumulative Electricity Saving Potential (TWh)		Cumulative Fuel Saving Potential (PJ)		Cumulative Carbon Dioxide Emission Reduction (MtCO2)	
	Cost-effective	Technical	Cost-effective	Technical	Cost-effective	Technical
Cumulative fuel saving potentials –Base case analysis	-	-	4,326	4,326	406	406
Cumulative fuel saving potentials –Scenario analysis	-	-	*41,85*	*4,220*	*391*	*395*
Cumulative electricity saving potentials –Base case analysis	251	279	-	-	144	161
Cumulative electricity saving potentials – Scenario analysis	*247*	*254*	-	-	*141*	*146*

Table 9. Cumulative CCE and CCF of all measures using base case and scenario analysis

	Base case analysis (with international technology only)	Scenario analysis (with both Chinese and international technology)
Cumulative CCF ($/GJ)	0.5	2.1
Cumulative CCE ($/MWh)	650.2	504.7

4.5. Barriers to the Adoption of Energy-Efficiency Technologies and Measures in the Cement Industry in China

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), 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 has a purchase price of approximately 30 million RMB, compared to the lower purchase price of only 8 million RMB for a less efficient ball mill system. Hence, if plant owners lack sufficient capital in the initial stage of building the plant, they cannot purchase the more efficient vertical mills.

In regards to the production of blended cement, the amount of cement available for blending is limited since preserving the basic properties of cement is a top priority. Currently, Chinese cement standards mandates the maximum amount of each type of supplementary cementitious materials in six categories of cement. For example, the national standard states that less than 20% of each type of supplementary cementitious materials can be blended into common Portland cement. If more than 20% of slag is blended, it will be classified as "slag cement" and if more than 20% of fly ash is blended, it will be classified as “fly ash cement”. If a large amount of supplementary cementitious materials is blended, cement characteristics may change. As a result, slag cement and fly ash cement are not popular in the Chinese market. In addition, concrete batching stations can blend certain amounts of supplementary cementitious materials into purchased common Portland cement in batching concrete to meet certain construction requirements.

The Chinese 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 China already result in resource utilization with higher economic benefits, scrap tires are less likely to be utilized by Chinese cement kilns. Additionally, more research, capacity building, and demonstration is still required for biomass applications in the cement industry.

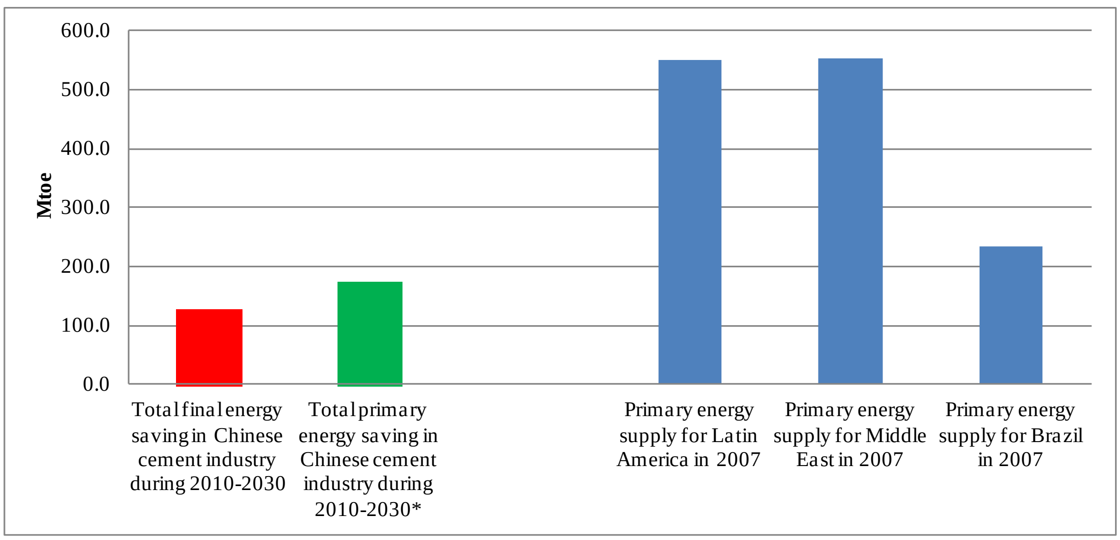
A similar study that investigated barriers to the implementation of cost-effective, energy-efficiency technologies and measures in Thailand (Hasanbeigi, 2009) found the following key barriers:

- **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.

5. Key Findings and Conclusions

Given the importance of the cement industry in China 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 reductions using a bottom-up model. Specifically, bottom-up Energy Conservation Supply Curves (i.e. ECSC and FCSC) were constructed for the Chinese 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 23 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 Chinese cement industry for 2010-2030 are estimated. By comparison, the total technical primary[2] energy saving achieved by the implementation of the studied efficiency measures in the Chinese cement industry over 20 years (2010-2030) is equal to around 32% of total primary energy supply of Latin America or the Middle East or around 74% of primary energy supply of Brazil in 2007 (IEA 2009). Figure 8 shows the comparison of the energy savings from the Chinese cement industry calculated in this study with the total primary energy supply of Latin America, the Middle East, and Brazil in 2007.



*: Mtoe: Million tonne of oil equivalent

Figure 8. Comparison of the calculated energy savings for the Chinese cement industry with the total primary energy supply of Latin America, the Middle East, and Brazil

We also developed a scenario in which instead of only implementing the international technologies in 2010-2030, we implement both international and Chinese domestic technologies during the analysis period and calculate the saving and cost of conserved energy accordingly.

[2] The electricity savings during 2010-2030 is converted to primary energy using the 2010 China's average final to primary electricity conversion factor (2.90).

The results show that both cost-effective and technical cumulative fuel and electricity saving potential for the scenario analysis is lower than the base case analysis in which only international technologies are implemented during the study period (2010-2030).

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, 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 for helping 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 country- and plant-specific conditions. This study shows that in China's case, an efficiency gap remains in the cement industry as many of the identified cost-effective opportunities for energy efficiency improvement still have not been adopted. The persistence of this efficiency gap result from 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

Appendix1. Description of Energy Efficiency Technologies/Measures for the Cement Industry Included in This Study

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.

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. Review of other Studies on Energy Efficiency in the Chinese Cement Industry [3]

In 2002, the World Business Council on Sustainable Development (WBCSD) produced a study of China's cement industry covering the industry's structure, production and technology trends, energy use and emissions, and future opportunities (Soule et al., 2002). At the time of this report, cement production in China was projected to grow relatively slowly (2.8% per year during the 10^{th} Five Year Plan to a total of 660 Mt in 2005, followed by even slower growth of 2.5% per year during the 11^{th} Five Year Plan) with relatively rapid improvement in energy efficiency expected as older facilities were replaced with more modern plants (Soule et al., 2002).

In 2004, the United Nations Industrial Development Organization (UNIDO) published a report on the Chinese cement industry by the Institute of Technical Information for the Building Materials Industry of China (ITIBMIC). This comprehensive report discussed the cement industry's present conditions and developments, the key policies and regulations, the leading cement equipment manufacturers, the main design institutes, energy-saving and emission-reducing technologies, and provided provincial-level reports for Zhejiang, Hubei, and Shandong Provinces (ITIBMIC, 2004).

In 2006, researchers from Tsinghua University and the Center for Clean Air Policy (CCAP) published an assessment of the GHG emissions and mitigation potential for China's cement industry which produced marginal abatement cost curves for 2010, 2015, and 2020 and documented the costs and emissions reductions from the adoption of 12 mitigation options under three scenarios (Tsinghua and CCAP, 2006). CCAP and Tsinghua University are currently collaborating on a project to identify GHG mitigation options and policy recommendations in China's electricity, cement, iron and steel, and aluminum industry sectors. The cement sector work is focused on the identification of emissions mitigation measures in Shandong Province, with a focus on the barriers and opportunities for further implementation of waste heat recovery power generation (Ziwei Mao, 2009).

The China Cement Association (CCA) began publishing an annual review of statistics and information regarding China's cement industry in 2001. Recent versions of the *China Cement Almanac* include numerous articles on energy consumption ("Cement industry energy consumption status quo and energy saving potential"), CO_2 emissions ("On CO_2 emission reduction of Chinese cement industry"), energy-efficiency technologies ("The opportunity is mature for cement industry promoting power generation by pure low temperature remnant heat"), restructuring ("Important moves to develop Chinese cement industry through quality replacing quantity"), and other aspects of China's cement industry (CCA, 2008; CCA, 2009). CCA staff members frequently publish articles and make presentations regarding the current status of China's cement industry (Zeng, 2004; Zeng, 2006; Zeng, 2008).

[3] Most of this section is excerpted from the previous LBNL report, Price et al. (2009).

As part of the Asia Pacific Partnership on Clean Energy and Climate (APP), a team of researchers from NDRC, CCA, the China Digital Cement Network, CBMA, and the Productivity Center of Building Materials Industry surveyed 120 Chinese cement plants in 2006. The surveyed companies accounted for 11% of the total cement production in China that year. The survey covered 187 NSP and 24 VSK kiln cement plants. The study found that outdated processes still dominate the industry, labor productivity is low and there is a large share of low quality products, energy consumption is high and the damage to the environment and the resource base is serious, and cement manufacturing experiences strong competition because of surplus capacity and overlapping markets (Liu et al., 2007).

Chinese researchers at the China Building Materials Academy (CBMA) and ITIBMIC also contribute research results and information related to energy efficiency in the Chinese cement industry. A 2007 article concluded that the keys to reaching the CCA's energy-saving target of a 25% improvement between 2005 and 2010 are adoption of energy-efficient technology, energy management, and especially eliminating backward technology (Wang, S., 2007). CBMA has recently developed a number of codes and standards related to energy efficiency for the Chinese cement industry, including standards on *limitation of energy consumption for unit cement product*, *cement plant design code for energy saving*, *energy consumption auditing for cement production*, and *power measurement equipment for cement manufacturing* (Wang, L., 2009). Recent research has focused on the increased use of alternative fuels in China (Wang, S., 2008) and development of alternative fuel co-processing standards (Wang, L., 2009).

In 2008, the World Wide Fund for Nature (WWF) developed a *Blueprint for a Climate-Friendly Cement Industry* for the Chinese cement industry. The report noted that "the Chinese cement market is the largest single cement market on Earth and the output in a single province is as large as those found for some main developing countries." The report's pathway to a low carbon cement industry includes the following: 1) use cement more efficiently, 2) further expand the use of additives and substitutes to produce blended cements, 3) improve the thermal efficiency of kilns, 4) improve the electrical efficiency of plants, 5) increase the share of biomass in the fuel mix, and 6) develop carbon capture and storage to sequester a high share of CO_2 emissions by 2050 (Müller and Harnish, 2008).

In early 2008, the World Bank's Asia Alternative Energy Unit (ASTAE) initiated a study to assess the current status of cement manufacturing in the three Chinese provinces: Shandong, Hebei, and Jiangsu. The goal of the project was to develop implementation plans and policy recommendations for energy-efficiency improvement in the cement sector at the provincial level.

Phase I of the project focused on data collection in order to characterize the cement sector at the provincial and national levels. This work was undertaken by the China Cement Association's Technology Center (CCATC) and completed in June 2008. The main conclusions of the Phase I effort were that even though China's cement sector is undergoing rapid modernization, inefficient and obsolete production technologies are still used and there are energy-efficiency opportunities available even for the more modern NSP kiln cement plants.

Phase II of the project involved more detailed analysis of the situation regarding both the costs and benefits of the VSK plant closures and the untapped energy-efficiency opportunities for the NSP kiln plants at the provincial level. The VSK plant closure analysis investigated the socio-economic, fiscal, and regulatory implications of implementing the closure of inefficient cement production facilities and recommended policy and regulatory changes/initiatives to address the key issues arising from plant closures. The NSP kiln plant analysis conducted by Lawrence Berkeley national Laboratory in collaboration with China Building Material Academy. In this study by LBNL and CBMA, sixteen cement plants with New Suspension Preheater and pre-calciner (NSP) kiln were surveyed. Plant energy use was compared to both domestic (Chinese) and international best practice using the Benchmarking and Energy Saving Tool for Cement (BEST-Cement). This benchmarking exercise indicated an average technical potential primary energy savings of 12% would be possible if the surveyed plants operated at domestic best practice levels in terms of energy use per ton of cement produced. Average technical potential primary energy savings of 23% would be realized if the plants operated at international best practice levels. Then, using the bottom-up ECSC model, the cost-effective electricity efficiency potential for the 16 studied cement plants in 2008 was estimated to be 373 gigawatt-hours (GWh), and total technical electricity-saving potential was 915 GWh, which accounts for 16 and 40% of total electricity use in the studied plants in 2008, respectively. The FCSC model showed the total technical fuel efficiency potential was equal to 7,949 terajoules (TJ), accounting for 8% of total fuel used in the studied cement plants in 2008. All the fuel efficiency potential was shown to be cost effective. (Hasanbeigi et al. 2010c).

Appendix 3. Time Dependent Key Model Inputs

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Emissions Factors																						
CO_2 Emission factor for grid electricity (tonne CO_2/MWh)	0.82	0.793	0.770	0.746	0.723	0.700	0.676	0.653	0.638	0.624	0.609	0.594	0.580	0.565	0.550	0.535	0.520	0.505	0.492	0.478	0.465	0.451
CO_2 Emission factor for fuel (tonne CO_2/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	94.6
Industry Product Capacity Growth Rate (Change compared to Base Year)																						
Clinker -NSP kilns	-	16%	16%	15%	15%	14%	13%	11%	10%	9%	7%	0%	-10%	-18%	-19%	-21%	-23%	-25%	-27%	-29%	-27%	-33%
Cement -NSP kilns	-	16%	16%	15%	15%	14%	13%	11%	10%	9%	7%	0%	-10%	-18%	-19%	-21%	-23%	-25%	-27%	-29%	-27%	-33%

Source: Fridley et al. (2011); Ke et al. (2012)

Appendix 4. The questionnaire used to collect Chinese data

Questionnaire for China's cement industry

Basic Information of China's cement industry	Kiln Type		References
	NSP kiln	VSK	
Number of cement plants in 2009			

Production data of China's cement industry	Kiln Type		References
	NSP Kilns	VSK	
	2009 (tonne/year)		
Production:			
Clinker Production **Capacity**			
Cement Production **Capacity**			
Actual Clinker Production			
Actual Cement Production			
Trade:			
Clinker export to other countries			
Clinker import to China			
Cement export to other countries			
Cement import to China			

Production of cement by the cement type in China	Kiln Type		References
	NSP Kilns	VSK	
	2009 (tonne/year)		
Cement Type:			
Pure Portland Cement			
Common Portland Cement			
Slag Cement			
Pozzolana Cement			
Fly Ash Cement			
Blended Cement			
Others			
Add Row as Necessary			
Total	*0*	*0*	

Energy consumption in cement industry in China

	2009 Quantity	Units	Heating Value	Heating Value Units	References
Fuel Comsumption:					
Coal					
Other (Please Specify)					
Add Row as Necessary					

	2009 Quantity	References
Electricity Comsumption:		
Purchased Electricity (MWh)		
Electricity Generated Onsite (MWh)		
Total Electricity used in Cement industry (MWh)	*0*	

	2009 Quantity	Units	Heating Value	Heating Value Units	References
Fuel used to Generate Electricity onsite (Do not include the electricity generated in cement plants from waste hear recovery)					
Coal					
Other (Please Specify)					
Add Row as Necessary					

	2009 Quantity	Units	References
Energy Price:			
Average coal price (if you have the coal price by province and cement production by province, then you can calculate the national weighted average coal price)			
Average electricity price			
Other (Please Specify)			
Add Row as Necessary			

			Typical Chinese Domestic Technology		
No.	Energy-Efficiency Measures / Technologies	Measure Description	Typical electricity saving	Typical fuel saving	References
	Fuel Preparation:		kWh / tonne coal		
1	**Replacing a ball mill with vertical roller mill for coal grinding**	Energy saved by vertical roller mill compared to the ball mill			
2	**High efficiency drive and fan system in coal grinding mill**	Energy saved by installing high efficiency drive and fan for the fan system of the coal grinding mill			
	Raw Materials Preparation		kWh / tonne clinker		
3	**High Efficiency classifiers/separators for raw material grinding**	Energy saved by high effiicency classifier compared to conventional classifiers. Conventional classifiers may have low separation efficiency, leading to the recycling of fine particles and resulting in to extra power use in the grinding mill.			
4	**Replacing a ball mill with vertical roller mill /High pressure roller presses**	Energy saved by vertical roller mill/High pressure roller presses compared to the ball mill			
5	**Efficient (mechanical) transport system for raw materials preparation**	Energy saved by Mechanical conveyor compared in the raw material preparation process.			
6	**Raw meal blending (homogenizing) systems**	Energy saved by Gravity-type homogenizing system compared to mechanical system for homogenizing.			
7	**High efficiency drive and fan system in raw material grinding mill**	Energy saved by installing high efficiency drive and fan for the fan system of the raw material grinding mill			
	Clinker Making		kWh / tonne clinker	kgce / tonne clinker	
8	**Reducing heat loss of kiln system (Improved refractories)**	The use of better insulating refractories (for example Lytherm) can reduce heat losses in rotary kiln system. Here we need the energy saving by energy efficient refractory compared to the conventional refractory.			
9	**Energy management and process control systems in clinker making**	Automated computer control systems may help to optimize the combustion process and process conditions. Most modern systems use so-called 'fuzzy logic' or expert control, or rule-based control strategies. Here we need the energy saved by installation of this system compared to the pre-installation situation.			
10	**Optimize heat recovery/upgrade clinker cooler**	In the grate cooler, heat recovery can be improved through reduction of excess air volume, control of clinker bed depth and new grates such as ring grates. Here we need the energy saving achived after the improvement of the grate cooler.			
11	**Pure Low temperature Waste Heat Recovery power generation**	Power generation from the waste heat. Her ewe need the electricity produced per tonne of clinker production (kWh/tonne clinker)			
12	**Upgrading of a dry kiln to a Preheater/Precalciner Kiln**	The energy saving achived by ubgrading a dry kiln to Preheater/Precalciner Kiln.			
13	**Upgrading of a Preheater kiln to a Preheater/Precalciner Kiln**	The energy saving achived by ubgrading a preheater kiln to Preheater/Precalciner Kiln.			
14	**Low pressure drop cyclones for suspension preheater**	The energy saving achived by installation of newer cyclones in a plant with lower pressure losses.			
	Finish Grinding		kWh/tonne cement		
15	**Energy management & process control in grinding**	This is the automated computer expert control systems. The systems control the flow in the mill and classifiers, attaining a stable and high quality product resulting to the energy saving too. Here we need the energy saved by installation of this system compared to the pre-installation situation.			
16	**Replacing a ball mill with vertical roller mill**	Energy saved by vertical roller mill compared to the ball mill			
17	**High pressure roller press as pre-grinding to ball mill**	Energy saved by installation of High pressure roller press as pre-grinding to ball mill compared to the ball mill alone			
18	**Improved grinding media for ball mills**	Grinding media are usually selected according to the wear characteristics of the material. Increases in the ball charge distribution and surface hardness of grinding media and wear resistant mill linings have shown a 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. Here we need the energy saved after these improvements.			
19	**High-Efficiency classifiers for finish grinding**	Energy saved by high effiicency classifier compared to conventional classifiers. Conventional classifiers may have low separation efficiency, leading to the recycling of fine particles and resulting in to extra power use in the grinding mill.			
20	**High efficiency drive and fan system in finish grinding mill**	Energy saved by installing high efficiency drive and fan for the fan system of the finis grinding mill			
	General measures		kWh/tonne cement		
21	**High efficiency motors**	Total energy saving achieved by replacing the standard motors larger than 10 kW with energy efficient motors in a cement plant.			
22	**Adjustable Speed Drives**	Total energy saving achieved by installation of VSD on the motors that have variable loads.			
	Product Change		kWh/tonne cement	kgce / tonne clinker	
23	**Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag)**	Average energy saving achieved by the production of these types of cement compared to the Pure Portland Cement or Common Portland Cement in China.			

					Domestic technology (all values should be in base year 2009 currency)			
No.	Energy-Efficiency Measures / Technologies	Adoption rate in Chinese cement industry as % of total Clinker production	Is the technology produced domestically in China? (Yes or No)	Share of implemented technology in Chinese cement industry that is domestically produced	Cost Units	Equipment cost	Installation cost (civil, engineering, and other costs)	Total Ave. Investment Cost (full cost of project)
	Fuel Preparation:							
1	**Replacing a ball mill with vertical roller mill for coal grinding**							0
2	**High efficiency drive and fan system in coal grinding mill**							0
	Raw Materials Preparation							
3	**High Efficiency classifiers/separators for raw material grinding**							0
4	**Replacing a ball mill with vertical roller mill /High pressure roller presses**							0
5	**Efficient (mechanical) transport system for raw materials preparation**							0
6	**Raw meal blending (homogenizing) systems**							0
7	**High efficiency drive and fan system in raw material grinding mill**							0
	Clinker Making							
8	**Kiln shell heat loss reduction (Improved refractories)**							0
9	**Energy management and process control systems in clinker making**							0
10	**Optimize heat recovery/upgrade clinker cooler**							0
11	**Low temperature Waste Heat Recovery power generation**							0
12	**Upgrading of a dry kiln to a Preheater/Precalciner Kiln**							0
13	**Upgrading of a Preheater kiln to a Preheater/Precalciner Kiln**							0
14	**Low pressure drop cyclones for suspension preheater**							0
	Finish Grinding							
15	**Energy management & process control in grinding**							0
16	**Replacing a ball mill with vertical roller mill**							0
17	**High pressure roller press as pre-grinding to ball mill**							0
18	**Improved grinding media for ball mills**							0
19	**High-Efficiency classifiers for finish grinding**							0
20	**High efficiency drive and fan system in finish grinding mill**							0
	General measures							
21	**High efficiency motors**							0
22	**Adjustable Speed Drives**							0
	Product Change							
23	**Blended cement (Additives: fly ash, pozzolans, limestone or/and blast furnace slag)**							0