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Analysis of Energy-Efficiency Opportunities for the Cement Industry in Shandong Province, China

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Disclaimer

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ABSTRACT

China's cement industry, which produced 1,388 million metric tons (Mt) of cement in 2008, accounts for almost half of the world's total cement production. Nearly 40% of China's cement production is from relatively obsolete vertical shaft kiln (VSK) cement plants, with the remainder from more modern rotary kiln cement plants, including plants equipped with new suspension pre-heater and pre-calciner (NSP) kilns. Shandong Province is the largest cement-producing Province in China, producing 10% of China's total cement output in 2008. This report documents an analysis of the potential to improve the energy efficiency of NSP kiln cement plants in Shandong Province. Sixteen NSP kiln cement plants were surveyed regarding their cement production, energy consumption, and current adoption of 34 energy-efficient technologies and measures. 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. Energy conservation supply curves for both fuel and electricity savings were then constructed for the 16 surveyed plants. Using the bottom-up electricity conservation supply curve model, the cost-effective electricity efficiency potential for the studied cement plants in 2008 is estimated to be 373 gigawatt-hours (GWh), which accounts for 16% of total electricity use in the 16 surveyed cement plants in 2008. Total technical electricity-saving potential is 915 GWh, which accounts for 40% of total electricity use in the studied plants in 2008. The fuel conservation supply curve model shows the total technical fuel efficiency potential 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 is shown to be cost effective. Carbon dioxide (CO_2) emission reduction potential associated with cost-effective electricity saving is 383 kiloton (kt) CO_2, while total technical potential for CO_2 emission reduction from electricity-saving is 940 ktCO_2. The CO_2 emission reduction potentials associated with fuel-saving potentials is 950 ktCO_2.

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Executive Summary

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China's cement industry, which produced 1,388 million metric tons (Mt) of cement in 2008, accounts for almost half of the world's total cement production. Nearly 40% of China's cement production is from relatively obsolete vertical shaft kiln (VSK) cement plants, with the remainder from more modern rotary kiln cement plants, including plants equipped with new suspension pre-heater and pre-calciner (NSP) kilns.

Shandong Province is the largest cement-producing Province in China, producing 10% of China's total cement output in 2008. The average annual growth rate (AAGR) of cement production in Shandong Province between 2000 and 2008 was 10%. This growth was dominated by the increase in rotary kiln production, which was mostly due to the increased share of NSP kilns. Production from rotary kilns grew from 11% of total cement production in 2000 to 58% in 2008.

This report documents an analysis of the potential to improve the energy efficiency of NSP kiln cement plants in Shandong Province. Sixteen NSP kiln cement plants were surveyed regarding their cement production, energy consumption, and current adoption of 34 energy-efficient technologies and measures.

The 16 surveyed cement plants were compared to both domestic (Chinese) and international best practice in terms of energy efficiency using the Benchmarking and Energy Saving Tool for Cement (BEST-Cement) developed by Lawrence Berkeley National Laboratory in collaboration with the Energy Research Institute, the China Building Materials Academy, and the China Cement Association. Such a comparison provides an initial assessment of the technical potential for energy-efficiency improvement by comparing a plant to an identical model of itself using the most energy-efficient technologies and measures available. 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.

An energy conservation supply curve is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. Energy conservation supply curves

for both fuel and electricity savings were constructed for the 16 surveyed plants to determine the potentials and costs of energy-efficiency improvements by taking into account the costs and energy savings of 34 different technologies that could be used in the plants. Using the bottom-up electricity conservation supply curve model, the cost-effective electricity efficiency potential for the studied cement plants in 2008 is estimated to be 373 gigawatt-hours (GWh), which accounts for 16% of total electricity use in the 16 surveyed cement plants in 2008. Total technical electricity-saving potential is 915 GWh, which accounts for 40% of total electricity use in the studied plants in 2008. Carbon dioxide (CO_2) emission reduction potential associated with cost-effective electricity saving is 383 kiloton (kt) CO_2, while total technical potential for CO_2 emission reduction is 940 ktCO_2. The fuel conservation supply curve model shows the total technical fuel efficiency potential 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 is shown to be cost effective. The CO_2 emission reduction potential associated with fuel saving potentials is 950 ktCO_2.

This study identified a number of cost-effective energy-efficiency technologies and measures that have not been fully adopted in the 16 surveyed cement plants in Shandong Province. In addition, a few energy-efficiency technologies and measures that are not cost-effective, but that are very close to being cost-effective at the current price of energy, and that have large energy savings were also identified. These technologies and measures and their potential energy-savings in Shandong Province are listed in Table ES-1.

Thirteen cost-effective electricity-saving technologies and measures that have not been fully adopted are all related to improving the efficiency of motors and fans, fuel preparation, and finish grinding. In addition, two finish grinding options (replacing a ball mill with a vertical roller mill and using a high pressure roller press for pre-grinding for a ball mill) have large electricity-saving potential and were nearly cost-effective. In addition, six cost-effective fuel-saving technologies and measures were identified that have not been fully adopted in the 16 surveyed cement plants, including expanding the use of blended and Limestone Portland cement and using alternative fuels in the cement kiln.

There are various reasons cited by cement plant personnel and Chinese cement experts regarding why the plants have not adopted the cost-effective energy-efficient technologies and measures. Some of the common reasons are 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, plant-specific operational conditions (e.g., in one of the studied plants, due to the low cooling performance of the grate cooler, fans are on full speed so installing a VFD in the cooler fan of grate cooler is not possible), investors preferences, and high initial capital costs despite the fact that the payback period of the technology is short.

Table ES-1. Cost-Effective Energy-Efficient Technologies and Measures Not Fully Adopted in the 16 Surveyed Cement Plants in Shandong Province

Electricity-Saving Technologies and Measures	Electricity Saving Potential (GWh)	CO2 Emission Reduction Potential (kt CO_2)
Motor and Fans		
Adjustable Speed Drives	147.85	151.99
Adjustable speed drive for kiln fan	26.68	27.43
High efficiency motors	52.97	54.45
Variable Frequency Drive (VFD) in raw mill vent fan	6.12	6.29
Variable Frequency Drive in cooler fan of grate cooler	1.83	1.88
Installation of Variable Frequency Drive & replacement of coal mill bag dust collector's fan	1.53	1.57
Replacement of Cement Mill vent fan with high efficiency fan	1.37	1.41
High efficiency fan for raw mill vent fan with inverter	7.23	7.44
Replacement of Preheater fan with high efficiency fan	4.97	5.11
Fuel Preparation		
Efficient coal separator for fuel preparation	2.20	2.26
Efficient roller mills for coal grinding	17.18	17.66
Finish Grinding		
Energy management & process control in grinding	34.98	35.96
Improved grinding media for ball mills	11.72	12.04
Replacing a ball mill with vertical roller mill	68.46	70.38
High pressure roller press as pre-grinding to ball mill	181.20	186.27
Power Generation		
Low temperature waste heat recovery power generation	56.06	57.63
Fuel-Saving Technologies and Measures	**Fuel Savings (TJ)**	**CO2 Emission Reduction Potential (kt CO_2)**
Blended cement (Additives: fly ash, pozzolans, and blast furnace slag)	2,011	378.1 [a]
Limestone Portland cement	105	20.3 [a]
Kiln shell heat loss reduction (Improved refractories)	2,177	206.0
Use of alternative fuels	1,749	165.4
Optimize heat recovery/upgrade clinker cooler	231	22.0
Energy management and process control systems in clinker making	1,676	157.8

Note: measures shaded in grey are not cost-effective, but are very close to being cost-effective and have high energy savings

[a]: CO_2 emission reduction from reduced energy use as well as reduced calcination in clinker making process.

Based on the findings of this report, it is recommended that the BEST-Cement tool be further utilized by the 16 surveyed cement plants. The findings presented in this study indicate that there are a number of cost-effective energy-efficiency technologies and measures that can still be implemented in these plants. Now that the input data has been acquired and entered into BEST-Cement for each plant, the tool is ready for application at the plant-level. Such application involves working with the plant engineers to identify packages of energy-efficiency technologies and measures that they would like to install at the plant. BEST-Cement allows the plant engineers to develop various packages and provides them with information on the individual measure and total package implementation costs, O&M costs, energy savings, simple payback time, and CO_2 emissions reductions. Such packages can be developed in order to meet a specific energy-saving or CO_2 emissions reduction target or to meet a specific energy-saving financial budget.

It is also recommended that further research related to the implementation barriers for the identified cost-effective technologies and measures be undertaken. Now that a number of cost-effective technologies and measures have been identified, it is important to understand why they haven't been adopted by the 16 surveyed cement plants. An understanding of the barriers is an important first step in developing programs and policies to promote further implementation of energy-efficiency opportunities.

Finally, once the barriers have been identified and are understood, it is important to develop effective programs and policies to overcome the barriers to adoption. Such programs and policies could include development of energy-efficiency information resources, technical assistance in identifying and implementing energy-efficiency measures, and financing programs for the identified technologies and measures.

Analysis of Energy-Efficiency Opportunities for the Cement Industry in Shandong Province, China

Table of Contents

I. Introduction

China's cement industry, which produced 1,388 million metric tons (Mt) of cement in 2008, accounts for nearly half of the world's total cement production (Shandong ETC and CBMA, 2009; USGS, 2009). Nearly 40% of China's cement production is from relatively obsolete vertical shaft kiln (VSK) cement plants, with the remainder from more modern rotary kiln cement plants, including plants equipped with new suspension pre-heater and pre-calciner (NSP) kilns. Official Chinese government policy is that the VSK cement plants will be phased out and completely replaced by more modern kilns (NDRC, 2006). Figure 1 and Table 1 show that cement production from rotary kilns has grown rapidly in recent years, jumping from 116 Mt in 2000 to 833 Mt in 2008 (ITIBMIC 2004; Kong, 2009).

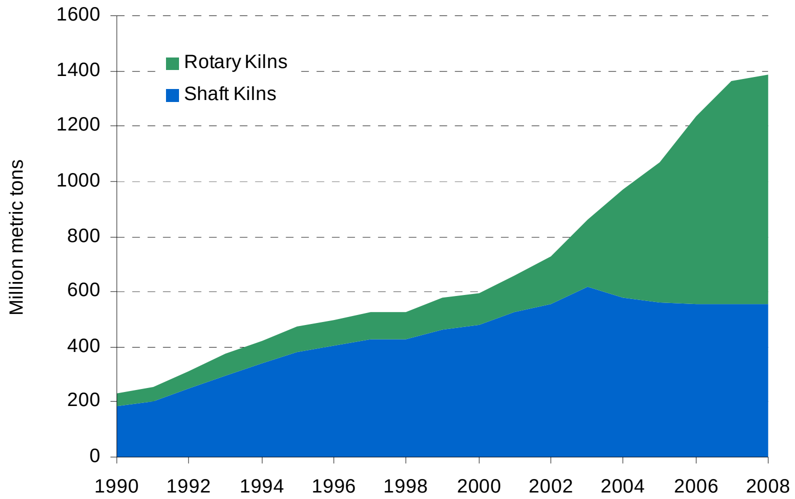

Figure 1. Cement Production in China by Major Kiln Type, 1990-2008 (ITIBMIC 2004; Kong, 2009)

Table 1. Cement Production in China by Major Kiln Type, 1990-2008 (Mt)

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008
Shaft Kilns	183	383	481	528	555	616	578	561	552	554	555
Rotary Kilns	49	93	116	133	170	246	395	508	684	807	833
Total	232	476	597	661	725	862	973	1069	1236	1361	1388

Source: ITIBMIC 2004; Kong, 2009

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 involves 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 will investigate the socio-economic, fiscal, and regulatory implications of implementing the closure of inefficient cement production facilities and will recommend policy and regulatory changes/initiatives to address the key issues arising from plant closures. The NSP kiln plant analysis will evaluate selected representative cement plants in each province in order to identify specific energy-efficiency technology options and evaluate their energy savings and associated costs to improve the energy efficiency of cement production by these facilities. The analysis includes an estimate of the provincial level energy-efficiency improvement opportunity for NSP plants and analysis of the net energy savings of replacing VSK plants by modern NSP plants in view of provincial plans for plant closure.

The Phase II work also aims to develop provincial-level policy recommendations for the cement sector based on broader analysis of sector issues, including the phasing out of inefficient production capacities. The main objective of the proposed ASTAE project is to form a sector assistance strategy for the World Bank to capture the large energy savings achievable in the cement industry of China.

This report provides the results of the NSP kiln cement plant analysis for Shandong Province. It begins with a brief introduction to the cement industry in China, followed by a characterization of the cement industry in Shandong Province. Next, the methodology for the study is presented including a description of the data collection efforts, the use of the Benchmarking and Energy Saving Tool for the Chinese cement industry (BEST-Cement), and the construction of energy-conservation supply curves for NSP kilns in Shandong Province. The results of the BEST-Cement analysis are presented in the next section, followed by a description of the energy-conservation supply curve analysis. The report concludes with identification of key energy-efficiency technologies and measures that can be implemented in NSP kiln cement plants in Shandong Province along with recommendations for capturing the identified opportunities through policies, programs, and financing efforts.

II. Overview of Cement Industry in China and Shandong Province

A. Cement Industry in China

China produces nearly half of the world's cement using myriad types of cement kilns of diverse vintages and levels of technological advancement. In 2008, China produced 1,388 million metric tons (Mt) of cement (Shandong ETC and CBMA, 2009), far surpassing the next two largest producers: India (175 Mt) and the U.S. (89 Mt) (USGS, 2009). In China, there are basically two types of cement kilns used for the production of clinker, the key ingredient in cement: vertical shaft kilns (VSKs) and rotary kilns (see Figures 2 and 3).

Figure 2. Vertical Shaft Kilns in Shandong Province

Figure 3. Rotary Kilns in Shandong Province

VSKs are basically a large drum set 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 pre-calciners 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., 2008).

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, 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).

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 10th Five Year Plan to a total of 660 Mt in 2005, followed by even slower growth of 2.5% per year during the 11th 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).

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, 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, 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, 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).

B. Cement Production in Shandong Province

Shandong Province is the largest cement-producing Province in China, producing 10% of China's total cement output in 2007 (CCA, 2009). Table 2 provides information on cement and clinker production levels in Shandong Province from 2000 to 2008. The average annual growth rate (AAGR) of cement production in Shandong Province between 2000 and 2008 was 10%. This growth was dominated by the increase in rotary kiln production, which was mostly due to the increased share of NSP kilns. Production from rotary kilns increased at an average of 36% per year since 2000, growing from 11% of total cement production in 2000 to 58% in 2008. Clinker production in Shandong Province in 2008 was 88 Mt; thus, the provincial level clinker-to-cement ratio was 0.63 that year.

Table 2. Cement and Clinker Production in Shandong Province, 2000-2007

	2000	2001	2002	2003	2004	2005	2006	2007	2008	AAGR 2000-08
Cement Production (Mt)	66	69	82.5	93	124	142	167	149	139	10%
Vertical Shaft kilns (Mt)	59	63	74	78	93	97	104	77	58	0%
Rotary (NSP + other) kilns (Mt)	7	6	8.5	15	31	45	63	72	81	36%
Clinker Production (Mt)							108	96	88	
Clinker-Cement Ratio							0.65	0.64	0.63	

Sources: Shandong ETC and CBMA, 2009; CCA, 2009; Liao, 2007; Liao, 2008a; Wang, F., 2008; Diao, 2009. Note: expert judgment used when conflicting values were presented by different sources.

Shandong Province is also a large cement-exporting Province. Table 3 shows that over 20% of the clinker and cement exported from China in 2007 was produced in Shandong Province (CCA, 2008; CCA, 2009).

Table 3. China and Shandong Province Exports of Cement and Clinker

	Cement Exports (Mt)		Clinker Exports (Mt)	
	China	Shandong	China	Shandong
2001	6.11		0.10	
2002	5.09		0.09	
2003	4.95		0.38	
2004	6.02		1.03	
2005	11.37	5.07	10.78	3.08
2006	19.41	6.23	16.72	4.85
2007	15.19	4.74	17.81	5.90

Source: CCA, 2008; CCA, 2009.

Cement enterprises in Shandong Province are found in 17 prefecture-level cities, with the highest concentration in Zaozhuang, Zibo, Jinan, Yantan, Tai'an, Linyi, and Weifang. Over a quarter of the cement capacity in Shandong Province is in Zaozhuang (Shandong ETC and CBMA, 2009).

During the 10th Five-Year Plan (2000-2005), construction of modern cement plants using new suspension preheater/precalciner (NSP) technology was promoted and there was a goal of reaching 40% of cement production capacity from NSP kilns by the end of the FYP. In 2000, 310 outdated small cement production lines were either banned or closed in Shandong Province, eliminating 8.6 Mt of capacity using backward cement production technologies (Shandong ETC and CBMA, 2009).

In 2006, there were 980 VSK production lines and 61 rotary kiln production lines in operation in Shandong Province (CCATC, 2008). Of the 61 rotary kilns production lines, 52 had NSP kilns. These kilns produced 43 Mt of clinker and 61 Mt of cement. Table 4 provides a breakdown of the types of cement plants and their clinker and cement production in 2006 (CCATC, 2008).

Table 4. Breakdown of 2006 Clinker and Cement Production by Kiln Type in Shandong Province

	# Factories (Production Lines)	**Clinker Production (Mt)**	**Clinker to Cement Ratio**	**Cement Production (Mt)**
Vertical Shaft Kiln – Mechanical	979	68.6	0.66	104
Vertical Shaft Kiln – Improved	1	0.14	0.88	0.2
Rotary Kiln – Shaft Pre-heater	1	0.07	0.65	0.1
Rotary Kiln – Cyclone Pre-heater	1	0.30	0.67	0.4
Rotary Kiln – NSP	52	42.9	0.70	61.3
Rotary Kiln – Wet	7	0.88	0.75	1.2
Exported Clinker	--	4.85	--	--
Total	**1,041**	108	0.65	167

Source: CCATC, 2008 (with LBNL analysis).

C. Energy Consumption of Shandong Province Cement Industry

Cement production in Shandong Province consumed 15.72 million tons of coal equivalent (Mtce) in 2006 (CCA, 2008). Table 5 provides information on the energy use of the various types of cement kilns found in Shandong Province in 2006 based on the detailed survey undertaken by the China Cement Association Technology Center (CCCATC, 2008).

From this table, it is clear that VSK cement plants are more energy-intensive than NSP kiln cement plants. Roughly 90% of the final energy and 70% of the primary energy consumed in cement manufacturing is fuel combusted in the kiln, with the remainder used to power motors, conveyers, and other equipment with electricity. In Shandong Province, the average fuel intensity for mechanical VSKs was 148 kilograms of coal equivalent/ton (kgce/t) clinker,[1] compared to a range of 101-103 kgce/t clinker for NSP kilns of 2000 tons per day (tpd) capacity or larger in 2006. Electricity intensities for the two types of kilns are similar: 96 kilowatt-hours/t (kWh/t) cement for mechanical VSKs and 94-111 kWh/t cement for NSP kilns. Thus, manufacturing a ton of clinker using an NSP kiln of more than 2000 tpd capacity will save about 45 kgce/t clinker compared to manufacturing the same ton of clinker using a VSK. If all of the cement produced in Shandong Province by VSKs in 2006 had instead been produced by NSP kiln cement plants of at least 2000 tpd capacity, the fuel savings would have been 3.07 Mtce, a reduction of 22% below the actual fuel used that year.

[1] Recent survey data for four VSKs in Shandong Province showed a range from 115 to 171 kgce/t clinker (Jai, 2009).

Table 5. Energy Consumption by Kiln Type in Shandong Province, 2006.

	Fuel Intensity (kgce/t clinker)	Electricity Intensity (kWh/t cement)	Fuel Use (Mtce)	Electricity Use (TWh)	Final Energy (Mtce)	Primary Energy (Mtce)
Vertical Shaft Kiln – Mechanical	148	96	10.15	9.98	11.38	14.18
Vertical Shaft Kiln – Improved	112	75	0.02	0.01	0.02	0.02
Rotary Kiln – Shaft Pre-heater	149	121	0.01	0.01	0.01	0.02
Rotary Kiln – Cyclone Pre-heater	141	119	0.04	0.05	0.05	0.06
Rotary Kiln – NSP ≤ 2000 tpd w/o WHR	114	111	0.55	0.75	0.64	0.85
Rotary Kiln – NSP 2000-4000 tpd w/o WHR	103	96	1.81	2.42	2.11	2.79
Rotary Kiln – NSP 4000-6000 tpd w/o WHR	102	95	1.22	1.63	1.42	1.88
Rotary Kiln – NSP ≥ 6000 tpd w/o WHR	101	94	0.17	0.23	0.20	0.27
Rotary Kiln – NSP 2000-4000 tpd w/WHR	103	97	0.43	0.57	0.50	0.66
Rotary Kiln – NSP 4000-6000 tpd w/WHR	103	97	0.27	0.37	0.32	0.42
Rotary Kiln – Wet	195	114	0.17	0.13	0.19	0.23
Total			**14.84**	**16.16**	**16.83**	**21.37**

Source: CCATC, 2008.

Notes: tpd = tons per day; WHR = Waste Heat Recovery (for power generation); Electricity converted to final energy using a conversion factor of 0.0001229 kWh/ton coal equivalent (tce); electricity converted to primary energy using a conversion factor of 0.000404 kWh/tce.

III. Methodology

A. Data Collection

Phase I of this 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 results of CCATC's data collection for Shandong Province are used in this report to provide an overview of the cement industry in Shandong Province in 2006 (CCATC, 2008).

Phase II of this project focuses on characterizing the energy use and energy-efficiency potential of 16 NSP cement plants in Shandong Province. Detailed data collection forms were developed and used to collect information on cement production and energy use from the 16 surveyed cement plants. These forms requested specific information on the number of production lines at the plant, their age, their clinker and cement-making capacity, their actual clinker and cement production levels in 2007 and 2008, energy used at the facility for clinker and cement production, raw materials and additives used, costs of materials and energy, technologies implemented, recent energy-efficiency upgrades, and current energy-efficiency upgrade plans. In addition, the forms requested information on whether the facilities had adopted any of 32 energy-efficiency measures and, if the measure had not been adopted, the reason. A copy of the detailed data collection form is provided in Appendix A.

The Phase II project team is comprised of Lynn Price, Zhou Nan, and Lu Hongyou of Lawrence Berkeley National Laboratory (LBNL), Wang Lan of the China Building Materials Academy (CBMA), Diao Lizhang of the Shandong Energy Conservation Association, and Ali Hasanbeigi, a consultant to the World Bank.[2] Most members of the Phase II project team conducted on-site surveys of two cement plants on March 13, 2009. Wang Lan and Diao Lizhang conducted surveys of the remaining cement plants during the week of March 16, 2009. The responses to the data collection surveys were then reviewed by the Phase II project team members and additional clarifying questions were compiled due to missing or unclear responses from some of the cement plants. Wang Lan and Diao Lizhang returned to the cement plants during the end of May, 2009 to finalize the data collection. In addition to the detailed data collection for the 16 cement plants, the Shandong Energy Conservation Association also provided summary data for an additional 19 NSP cement plants.

There were some issues and difficulties regarding the data collection. In some cases, the plants did not have or did not provide answers to all of the questions on the survey. Some data was provided in different units or formats from that requested in the survey. In the portion of the survey in which the plants were requested to indicate whether they had implemented the list of energy-efficiency technologies and measures, some plants either did not understand the question or were unfamiliar with the energy-efficiency measure. Even though clarifying questions were asked of the cement plants, there were still situations where assumptions had to be made regarding data (average values per unit of production for the other plants were then used) or implementation of measures. The Chinese cement experts were consulted regarding these assumptions and were helpful in resolving them in a manner in which it is expected that they do not significantly impact the results or the reliability of the overall assessment.

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[2] Ali Hasanbeigi was hired by LBNL as a Post Doctoral Fellow in August 2009.

B. Conversion Factors and Assumptions

To convert electricity to primary energy, the conversion factor of 3.11 is used that is equivalent to China's national average efficiency of thermal power generation of 32.15% in 2008, including transmission and distribution losses[3] (NBS, 2008; Anhua and Xingshu, 2006; Kahrl and Roland-Holst, 2006). Low Heating Value (LHV) of the fuel is used in the analysis. However, since the heating value of different kinds of coal varies, it was not proper to use the IPCC factors. Thus, the average of the heating values given specifically by each plant for the coal they consumed in 2008 was used.

Costs are reported in Chinese Renminbi (RMB) and U.S. dollars. To convert the costs from US$ to RMB, the conversion factor of 6.84 RMB/US$ is used (BOC 2009). Energy savings are expressed in Standard International units (SI) and coal equivalents, which are energy units commonly used in China.

Carbon dioxide (CO_2) emissions are expressed in kilotonnes of CO_2. The carbon conversion factors 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 1.028 kg CO_2/kWh which is the Combined Margin factor based on Project Design Documents (PDDs) of a Clean Development Mechanism (CDM) project implemented in a cement plant in the Jinan city of Shandong Province in 2008 (UNFCCC, 2008).

The unit price of electricity and fuels used in each cement plant is provided in the plant survey responses. The average unit price of electricity paid by the studied cement plants in 2008 is used as the electricity price in electricity conservation supply curve. For fuels however, since the small amount of diesel used in some of the plants is negligible compared to coal consumption, the diesel price was not taken into account. Thus, the average unit price of coal consumed in studied cement plants in 2008 is used as the fuel price in the fuel conservation supply curve.

An important issue is the grid emission factor in the future. Whether electricity is more or less carbon intensive will affect the CO_2 emission reduction potential in the future. Similarly, the future fuel mix used in the cement industry and its emission factor will also affect the CO_2 emission reduction potential in the future.

[3] China's national average efficiency of thermal power plants: 34.78% (NBS, 2008), and China's electricity transmission and distribution losses: 7.55% (Anhua and Xingshu, 2006; Kahrl and Roland-Holst, 2006).

C. Benchmarking and Energy-Saving Tool for Cement (BEST-Cement) for China[4]

Benchmarking

Benchmarking is a commonly-used term that generally means comparing a defined characteristic of one facility to other facilities or other "benchmarks". In the context of this study, benchmarking focuses on energy consumption in a cement plant. Instead of comparing the level of energy consumption in the cement plant to other cement plants which might have different configurations, use different raw materials, and produce different types of cement, this study compares a cement facility to an identical hypothetical cement facility that uses commercially-available "best practice" technologies for each major manufacturing process.

BEST-Cement for China

The Benchmarking and Energy Savings Tool (BEST) Cement is a process-based tool based on commercially available energy-efficiency technologies used anywhere in the world applicable to the cement industry. This version has been designed for use in China (see Figure 4) and benchmarks cement facilities to both Chinese and international best practice.[5]

Figure 4. Benchmarking and Energy-Saving Tool (BEST) for China's Cement Industry.

[4] Excerpted from LBNL and ERI, 2008.
[5] BEST-Cement for China can be downloaded from: http://china.lbl.gov/best-cement-china

No actual cement facility with every single efficiency measure included in the benchmark will likely exist; however, the benchmark sets a reasonable standard by which to compare for plants striving to be the best. The energy consumption of the benchmark facility differs due to differences in processing at a given cement facility. The tool accounts for most of these variables and allows the user to adapt the model to operational variables specific for the cement facility. Figure 5 illustrates the boundaries included in a plant modeled by BEST-Cement.

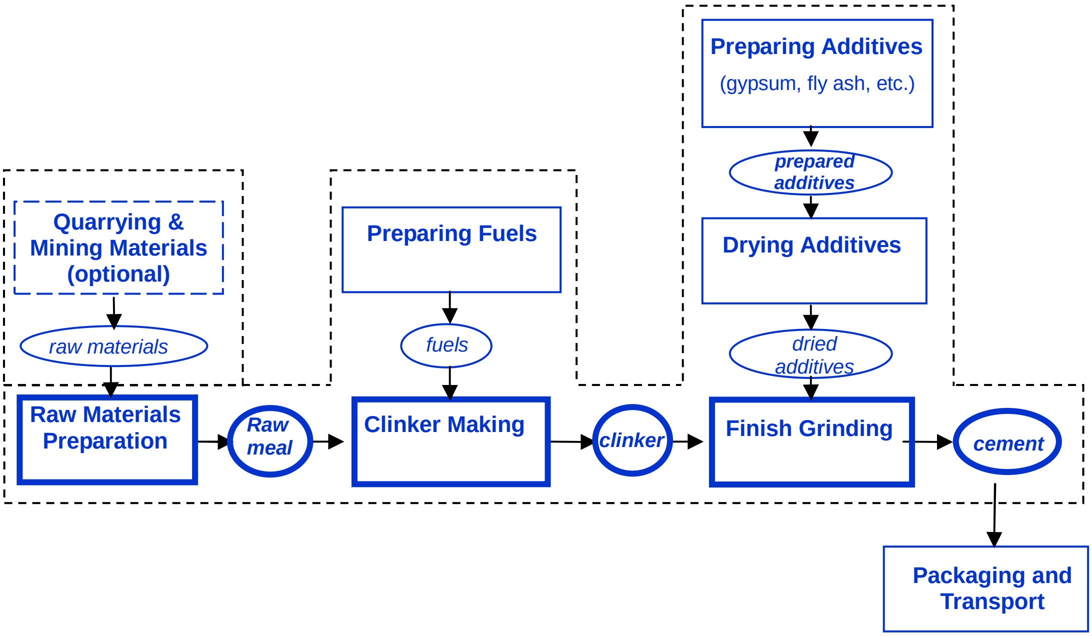


Figure 5. Boundary Conditions for BEST Cement

In order to model the benchmark, i.e., the most energy-efficient cement facility, so that it represents a facility similar to the cement facility to be benchmarked, input production variables are entered in the input sheet. These variables allow the tool to estimate a benchmark facility that is similar to the user's cement plant, giving a better picture of the potential for that particular facility, rather than benchmarking against a generic one.

The input variables required include the following:

- the amount of raw materials used in tonnes per year (limestone, gypsum, clay minerals, iron ore, blast furnace slag, fly ash, slag from other industries, natural pozzolans, limestone powder (used post-clinker stage), municipal wastes and others); the amount of raw materials that are pre-blended (pre-homogenized and proportioned) and crushed (in tonnes per year);
- the amount of additives that are dried and ground (in tonnes per year);
- the production of clinker (in tonnes per year) from each kiln by kiln type;
- the amount of raw materials, coal and clinker that is ground by mill type (in tonnes per year);
- the amount of production of cement by type and grade (in tonnes per year);
- the electricity generated onsite; and,
- the energy used by fuel type; and, the amount in Chinese Renminbi (RMB) per year spent on energy.

The tool offers the user the opportunity to do a quick assessment or a more detailed assessment – this choice will determine the level of detail of the energy input. The detailed assessment will require energy data for each stage of production while the quick assessment will require only total energy used at the entire facility. The benchmarking tool provides two benchmarks – one for Chinese best practices and one for international best practices.

Energy use at a cement facility is modeled based on the following main process steps:

1. Raw material conveying and quarrying (if applicable)
2. Raw material preparation:
    a. pre-blending (pre-homogenization and proportioning)
    b. crushing
    c. grinding
3. Additive preparation
4. Additive drying
5. Fuel preparation
6. Homogenization
7. Kiln systems
    a. pre-heater (if applicable)
    b. pre-calciners (if applicable)
    c. kiln
    d. clinker cooler
8. Final grinding

All energy used for each process step, including motors, fans, pumps and other equipment should be included in the energy use entered for each step.

In addition, the model separately calculates energy requirements for other conveying and auxiliaries and for additional non-production uses, such as lighting, office equipment and other miscellaneous electricity uses. Any energy not accounted for elsewhere but included in the boundary in Figure 5 should be included here in this input variable.

Because clinker making accounts for about 90% of the final energy consumed in the cement making process, reducing the ratio of clinker to final cement by mixing clinker with additives can greatly reduce the energy used for manufacture of cement. Best practice values for additive use are based on the following European ENV 197-2 standards: for composite Portland cements (CEM II), up to 35% can be fly ash and 65% clinker; for blast furnace slag cements (CEM III/A), up to 65% can be blast furnace slag and 35% clinker.

To determine Chinese (domestic) best practice values, four modern Chinese cement plants were audited and best practices determined at each plant by the Energy Research Institute (ERI) and the China Cement Association. Two of these plants were 2000 tonnes per day (tpd) and two were 4000 tpd. Chinese best practices for each stage of production were determined from these plants. Where no data was available (for example, non-production energy use), international best practices were used. For the international best practices at each stage of production, data were gathered from public literature sources, plants, and vendors of equipment. These data and calculations are described in Appendix B.

BEST-Cement compares a facility to international or domestic best practice using an energy intensity index (EII) which is calculated based on the facility's energy intensity and the benchmark energy intensity. The EII is a measurement of the total production energy intensity of a cement facility compared to the benchmark energy intensity as in the following equation:

$$EII = 100 * \frac{\sum_{i=1}^{n} P_i * EI_i}{\sum_{i=1}^{n} P_i * EI_{i,BP}} = 100 * \frac{E_{tot}}{\sum_{i=1}^{n} P_i * EI_{i,BP}} \qquad \text{(Equation 1)}$$

where

EII	= energy intensity index
n	= number of products to be aggregated
EI_i	= actual energy intensity for product i
$EI_{i,BP}$	= best practice energy intensity for product i
P_i	= production quantity for product i.
E_{tot}	= total actual energy consumption for all products

The EII is then used to calculate the energy efficiency potential at the facility by comparing the actual cement plant's intensity to the intensity that would result if the plant used "reference" best technology for each process step. If a detailed assessment was performed, the difference between the actual intensity (the energy used at the facility per tonne of cement produced), and that of the reference or benchmark facility is calculated for each of the key process steps of the facility and then aggregated for the entire cement plant. If the quick assessment was executed, only total aggregated energy intensities are compared.

The EII provides an indication of how the actual total production intensity of the facility compares to the benchmark or reference intensity. By definition (see equation 1), a plant that uses the benchmark or reference technology will have an EII of 100. In practice, actual cement plants will have an EII greater than 100. The gap between actual energy intensity at each process step and the reference level energy consumption can be viewed as the technical energy efficiency potential of the plant. Results are provided in terms of primary energy (electricity includes transmission and generation losses in addition to the heat conversion factor) or final energy (electricity includes only the heat conversion factor).

BEST-Cement also provides an estimate of the potential for annual energy savings (both for electricity and fuel) and energy costs savings, if the facility would perform at the same performance level as the benchmark or "reference" cement plant.

All intensities are given as comprehensive intensities. Comprehensive electricity intensity is equal to the total electricity consumed per tonne of cement produced. It only includes adjustments based on the raw materials used and the types of cement produced. It does not include other factors such as altitude adjustments or temperature or climatic adjustments. Similarly, comprehensive fuel intensity is equal to the total fuel consumed per tonne of clinker produced, based on the raw materials input. It does not include other factors such as altitude adjustments or temperature or climatic adjustments.

Once the EII has been calculated, BEST-Cement can be used to preliminarily evaluate the potential for energy efficiency improvement, by going through a menu of opportunities. The menu of energy efficiency measures is split into six sheets, according to process steps, as follows:

1. Raw materials preparation
2. Fuels preparation
3. Kiln
4. Cement grinding
5. Product and feedstock changes
6. Utility systems

A list of energy-efficiency measures is given for the major process steps. For each measure, a description of the measure is provided (by double clicking on the cell with the name of the measure). Also provided is typical energy savings, capital costs and payback periods for that measure. The user determines whether to implement the measure as well as the level of implementation for each measure by selecting from the three options in the drop down menu: yes, completely; yes, partially; or no. If yes, partially is selected, the percentage of application must be entered in the next column.

The estimates for energy savings and costs are necessarily based on past experiences in the cement and other industries; however, actual performance and very specific characteristics for the user's cement facility may go beyond the capabilities of BEST and change the results. Hence, BEST-Cement gives an estimate of actual results for a preliminary evaluation of cost effective projects for the user's cement plant; for a more detailed and exact assessment, a specialized engineer or contractor should be consulted.

The Self Assessment Results provide information on the facility's actual energy use, the projected energy use with the selected measures implemented, and the international and domestic best practice energy use. In addition the results provide the actual EII and the EII after all the selected energy-efficiency measures are implemented. Both international and domestic EII's are provided and results are provided in either primary energy (electricity includes transmission and generation losses in addition to the heat conversion factor) or final energy (electricity includes only the heat conversion factor). Results also include the energy savings potential and the savings for the selected measures (kgce/year), the cost reduction potential and savings for the selected measures (RMB/year), and the emissions reductions potential and savings for the selected measures (tonne CO_2/year). Emissions reductions are based on final energy.

D. Energy-Conservation Supply Curves

The concept of a “Conservation Supply Curve” was used to make a bottom-up model in order to capture the cost effective as well as the technical potential for energy efficiency improvement and CO_2 emission reduction in the representative cement plants in Shandong Province. The Conservation Supply Curve (CSC) is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy. It was first introduced by Rosenfeld and his colleagues at the Lawrence Berkeley National Laboratory (Meier 1982). Later CSCs were used in various studies to capture energy efficiency potentials in different economic sectors and industries (Hasanbeigi, 2009a; Koomey et al., 1990; Levine and Meier, 1999; Lutsey, 2008; Martin et al., 1999; Worrell, 1994; Worrell, et al., 2001). Recently, McKinsey & Company (2008) has also developed GHG abatement cost curves for different countries using the concept of the conservation supply curve. The Conservation Supply Curve can be developed for a plant, a group of plants, an industry, or for the whole economic sector.

The work presented in this report is a unique study for Shandong Province in China, as it provides a detailed analysis of energy-efficiency improvement opportunities in the representative cement plants in the Province. In addition, compared with other studies, the potential application of a larger number of energy efficiency technologies is assessed.

The Cost of Conserved Energy (CCE) required for constructing the CSC can be calculated as shown in Equation 2:

$$\text{CCE} = \frac{(\text{annualized capital cost + annual change in operations \& maintenance costs})}{\text{annual energy savings}} \qquad \text{(Equation 2)}$$

The annualized capital cost can be calculated from Equation 3.

$$\text{Annualized capital cost} = \text{Capital Cost}*(d/\ (1-(1+d)^{-n}) \qquad \text{(Equation 3)}$$

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

After calculating the CCE for all energy-efficiency measures separately, the measures were ranked in ascending order of their CCE to construct the Energy CSC. In an Energy CSC, an energy price line is determined that reflects the current cost of energy. All measures that fall below the energy price line are so-called “cost-effective”. Furthermore, the CSC can show us the total technical potential for electricity or fuel saving which is the accumulated saving from all the applicable measures. On the curve, the width of each measure (plotted on the x-axis) represents the annual energy saved by that measure. The height (plotted on the y-axis) shows the measure’s CCE.

Discount Rate

In this study, a real discount rate equal to 30% is used for the base case analysis to reflect the barriers to energy-efficiency investment in China's cement industry. 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). Other industrial sector analyses use varying real discount rates. Garcia et al. (2007) used three discount rates of 12%, 15%, and 22% in three different investment scenarios for high efficiency motors in Brazil. Carlos (2006) used the range of 10% to 16% discount rate in the financial analysis for cogeneration projects in Thailand. Banerjee (2005) argues that the discount rates used for investment in power generation plants in India are 10-12%, which are usually significantly lower than the discount rates used by industry (20-30%), commercial (30% and more) and residential (50% or more) sectors for energy efficiency investment (Banerjee, 2005).

These examples show that the discount rate of 30% is relatively high for the financial calculation of the energy projects in the Shandong's cement industry. However, in this study, this high discount rate is used for calculating cost of conserved energy and constructing CSCs to provide a means for accounting for the aforementioned barriers to energy-efficiency improvement, in order to avoid the overestimation of cost-effective energy-saving potential. Nonetheless, it should be noted that the choice of the discount rate also depends on the purpose of the analysis and the approach (prescriptive versus descriptive) used. A prescriptive approach uses lower discount rates (4% to 8%), 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 equally to current generations, but they also may cause relatively certain, near-term effects to be ignored in favor of more uncertain, long-term effects. A descriptive approach, 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).

Methodology for Constructing the Energy Conservation Supply Curve

This part of the analysis of Shandong's cement industry draws upon the work done by LBNL regarding the assessment of energy efficiency and CO_2 emission reduction potentials in the U.S. cement industry (Worrell et al., 2000; Martin et al., 1999; Worrell et al., 2008; LBNL & ERI, 2008). Many of the energy-efficiency technologies from LBNL's publications and reports are used in this analysis because although there are many other studies on energy efficiency in the cement industry, there are not many publications available which contain data about energy saving, CO_2 emission reductions, and the cost of different technologies. Nevertheless, it should be noted that some information about some of the technologies is also presented in other studies. Furthermore, the methodology used for this analysis, i.e. construction of the energy conservation supply curve for Shandong's cement industry, is also used by LBNL for the U.S. cement industry (Worrell et al., 2000; Martin et al., 1999). In addition, information on a substantial number of energy-efficiency technologies for the cement industry was derived from Project Design Documents (PDDs) of Clean Development Mechanism (CDM) projects which are available at United Nations Framework Convention on Climate Change's website (UNFCCC, 2005; UNFCCC, 2007 a,b,c,d,e,f,g,h).

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

1. Establish the year 2008 as the base year for energy, material use, and production in the representative cement plants in Shandong's cement industry.
2. Develop list of 34 energy-efficiency technologies and measures commercially available to improve energy efficiency in the cement industry to use in this study for construction of the conservation supply curves.
3. Determine the potential application of energy-efficiency technologies and measures in the representative cement plants in Shandong's cement industry based on information collected from the cement plants.
4. Construct an Electricity Conservation Supply Curve (ECSC) and a Fuel Conservation Supply Curve (FCSC) separately in order to capture the cost-effective and total technical potential for electricity and fuel efficiency improvement in the studied cement plants at the province level. Calculate the Cost of Conserved Electricity (CCE) and Cost of Conserved Fuel (CCF) 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 Electricity Conservation Supply Curve (ECSC) and a Fuel Conservation Supply Curve (FCSC), respectively. The reason for constructing two separate curves for electricity and fuel is that the cost-effectiveness of energy-efficiency measures highly depends on the price of energy. Since average electricity prices and average fuel prices for Shandong's cement industry in 2008 are different and because many technologies save either solely electricity or fuel, it is more relevant and appropriate to separate electricity and fuel saving measures. Hence, the Electricity Conservation Supply Curve (ECSC) with average electricity price for studied cement plants in 2008 only plots technologies that save electrical energy. The Fuel Conservation Supply Curve (FCSC) with average fuel price for the studied cement plants in 2008 only plots technologies that save fuel. However, it should be noted that there are a few technologies that either save both electricity and fuels, or increase electricity consumption as a result of saving fuel. For those technologies, the fuel savings accounted for a significant portion of the total primary energy savings, so they are included in the Fuel Conservation Supply Curve (FCSC) taking into account their primary energy saving.

It should be highlighted that the CSC model developed is a good screening tool to present energy-efficiency measures and capture the potentials for improvement. However, in reality, the energy-saving potential and cost of each energy-efficiency measure and technology may vary and will depend on various conditions such as raw material quality (e.g. moisture content of raw materials and hardness of the limestone), the technology provider, production capacity, size of the kiln, fineness of the final product and byproducts, time of the analysis, etc. Recently, some Chinese companies have provided less expensive technology; however, the specific energy savings of the Chinese technologies have not been thoroughly investigated. Moreover, it should be noted that some energy-efficiency measures provide productivity and environmental benefits in addition to energy savings, but it is difficult and sometimes impossible to quantify those benefits. 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).

Sensitivity Analyses

Since several parameters play important roles in the analysis of energy-efficiency potentials using the energy conservation supply curves, it is important to see how changes in those parameters can influence the cost-effectiveness of the potentials. Hence, a sensitivity analysis was conducted for four key parameters: discount rate, electricity and fuel prices, investment cost of the measures, and energy saving of the measures.

In general, the cost of conserved energy is directly related to the discount rate. In the other words, reduction of the discount rate will reduce the cost of conserved energy which may or may not increase the cost-effective energy-saving potential, depending on the energy price. A sensitivity analysis for discount rates was conducted using discount rates of 15, 20, 25, 30, and 35% in order to compare the effect of the changing discount rate on the cost of conserved energy and cost-effective energy savings.

Energy price can also directly influence the cost-effectiveness of energy saving potentials. A higher energy price could result in more energy-efficiency measures being cost effective, as it could cause the cost of conserved energy to fall below the energy price line in more cases in the conservation supply curve. A sensitivity analysis for assessing the impact of changing electricity and fuel prices was conducted by assuming 5, 10, 20, 30% increases in energy prices along with one case with a 10% decrease in the energy prices.

Variations in the investment cost and energy savings amount of energy-efficiency measures will change the results. A change in either the investment cost or the energy savings amount will directly change the Cost of Conserved Energy (CCE) (Equation 2) and if the change in the investment cost or/and the energy saving is large enough to change the position of the CCE of any energy-efficiency measure against the energy price line in the conservation supply curve (bring it below the line, while it was above the energy price line before the change or vice versa), then it will change the cost-effective energy saving potential. Furthermore, the change in the energy saving of any energy efficiency measure will change the total amount of energy saving potential regardless of its cost-effectiveness.

A sensitivity analysis was conducted for changes in investment cost and energy savings separately to assess the impact of such changes on the results of this study. Two cases (10% and 20%) were assumed for the increase in investment cost or energy savings and two cases (10% and 20%) were assumed for the decrease in those parameters. These changes of the investment cost or energy saving were applied to each energy-efficiency measure to assess the changes in the final result.

E. Energy-Efficiency Technologies and Measures for Cement Industry

Thirty-four energy-efficiency technologies and measures were evaluated using both BEST-Cement and CSCs to assess the potential for energy-efficiency improvement in cement plants using NSP kilns in Shandong Province. Table 6 presents the typical fuel and electricity savings (compared to typically installed, lower efficiency technologies or measures), capital costs, and change in annual operations and maintenance (O&M) costs for each energy-efficiency technology and measure. Appendix C provides a brief description of each of the 34 energy-efficiency technologies or measures evaluated in this study (Worrell et al., 2008; UNFCCC, 2007a, b, c, d). All of the energy-efficiency measures are applicable to NSP kilns.

For most of the energy-efficiency measures there was a range for energy savings reported in the literature, whereas for costs the literature mostly reported specific capital costs of the measures. Therefore, for measures where there was just one value for energy saving or cost, that specific value was used. However, in cases where there was a range for energy saving, middle value was used. The reason for this variation in the reported energy savings of the measures is that the energy performance of different cement plants before the implementation of the energy-efficiency measure varies. Therefore, the energy-saving changes on a plant-by-plant basis and reported values are different. The average value is used when there is a range reported in the literature. Thus, the assumed baseline for the energy savings is based on the average energy savings of the measures reported in different literature sources.

The 16 cement companies in this study provided information regarding whether or not they had already applied these measures or had these technologies in their plants. Based on the responses, the measures or technologies were applied to specific portions of the overall production capacity of studied cement plants in each cement production step. The calculated potential application of each energy-efficiency technology or measure is presented in Table 6.

In order to make the results of the study more accurate and reliable and prevent the overestimation of the energy-saving potential for the studied cement plants, the considerations described below and the suggestions from cement industry experts were taken into account in assessing the potential application of each energy-efficiency technologies.

Measure 3: Installation of variable frequency drive (VFD) and replacement of the fan for coal mill's bag dust collector. Some plants in Shandong Province do not have this technology, but answered that because they are using the coal mill at full capacity, they do not need to use VFDs. Hence, the application and energy saving of this measure highly depends on the plant-specific situation.

Measure 16: Low temperature waste heat recovery power generation. The source of data on this measure is PDDs of CDM projects recently implemented in China. Cement plants in China, India, and other countries are using the CDM for the implementation of this technology. The revenue obtained through the CDM program from the selling of Certified Emission Reductions (CERs) of this technology reduces the cost of conserved energy and payback period of the technology and makes it more attractive for cement companies. However, some of the cement plants in Shandong Province noted that applying for CDM project for implementation of this technology is complicated and difficult.

Measure 18: Upgrading the pre-heater from 5 stages to 6 stages. Some engineers in cement plants in Shandong Province said that there is significant difficulty in constructing and changing the structure of the pre-heater. The advantage of this measure is that cement plants can recover more heat. However, the disadvantages of adding one stage to a pre-heater are: 1 - Pressure loss in the pre-heater and as a result increased electricity consumption in the fan, 2 - If there is waste heat recovery power generation installed on the kiln, then the waste heat is needed for power generation, thus, it is better not to put an extra stage on the pre-heater. Most of the surveyed cement plants have waste heat recovery power generation and the ones which do not have it are planning to install it in the near future. Thus, in this study, measure 18 was not applicable to any of the surveyed plants.

Measure 25: Replacing a ball mill with vertical roller mill. This measure is applied to ball mills older than 10 years old. ***Measure 26: high pressure roller press as pre-grinding to ball mill***, is applied to ball mills younger than 10 years old. The reason for these assumptions are used for the calculation of the potential application of measures 25 and 26 is that if ball mills are younger than 10 years old, it is more unlikely that a cement plant will completely replace its ball mill by a more efficient vertical roller mill. Instead, cement plants may prefer to just add a high pressure roller press as pre-grinding to the ball mill to increase the energy efficiency instead of completely replacing the ball mill. However, if the ball mill is already older than 10 years old, it is assumed that the cement plant would be willing to completely replaces its ball mill with vertical roller mill.

Measure 31: High Efficiency Motors. Motors are used throughout the cement production process. Measure 31 is a general measure covering motors in the cement plant overall. It is based on a study in U.S. for the wide-scale installation of high efficiency motors in a cement plant. The energy savings of this measure varies significantly on a plant-by-plant basis, ranging from 0 – 6 kWh/ton cement (Worrell, et al. 2008). In addition to this measure, there are a few individual measures related to the use of high efficiency motors in specific applications in the cement production process. Both the specific applications and the general measure for high efficiency motors are included since there are around 500 – 700 electric motors with different sizes in typical cement plant (Worrell et al., 2008). However, in order to not double-count or over-estimate the savings from measure 31, a median savings value of 3 kWh/ton cement for electricity savings is used.

Measure 32: Variable Frequency Drives (VFDs, also called adjustable speed drives, ASDs). The situation for VFDs is similar to that for high efficiency motors. The electricity savings for wide-scale application of VFDs is in the range of 6 to 8 kWh/ton cement (Worrell et al., 2008). Energy savings of 6 kWh/ton cement are assumed in this analysis to avoid overestimating energy savings, since there are a few other measures for the application of VFDs in cement plants shown in Table 6. It should be noted that energy savings of this measure strongly depends on the application and flow pattern of the system on which the VFD is installed (Martin et al., 1999).

Measure 33: Production of blended cement. For calculating the potential application for production of blended cement, a different approach was used compared to that of other measures. This measure is defined as an increased production level of blended cement based on the existing percentage of cementitious materials in the cement that the 11 cement-producing plants in the survey already produce (only 11 of the 16 surveyed plants produce cement and the other 5 plants just produce clinker and do not produce cement). The methodology for the calculation of the potential application is as follows. For each plant, the percentage of blended cement (sum of fly ash cement, slag cement, pozzolana, and blended cement produced by the plant, as reported in the questionnaire, divided by the total cement produced in that plant) was calculated. Then, the average percentage of blended cement of all 11 cement-producing plants was calculated. For six of the 11 cement-producing plants the calculated percentage of blended cement was less than the average for the 11 plants. Thus, the difference between the percentages of the blended cement in each of those 6 plants from the average value of the 11 plants was calculated and converted to the amount of cement by multiplying the calculated difference of the percentages by the total amount of cement produced in the plant. This serves as the potential for the increase of the production of blended cement in each plant. Finally, the total potential calculated for the 6 plants was divided by the total cement produced in all 11 plants and this value serves as the overall potential for increased use of blended cement in the studied plants. This is the value used for the energy savings and cost of conserved energy.

Measure 34: Production of Limestone Portland cement. For this measure, if the company is already producing this type of cement, then it is not applied. However, if they do not produce this type of cement, it is assumed that 5% of the production of non-blended cement (Pure Portland Cement plus Common Portland Cement) will be substituted with this type of cement. None of the cement-producing plants in the study produce Limestone Portland cement. Thus, this measure was applied to all 11 cement-producing plants. Cement experts in China explain that this type of cement is not popular and its reliability is suspected by the industry despite the fact that this type of cement is already produced in some other countries (Worrell et al., 2008). The Chinese cement experts note that research work needs to be conducted to support its application. Therefore, a small share of application (i.e. 5% of the production of non-blended cement) is assumed for this measure in order to avoid the overestimation of its energy-saving potential.

For both Measures 33 and 34, costs may vary by location and should be estimated based on the plant-specific situation. Energy savings also depend on the efficiency of current facilities. Furthermore, the increase in production of blended cements highly depends on the market and its acceptance. Thus, the market should be targeted for promotion of blended cements.

Measure 30: Use of alternative fuels. None of the studied cement plants in Shandong Province use alternative fuels. This is a key opportunity for China's cement industry which has not been tapped so far. Thus, based on the assessment in the studied plants, the potential for use of alternative fuels is 100%. However, since the realization of 100% alternative fuels use potential is rather unrealistic, 10% potential application is assumed for this measure based on a recent assessment of the potential adoption of alternative fuels in the cement industry in China that indicates a possible adoption of 10% alternative fuels by 2015 under the "Medium Development Scenario" (Wang, S., 2008).

Table 6. Typical Fuel and Electricity Savings, Capital Costs, and Change in Annual Operations and Maintenance (O&M) Costs for 34 Selected Energy-Efficiency Technologies and Measures

No.	Technology/Measure	Typical Fuel Savings (GJ/t clinker)	Typical Electricity Savings (kWh/t clinker)	Typical Capital Cost (RMB/t clinker)	Typical Change in Annual O&M cost (RMB/t clinker)
	Fuel Preparation				
1	New efficient coal separator for fuel preparation		0.26	0.08	0.0
2	Efficient roller mills for coal grinding		1.47	0.32	0.0
3	Installation of variable frequency drive & replacement of coal mill bag dust collector's fan		0.16	0.18	0.0
	Raw Materials Preparation				
4	Raw meal process control for Vertical mill		1.41	3.52	0.0
5	High Efficiency classifiers/separators		5.08	23.54	0.0
6	High Efficiency roller mill for raw materials grinding		10.17	58.85	0.0
7	Efficient (mechanical) transport system for raw materials preparation		3.13	32.10	0.0
8	Raw meal blending (homogenizing) systems		2.66	39.59	0.0
9	Variable Frequency Drive in raw mill vent fan		0.33	0.17	0.0
10	Bucket elevator for raw meal transport from raw mill to homogenizing silos		2.35	1.56	0.0
11	High efficiency fan for raw mill vent fan with inverter		0.36	0.23	0.0
	Clinker Making				
12	Kiln shell heat loss reduction (Improved refractories)	0.26		1.71	0.0
13	Energy management and process control systems in clinker making	0.15	2.35	6.84	0.0
14	Adjustable speed drive for kiln fan		6.10	1.57	0.0
15	Optimize heat recovery/upgrade clinker cooler	0.11	-2.00 [a]	1.37	0.0
16	Low temperature waste heat recovery power generation		30.80	9132 RMB/ kWh-Capacity	5.58
17	Efficient kiln drives		0.55	1.50	0.0
18	Upgrading the preheater from 5 to 6 stages	0.11	-1.17 [a]	17.37	0.0
19	Upgrading of a preheater kiln to a preheater/precalciner Kiln	0.43		123.12	-7.52
20	Low pressure drop cyclones for suspension preheater		2.60	20.52	0.0
21	VFD in cooler fan of grate cooler		0.11	0.08	0.0
22	Bucket elevators for kiln feed		1.24	2.41	0.0

No.	Technology/Measure	Typical Fuel Savings (GJ/t clinker)	Typical Electricity Savings (kWh/t clinker)	Typical Capital Cost (RMB/t clinker)	Typical Change in Annual O&M cost (RMB/t clinker)
23	Replacement of preheater fan with high efficiency fan		0.70	0.47	0.0
	Finish Grinding				
24	Energy management & process control in grinding		4.00	3.21	0.00
25	Replace ball mill with vertical roller mill		25.93	53.50	0.0
26	High pressure roller press as pre-grinding to ball mill		24.41	53.50	0.0
27	Improved grinding media for ball mills		6.10	7.49	0.0
28	High-Efficiency classifiers for finish grinding		6.10	21.40	0.0
29	Replacement of cement mill vent fan with high efficiency fan		0.13	0.06	0.0
	General Measures				
30	Use of alternative fuels	0.60		7.52	0.0
31	High efficiency motors		4.58	2.35	0.0
32	Adjustable Speed Drives		9.15	9.63	0.0
	Product Change [c]	**Fuel Savings (GJ/t cement)**	**Electricity Savings (kWh/t cement)**	**Capital Cost (RMB/t cement)**	**Change in Annual O&M cost (RMB/t cement)**
33	Blended cement (Additives: fly ash, pozzolans, and blast furnace slag)	1.77	-7.21[a]	4.92	-0.27
34	Portland limestone cement	0.23	3.30	0.82	-0.04

[a]: The negative value for electricity saving indicates that although the application of this measures saves fuel, it will increase the electricity consumption. However, it should be noted that the total primary energy savings of those measures is positive.

[b]: This CO_2 emission reduction is just for reduced energy use. However, since this type of cement contains less clinker, calcination-related emissions are lower compared to normal Portland cement and as a result CO_2 emission caused by calcination will be less. Nevertheless, in the calculation of total CO_2 reduction, the CO_2 reduction caused by reduced calcination is also taken into account according to the potential application of the measure.

[c]: 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 2008", 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.

IV. Results

A. Overview

Detailed data for 16 cement plants as well as general data for an additional 19 cement plants were collected by the Phase II project team during April and May, 2009. These 35 cement plants have 54 NSP clinker or cement production lines. Table 7 provides information on these 54 production lines.

The oldest production line began operation in 1978 and is now over 30 years old. Figure 6 provides a histogram illustrating how many of the 54 production lines from the total group of 35 cement plants began operation each year since 1978. Most of the NSP production lines were built in the period 2004-2008.

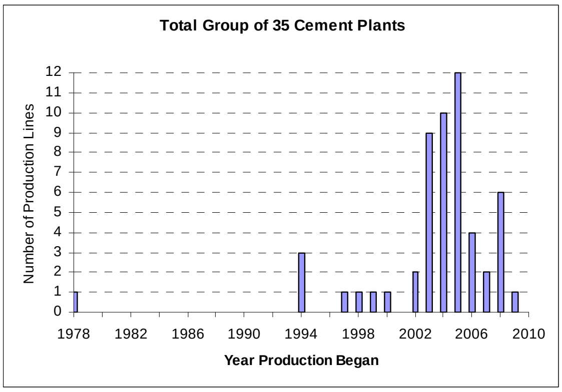


Figure 6. Distribution of Year Production Began at 54 Production Lines in the Total Group of Cement Plants in Shandong Province.

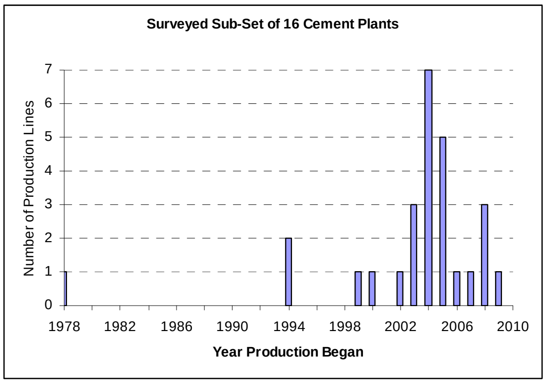


Figure 7. Distribution of Year of Production Began at 27 Production Lines in the Surveyed Sub-Set of 16 Cement Plants in Shandong Province.

There are 27 NSP production lines at the subset of 16 cement plants that were surveyed in more detail. Figure 7 illustrates when these production lines began operation. In addition to the one production line that started in 1978, three lines began operation in the 1990s, and the remainder commenced operation in the 2000s. Excluding the one out-lying line from 1978, the average and median age of the remaining 26 production lines is about 5 years.

The clinker production capacity of the 54 cement production lines ranges from 1000 to 7200 tons/day (tpd), averaging about 3400 tpd. Among the 16 surveyed cement plants, the clinker capacity ranges from 1000 to 6250 tpd, with the average value about 3500 tpd. Recently-built facilities are typically larger than older plants; excluding one out-lying 7200 tpd line constructed in 1997, kiln capacities generally ranged from 1000-3000 tpd for plants constructed up to 2004, from 3000-4000 tpd for plants constructed in 2004 and 2005, from 4000-6000 tpd for plants constructed from 2006 to 2009.

Table 7. Summary Information on Type of Grinding Mills, Waste Heat Recovery, and Variable Frequency Drives (VFDs) for Large Motors/Fans in 35 Cement Plants in Shandong Province

#	Clinker Capacity		Production Started	Raw Material Grinding Mill	Cement Grinding Mill	Waste Heat Recovery	VFD for Large Motors/Fans
	t/day	Mt/yr					
1	2000	0.64	1994	Ball Mill	Ball Mill	Yes	No
	2000	0.64	1994	Ball Mill	Ball Mill	Yes	N/A
	5000	1.60	2004	VRM	Ball Mill	Yes	Partially
2	4844	1.55	2005	VRM	--	Yes	N/A
	4656	1.49	2008	VRM	--	Yes	Yes
3	3125	1.00	2004	Ball Mill	--	Bidding	Mostly
	3125	1.00	2005	Ball Mill	--	Bidding	Large motors
	6250	2.00	2009	VRM	--	Bidding	Yes
4	5000	1.60	2006	VRM	Ball Mill + HPRP	Yes	Yes
5	3400	1.09	2003	Ball Mill	Ball Mill	No	N/A
	3800	1.22	2008				
6	5000	1.60	2004	VRM	VRM	No	N/A
	5000	1.60	2005	VRM	VRM	No	Yes
7	4688	1.50	2005	Ball Mill + HPRP	Ball Mill + HPRP	Yes	Yes
8	2970	0.95	2002	Ball Mill	Ball Mill + HPRP	Yes	Yes
9	5000	1.60	2003	Ball Mill	--	Yes	Yes
	5000	1.60	2004	--	--	N/A	N/A
10	1875	0.60	2003	Ball Mill	Ball Mill	No	No
11	2813	0.90	2005	Ball Mill	--	No	N/A
12	1563	0.50	1978	Ball Mill +RP	Ball Mill	Yes	Yes
	2500	0.80	1999	Ball Mill	Ball Mill	Yes	Yes
13	3125	1.00	2004	Ball Mill	Ball Mill	Yes	No
	2344	0.75	2007	Ball Mill	--	Yes	N/A
14	3500	1.12	2008	VRM	--	Yes	N/A
15	1000	0.32	2000	Ball Mill	Ball Mill + HPRP	No	Partially
16	3000	0.96	2004	Ball Mill	Ball Mill	Yes	Partially
	3000	0.96	2004	Ball Mill	Ball Mill	Yes	Partially
17	3000	0.96	2003	VRM	Ball Mill	Yes	Yes
	5000	1.60	2006				
18	3000	0.96	2006	VRM	VRM	Yes	Yes
19	2500	0.80	2003	Ball Mill	Ball Mill+ RP	Yes	Yes
20	2500	0.80	2003	Ball Mill	Ball Mill +RP	Yes	Yes
21	5000	1.60	2004	VRM	No	Yes	Yes
	5000	1.60	2008				
22	2500	0.80	2003	Ball Mill	Ball Mill	No	Yes
	2500	0.80	2005				
23	2500	0.80	2003	Ball Mill	Ball Mill	Yes	Yes
	5000	1.60	2004	VRM			
24	2500	0.80	2003	Ball Mill	Ball Mill	Yes	No
	2500	0.80	2005				
25	5000	1.60	2006	VRM	Ball Mill +RP	Yes*	Yes*
26	2500	0.80	2002	Ball Mill	Ball Mill	Yes *	Yes
	2500	0.80	2004				
27	6000	1.92	2007	VRM	Ball Mill +RP	Yes	Yes
28	7200	2.30	1997	VRM	No	No	Yes
29	2500	0.80	2005	Ball Mill, VRM	Ball Mill	No	Yes
	5000	1.60	2008		Ball Mill +RP		
30	3300	1.06	1994	VRM	Ball Mill	No	Yes
31	2500	0.80	2005	VRM	Ball Mill +RP	Yes	Yes
	4000	1.28	2008				
32	1000	0.32	1998	Ball Mill	Ball Mill	No	Yes
33	1200	0.38	2005	Ball Mill	Ball Mill	No	Yes
34	1200	0.38	2005	Ball Mill	Ball Mill	No	Yes
35	1200	0.38	2005	Ball Mill	Ball Mill	No	Yes

Notes: RP = roller press; HPRP = high pressure roller press; VRM = vertical roller mill. Some plants only produce clinker and do not grind cement ("- -"). Information not available (N/A) regarding the use of VFDs for all plants. *Under Construction/Renovation

Table 8 and Figures 8 and 9 provide summary information on electricity, fuel, final energy, and primary energy intensity for production of one ton clinker in the 16 surveyed plants in Shandong Province. Plant 2 consumes the least amount of electricity for the production of one ton of clinker, whereas plants 5 and 15 have the highest electricity intensity (Figure 8). Plant 11 has the lowest and plant 5 has the highest fuel, final, and primary energy intensity for the production of one ton of clinker (Figure 9).

Table 8. Summary Energy Intensity Information for Clinker Production in the 16 Surveyed Cement Plants in Shandong Province

Plant	Electricity Intensity	Fuel Intensity		Final energy Intensity		Primary energy [6] Intensity	
	kWh/t clinker	GJ/t clinker	kgce/t clinker	GJ/t clinker	kgce/t clinker	GJ/t clinker	kgce/t clinker
1	76.82	4.19	143.05	4.47	152.49	5.05	172.40
2	52.37	3.70	126.25	3.89	132.68	4.29	146.25
3	69.87	3.63	123.71	3.88	132.29	4.41	150.40
4	83.79	3.38	115.29	3.68	125.58	4.32	147.30
5	96.11	4.25	144.93	4.59	156.73	5.32	181.65
6	61.10	3.45	117.58	3.67	125.08	4.13	140.92
7	70.33	3.84	131.02	4.09	139.66	4.63	157.88
8	89.35	3.59	122.47	3.91	133.44	4.59	156.60
9	62.16	3.42	116.68	3.64	124.31	4.12	140.43
10	75.02	3.38	115.21	3.65	124.43	4.22	143.87
11	67.74	3.29	112.21	3.53	120.53	4.05	138.09
12	83.70	4.16	141.89	4.46	152.17	5.10	173.86
13	76.01	3.40	116.15	3.68	125.48	4.26	145.19
14	69.71	3.76	128.28	4.01	136.84	4.54	154.91
15	96.16	3.87	131.98	4.21	143.79	4.94	168.71
16	73.49	3.49	119.12	3.76	128.15	4.31	147.20

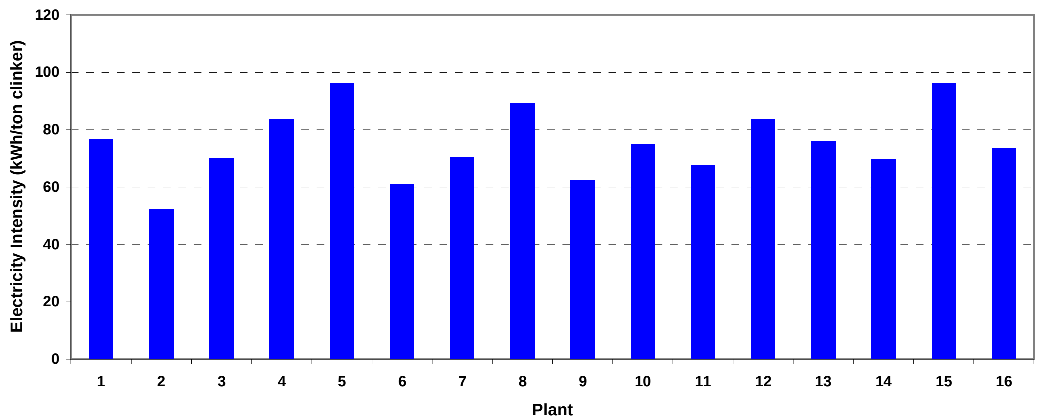


Figure 8. Electricity Intensity in the 16 Surveyed Cement Plants Based on 2008 Clinker Production.

[6] Primary energy savings calculated based on China's national average efficiency of thermal power generation including transmission and distribution losses in China (32.15%) (NBS, 2008; Anhua and Xingshu, 2006; Kahrl and Roland-Holst, 2006).

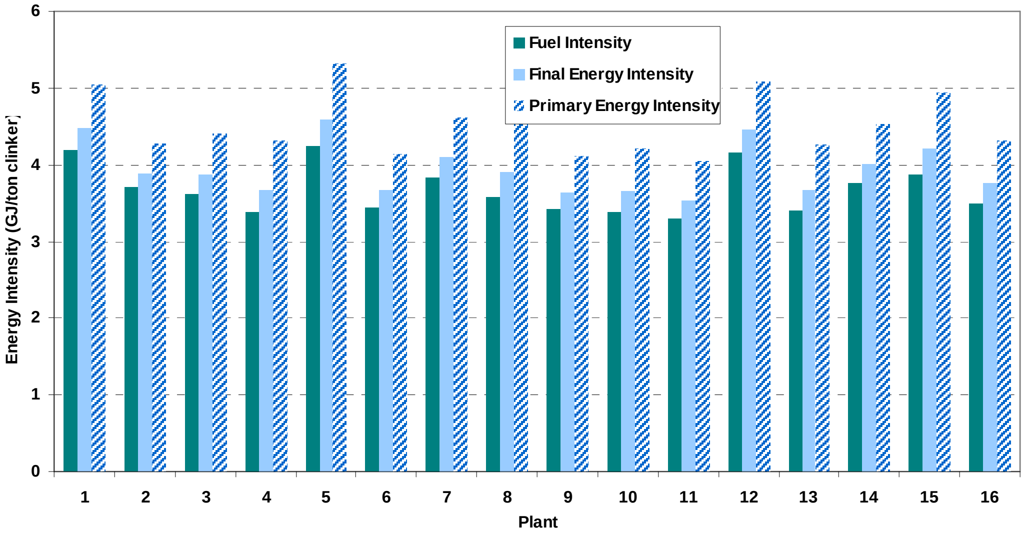


Figure 9. Fuel, Final Energy, and Primary Energy Intensity for Clinker Production in the 16 Surveyed Cement Plants in Shandong Province Based on 2008 Clinker Production

For the cement-producing plants, Table 9 and Figures 10 and 11 provide summary information on electricity, fuel, final energy, and primary energy intensity for production of one ton of cement in the 11 cement-producing surveyed plants in Shandong Province. In calculation of this indicator, the amount of clinker sold and the clinker: cement ratio is taken into account, reflecting the amount of energy used in each cement-producing plant for production of one ton of cement. Plant 6 has the lowest electricity intensity for the production of one ton cement among all the surveyed cement-producing plants, whereas plant 5 has the highest electricity intensity. Plant 10 has the lowest and plant 5 has the highest fuel, final and primary energy intensity for production of one ton cement among all the surveyed cement-producing plants in Shandong Province (Figure 11).

Table 9. Summary Energy Intensity Information for Cement Production in the 11 Cement-Producing Surveyed Plants in Shandong Province

Cement-producing Plants	Electricity Intensity	Fuel Intensity		Final energy Intensity		Primary energy Intensity	
	kWh/t cement	GJ/t cement	kgce/t cement	GJ/t cement	kgce/t cement	GJ/t cement	kgce/t cement
1	82.75	3.14	107.30	3.44	117.46	4.07	138.91
4	87.79	2.36	80.64	2.68	91.42	3.35	114.18
5	121.83	3.69	125.76	4.12	140.73	5.05	172.30
6	57.41	1.87	63.64	2.07	70.70	2.51	85.57
7	78.99	2.63	89.60	2.91	99.30	3.51	119.78
8	87.20	2.17	74.10	2.49	84.81	3.15	107.41
10	64.59	1.55	52.85	1.78	60.78	2.27	77.52
12	94.60	2.86	97.70	3.20	109.32	3.92	133.84
13	78.56	2.25	76.69	2.53	86.34	3.13	106.70
15	82.42	2.23	76.22	2.53	86.35	3.16	107.71
16	86.69	2.37	80.80	2.68	91.44	3.34	113.91

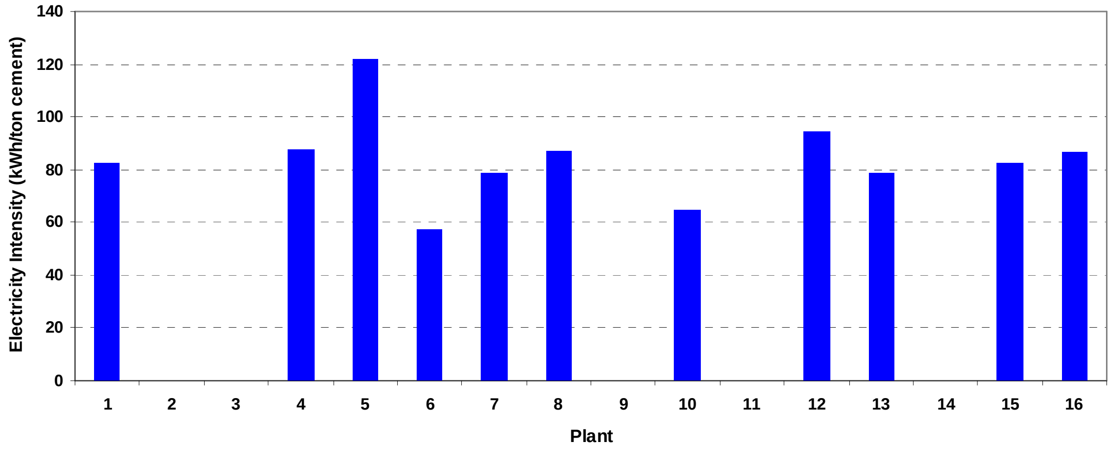


Figure 10. Electricity Intensity for Cement Production in the 11 Cement-Producing Surveyed Plants in Shandong Province Based on 2008 Cement Production

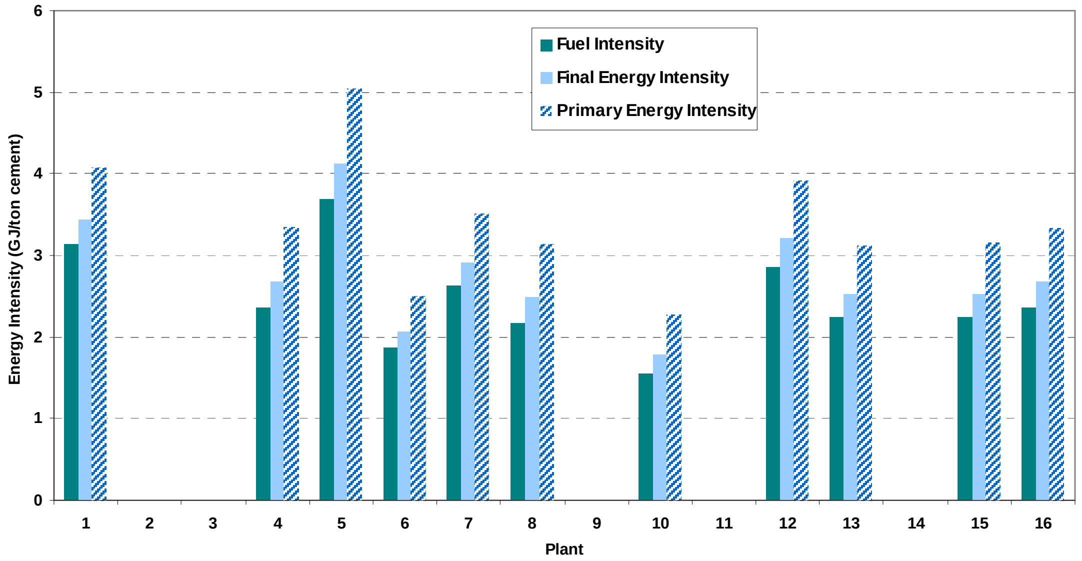


Figure 11. Fuel, Final Energy, and Primary Energy Intensity for Cement Production in the 11 Cement-Producing Surveyed Plants in Shandong Province Based on 2008 Cement Production

B. Benchmarking and Energy-Saving Tool for Cement (BEST-Cement)

Since detailed energy consumption and production data were not available for each process step at the 16 surveyed plants, the "quick assessment" feature of BEST-Cement was used to benchmark these plants to Chinese and international best practice. As explained above, this means that an identical plant was modeled for each of the 16 plants that produced the same amount of clinker or cement using the same raw materials but that used best practice energy-efficiency technologies or measures throughout the plant. The difference between the actual plant and its best-practice counterpart illustrates the technical potential for energy improvement. In order to compare the 16 plants, an energy intensity index (EII, see equation 1 above) is used to illustrate the distance between best practice, which is indexed at 100, and the plant's actual energy intensity.

Figure 12 shows the EII score for the 16 plants compared to international best practice (indexed to equal 100) based on the primary energy consumption of each plant. As expected, all 16 plants scored above the 100 value, indicating that none of them are considered to be at the international best practice level in terms of energy efficiency.

The EIIs of the 16 plants range from a low of 118, indicating that the primary energy use of that facility is 15% above international best practice, to a high of 158, indicating a 37% technical potential savings. The average primary energy technical savings potential of these 16 plants is 23% based on international best practice values.

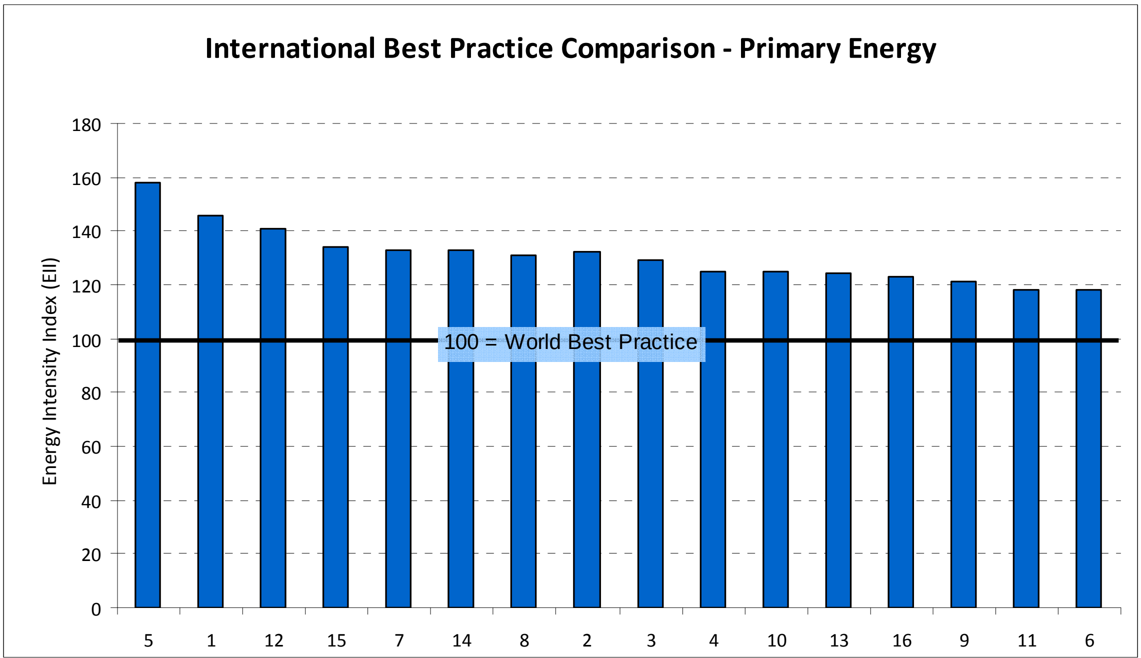


Figure 12. Benchmark Values for 16 Surveyed Cement Plants Compared to International Best Practice for Primary Energy Consumption

Figure 13 shows the EII score for the 16 plants compared to domestic (Chinese) best practice (indexed to equal 100) based on the primary energy consumption of each plant.[7] Again, all 16 plants scored above the 100 value, indicating that none of them are considered to be at the domestic best practice level. In this case, though, the 16 plants are much closer to best practice, indicating that many of them have adopted most of the energy-efficiency technologies and practices available domestically in China.

The EIIs of the 16 plants range from a low of 102, indicating that the primary energy use of that facility is 2% above domestic best practice, to a high of 132, indicating a 24% technical potential savings. The average primary energy technical savings potential of these 16 plants is 12% based on domestic best practice values.

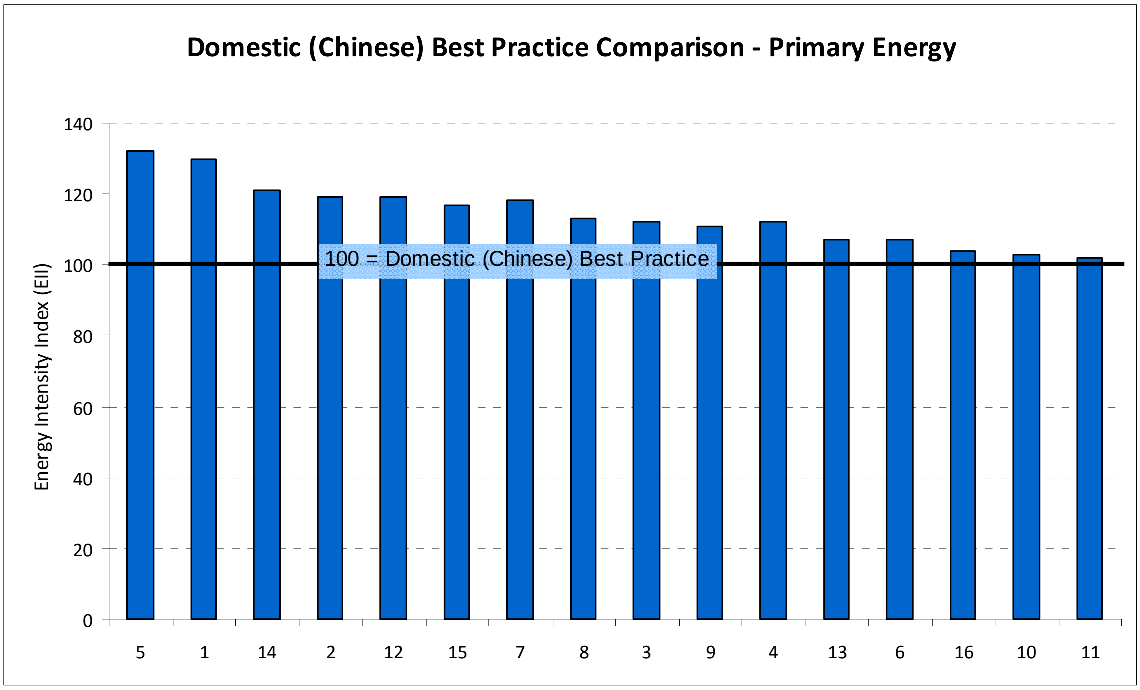


Figure 13. Benchmark Values for 16 Surveyed Cement Plants Compared to Domestic (Chinese) Best Practice for Primary Energy Consumption

[7] Note that it is possible for a plant's rank among the 16 plants to differ between the international and domestic benchmarking results because BEST-Cement calculates the Energy Intensity Index as a ratio of energy use of the plant compared to best practice energy use, which is determined based on the specific processes and technologies at each plant and which varies depending upon whether the plant is being compared to international or Chinese best practice.

C. Energy-Conservation Supply Curves

Based on the methodology explained in section III and the information from Table 10, an Electricity Conservation Supply Curve (ECSC) and a Fuel Conservation Supply Curve (FCSC) were constructed separately to capture the cost-effective and total technical potential for electricity and fuel efficiency improvement in the 16 studied cement plants in Shandong Province. Furthermore, the CO_2 emission reduction potential from the studied plants as the result of implementation of the energy efficiency technologies/measures applied to the plants was also calculated. Out of 34 energy-efficiency measures, 29 measures were applicable to the studied cement plants, 23 of which are electricity-saving measures that are included in ECSC and six of which are fuel-saving measures that form the body of FCSC.

In Table 10, the total production capacity of each cement process step for the 16 studied plants in given. For the fuel preparation measures, however, the production capacity is not given because the three measures in fuel preparation step are applied based on the total clinker production capacity of plants since the energy savings and cost were given per ton of clinker production capacity.

The application of the first 32 technologies is based on the total clinker production capacity of each production line since some plants do not produce cement and just produce clinker. The share of clinker production capacity to which the measure is applied is given in the last column in Table 10. For measures 33 and 34, however, the application of the measure is based on the cement-production capacity of the cement-producing plants that were studied. The share of cement production capacity to which measures 33 and 34 are applied is given in the last column of Table 10.

Primary energy savings shown in Table 10 is calculated based on China's national average efficiency of thermal power generation including transmission and distribution losses in China (32.15%) (NBS, 2008; Anhua and Xingshu, 2006; Kahrl and Roland-Holst, 2006). Hence, the calculated primary energy savings could be different in other countries. CO_2 emission reductions given in Table 10 are calculated based on the emission factors for the North China Power Grid (1.028 $kgCO_2$/KWh) (UNFCCC, 2008). Hence, the calculated CO_2 emission reductions also could be different in other countries.

Table 10. Energy Savings, Capital Costs and CO_2 Emission Reductions for Energy-Efficient Technologies and Measures Applied to 16 Shandong Cement Facilities

No.	Technology/Measure	Production Capacity (Mt/year)	Fuel Savings (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Primary Energy Savings (GJ/t-cl) [8]	Capital Cost (RMB/t-cl)	Change in annual O&M cost (RMB/t-cl)	CO_2 Emission Reductions (kg CO_2/t-cl) [9]	Share of clinker production capacity to which measure is applied
	Fuel Preparation								
1	New efficient coal separator	[a]		0.26	0.003	0.08	0.0	0.27	29.0%
2	Efficient roller mills for coal grinding	[a]		1.47	0.016	0.32	0.0	1.51	40.1%
3	Installation of VFD & replacement of coal mill bag dust collector's fan	[a]		0.16	0.002	0.18	0.0	0.16	32.8%
	Raw Materials Preparation								
4	Raw meal process control for vertical mill	45.74		1.41	0.016	3.52	0.0	1.45	5.3%
5	High efficiency classifiers/separators	45.74		5.08	0.057	23.54	0.0	5.23	16.5%
6	High efficiency roller mill	45.74		10.17	0.114	58.85	0.0	10.45	54.2%
7	Efficient transport system	45.74		3.13	0.035	32.10	0.0	3.22	9.3%
8	Raw meal blending (homogenizing) systems	45.74		2.66	0.030	39.59	0.0	2.73	0.0%
9	VFD in raw mill vent fan	45.74		0.33	0.004	0.17	0.0	0.34	63.6%
10	Bucket elevator for raw meal transport	45.74		2.35	0.026	1.56	0.0	2.42	0.0%
11	High efficiency raw mill vent fan w/inverter	45.74		0.36	0.004	0.23	0.0	0.37	68.9%
	Clinker Making								
12	Kiln shell heat loss reduction (Improved refractories)	29.14	0.26		0.260	1.71	0.0	24.60	28.7%
13	Energy management & process control systems	29.14	0.15	2.35	0.176	6.84	0.0	16.61	32.6%
14	Adjustable speed drive for kiln fan	29.14		6.10	0.068	1.57	0.0	6.27	15.0%
15	Optimize heat recovery/upgrade clinker cooler	29.14	0.11	-2.00 [c]	0.088	1.37	0.0	8.35	9.1%
16	Low temperature Waste Heat Recovery for power generation	29.14		30.80	0.345	9132 RMB/ kWh-capaciity	5.58	31.66	6.2%
17	Efficient kiln drives	29.14		0.55	0.006	1.50	0.0	0.57	39.8%
18	Upgrading preheater from 5 stages to 6 stages	29.14	0.111	-1.17 [c]	0.098	17.37	0.0	9.30	0.0%

[8] Primary energy saving is calculated based on China's national average efficiency of thermal power generation including transmission and distribution losses in China (32.15%) (NBS, 2008; Anhua and Xingshu, 2006; Kahrl and Roland-Holst, 2006). Hence, the calculated primary energy savings could be different in other countries.

[9] CO_2 emission reduction is calculated based on the emission factor for the North China Power Grid (1.028 kgCO_2/KWh) (UNFCCC, 2008). Hence, the calculated CO_2 emission reductions could be different in other countries.

No.	Technology/Measure	Production Capacity (Mt/year)	Fuel Savings (GJ/t-cl)	Electricity Savings (kWh/t-cl)	Primary Energy Savings (GJ/t-cl) [8]	Capital Cost (RMB/t-cl)	Change in annual O&M cost (RMB/t-cl)	CO_2 Emission Reductions (kg CO_2/t-cl) [9]	Share of clinker production capacity to which measure is applied
19	Upgrading to a preheater/precalciner Kiln	29.14	0.43		0.430	123.12	-7.52	40.68	0.0%
20	Low pressure drop cyclones for suspension preheater	29.14		2.60	0.029	20.52	0.0	2.67	51.9%
21	VFD in cooler fan of grate cooler	29.14		0.11	0.001	0.08	0.0	0.11	57.6%
22	Bucket elevators for kiln feed	29.14		1.24	0.014	2.41	0.0	1.27	0.0%
23	Use of high efficiency preheater fan	29.14		0.70	0.008	0.47	0.0	0.72	24.4%
	Finish Grinding								
24	Energy management & process control in grinding	18.51 [b]		4.00	0.045	3.21	0.00	4.11	30.0%
25	Replacing a ball mill with vertical roller mill	18.51		25.93	0.290	53.50	0.0	26.66	9.1%
26	High pressure roller press for ball mill pre-grinding	18.51		24.41	0.273	53.50	0.0	25.09	25.5%
27	Improved grinding media for ball mills	18.51		6.10	0.068	7.49	0.0	6.27	6.6%
28	High-Efficiency classifiers (for finish grinding)	18.51		6.10	0.068	21.40	0.0	6.27	28.7%
29	High efficiency cement mill vent fan	18.51		0.13	0.001	0.06	0.0	0.13	36.2%
	General Measures								
30	Use of alternative fuels	18.51	0.60		0.600	7.52	0.0	56.76	10.0%
31	High efficiency motors	18.51		4.58	0.051	2.35	0.0	4.70	39.7%
32	Adjustable Speed Drives	18.51		9.15	0.102	9.63	0.0	9.41	55.4%
	Product Change [10]	**Production Capacity (Mt/year)**	**Fuel Savings (GJ/t-cem)**	**Electricity Savings (kWh/t-cem)**	**Primary Energy Savings (GJ/t-cem)**	**Capital cost (RMB/t-cem)**	**Change in annual O&M cost (RMB/t-cem)**	**CO_2 Emission Reductions (kg CO_2/t-cem)**	**Share of cement production capacity to which measure is applied**
33	Blended cement	18.51	1.77	-7.21 [c]	1.689	4.92	-0.27	160.02 [d]	6.4%
34	Portland limestone cement	18.51	0.23	3.30	0.266	0.82	-0.04	25.10 [d]	2.1%

[a]: This measure applied based on the clinker production capacity of plants since the energy saving was given per ton of clinker production capacity.
[b]: Total cement production capacity in the studied plants is less than total clinker production capacity is that some of the plants just produce clinker and do not produce cement.
[c]: The negative value for electricity saving indicates that although the application of this measures saves fuel, it will increase electricity consumption. However, it should be noted that the total primary energy savings of those measures is positive.
[d]: This CO_2 emission reduction is just for reduced energy use. However, since this type of cement contains less clinker, calcination is reduced compared to Portland cement and as a result CO_2 emissions from the calcination process are lower. Nevertheless, in the calculation of total CO_2 reduction, this reduction in CO_2 emissions is also taken into account according to the potential application of the measure.

[10] 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 2008", the calculations are based on cement unlike the other measures for which the calculations are based on the clinker production capacity.

Electricity Conservation Supply Curve

As mentioned above, 23 energy-efficiency measures are included in the Electricity Conservation Supply Curve (ECSC). Figure 14 and Table 11 show that 14 energy-efficiency measures fall under the line of the average unit price of electricity in studied plants in 2008 (545 RMB/ megawatt-hour, MWh). Therefore, for these measures the CCE is less than the average electricity price. In another words, the cost of investing on these 14 energy-efficiency measures to save one MWh of electricity is less than purchasing one MWh of electricity at the current price of electricity. These are thus so-called “cost effective” energy-efficiency measures.

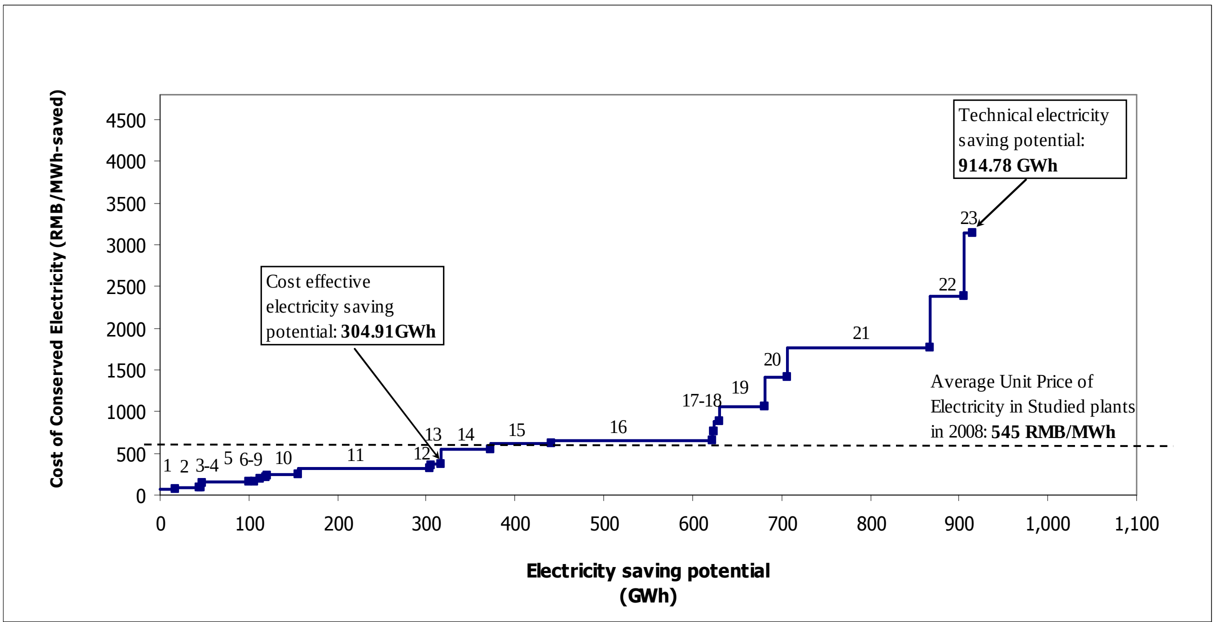


Figure 14. Electricity Conservation Supply Curve (ECSC) for 16 Studied Cement Plants in Shandong Province

Table 11 shows all of the electricity-efficiency measures applicable to the studied cement plants which are ranked by their Cost of Conserved Electricity (CCE). The annual electricity saving and CO_2 emissions reduction obtained by applying each measure to the 16 cement plants is also presented in the table. As shown in Figure 14, the first 14 measures are cost-effective. Efficient roller mills for coal grinding, adjustable speed drives for kiln fan, and new efficient coal separators for fuel preparation are the top three cost-effective energy-efficiency measures. However, it should be noted that the electricity savings obtained by these measures are not especially large.

Table 11. Electricity-Efficiency Measures for 16 Studied Cement Plants in Shandong Province Ranked by Cost of Conserved Electricity (CCE)

CCE Rank	Efficiency Measure	Measure No.	Electricity Saving (GWh)	Cost of Conserved Electricity (RMB/MWh- saved)	CO_2 Emission Reduction (kton CO_2)
1	Efficient roller mills for coal grinding	2	17.18	67.32	17.66
2	Adjustable speed drive for kiln fan	14	26.68	83.42	27.43
3	New efficient coal separator for fuel preparation	1	2.20	88.55	2.26
4	Replacement of Cement Mill vent fan with high efficiency fan	29	1.37	144.89	1.41
5	High efficiency motors	31	52.97	157.39	54.45
6	Variable Frequency Drive (VFD) in raw mill vent fan	9	6.12	158.55	6.29
7	High efficiency fan for raw mill vent fan with inverter	11	7.23	191.85	7.44
8	Replacement of Preheater fan with high efficiency fan	23	4.97	203.31	5.11
9	Variable Frequency Drive in cooler fan of grate cooler	21	1.83	230.41	1.88
10	Energy management & process control in grinding	24	34.98	245.56	35.96
11	Adjustable Speed Drives	32	147.85	321.94	151.99
12	Installation of Variable Frequency Drive & replacement of coal mill bag dust collector's fan with high efficiency fan	3	1.53	353.17	1.57
13	Improved grinding media for ball mills	27	11.72	375.60	12.04
14	Low temperature Waste Heat Recovery power generation	16	56.06	539.77 *	57.63
15	Replacing a ball mill with vertical roller mill	25	68.46	622.20	70.38
16	High pressure roller press as pre-grinding to ball mill	26	181.20	661.09	186.27
17	Raw meal process control for Vertical mill	4	2.18	764.94	2.24
18	Efficient kiln drives	17	6.38	883.06	6.56
19	High-Efficiency classifiers for finish grinding	28	51.10	1057.75	52.53
20	High Efficiency classifiers/separators for raw mill	5	24.40	1416.72	25.09
21	High Efficiency roller mill for raw materials grinding	6	160.54	1770.91	165.04
22	Low pressure drop cyclones for suspension preheater	20	39.32	2380.22	40.42
23	Efficient (mechanical) transport system for raw materials preparation	23	8.51	3139.33	8.75

* In the calculation of the CCE for low temperature waste heat recovery power generation, the revenue from CERs of the CDM project is not taken into account. If taken into account the value of CERs, CCE will be equal to 500.45 RMB/MWh-saved.

The annual cost-effective electricity-efficiency improvement potential in the studied cement plants in Shandong Province in 2008 is equal to 373 GWh. This is about 16% of the total electricity used in the 16 cement plants in 2008. The total annual technical electricity-saving potential is 915 GWh, which is about 40% of the total electricity used in the 16 studied cement plants in 2008 (Table 12). Annual CO_2 emission reductions associated with the cost-effective potential are 383 ktCO_2, while total annual CO_2 emission reductions associated with technical electricity saving potential are 940 ktCO_2. The calculation of CO_2 emissions reduction potential is based on China's grid emission factor of 1.028 kgCO_2/kWh used in this study. It may increase or decrease with the rise or decline in China's grid emission factor in the future, respectively.

Measure number 11, adjustable speed drives, and measure number 14, low temperature waste heat recovery power generation, are two cost-effective measures with the highest electricity-saving potential. However, in overall, it is measure number 16, high pressure roller press as pre-grinding to ball mill, that has highest electricity-saving potential among all other measures, but this measure is not cost-effective.

Although measure number 14, low temperature waste heat recovery power generation, is cost-effective, its CCE (539.77 RMB/MWh- saved) is just about 5 RMB/MWh more than the average unit price of electricity in 2008 (545 RMB/MWh). However, it should be noted that, in many cases, this measure is implemented through CDM projects which provide extra revenue from the implementation by selling the Certified Emission Reductions (CERs). Thus, if the benefit received from selling the CERs of CDM project for measure number 14 is taken into account, this will further decrease the CCE of this measure.

To evaluate how much the revenue from CERs can affect the CCE of low temperature waste heat recovery power generation, the following analysis was conducted. A price of 76.5 RMB per ton of CO_2 (UNFCCC, 2008) was used for the price of carbon credits. To determine the revenue from selling the carbon credits, the CO_2 savings per year was multiplied by the unit price of the carbon credits and divided by two to reflect the fact that the lifetime of low temperature waste heat recovery technology is 20 years, while the sale of carbon credits is just for 10 years. Since the capital cost of the technology is annualized based on 20 years lifetime, the revenue from selling the carbon credits was divided by two, so that it can be extended from 10 years to 20 years. This annual revenue is then subtracted from annualized capital cost in the CCE calculation (in equation 2). The resulted CCE for low temperature waste heat recovery power generation by taking into account the revenue from CERs is 500.45 RMB/MWh-saved which is about 39 RMB/MWh lower than the CCE without CERs revenue.

Table 12. Cost-Effective and Technical Potential for Annual Electricity Saving and CO_2 Emission Reduction in the 16 Studied Cement Plants in Shandong Province in 2008

	Annual Electricity Saving Potential (GWh)		Annual Carbon Dioxide Emission Reduction ($ktCO_2$)	
	Cost-Effective	Technical	Cost-Effective	Technical
Saving potentials for 2008	373	915	383	940
Share of total electricity used in / CO_2 emission from all studied plants in 2008	16%	40%	2%	4%

Table 12 summarizes the results for annual electricity savings and CO_2 emission reductions associated with the savings. The share of cost-effective and technical potential for CO_2 emission reductions from total CO_2 emissions from the studied cement plants in 2008 is about 2% and 4%, respectively. The reason for the small contribution of electricity savings to reduction of total CO_2 emission from the cement plants comparing to its large contribution to the energy saving, is that the electricity consumption is not the major source of CO_2 emission in cement plants. The major sources of CO_2 emission are fuel consumption as well as calcination in the clinker making process.

Fuel Conservation Supply Curve

Six energy-efficiency measures were used to construct the Fuel Conservation Supply Curve (FCSC). Figure 15 shows that all six energy-efficiency measures fall under the average unit price of coal in studied plants in 2008 (31.9 RMB/GJ). Therefore, for these measures the CCF is less than the average unit price of coal. In other words, the cost of investing in these six energy-efficiency measures to save one GJ of energy is less than purchasing one GJ of coal at the given price.

Table 13 presents the fuel efficiency measures applicable to studied cement plants ranked by their Cost of Conserved Fuel (CCF). The fuel saving and CO_2 emission reduction achieved by each measure in overall studied cement plants is also shown. Production of blended cement is the most cost-effective measure and gives the second-highest fuel savings among all other measures after the kiln shell heat loss reduction (improved refractories) measure, which is ranked third by its CCF. The production of Portland limestone cement is ranked second in the fuel conservation supply curve. However, it should be noted that the energy savings of the product change measures (i.e. blended cement and Portland limestone cement), highly depends on the plant-specific situation and the efficiency of current facilities. There are also preconditions for increasing the share of blended cement and Portland limestone cement in the production portfolio of the cement companies such as market considerations, supportive policy from government, the required regulations and standards, and the market and public acceptance.

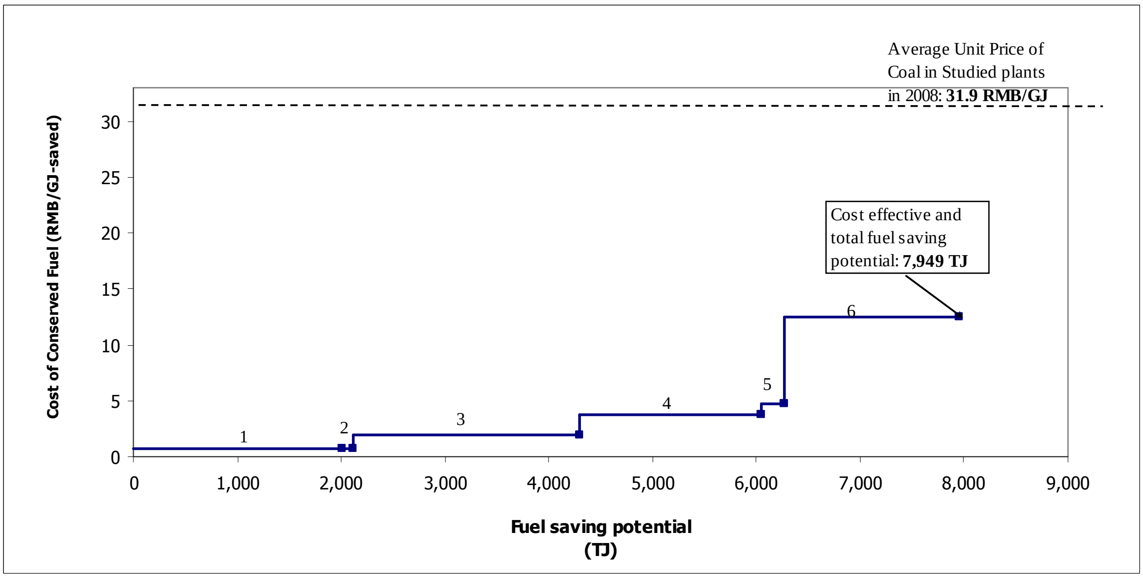


Figure 15. Fuel Conservation Supply Curve (FCSC) for 16 Studied Cement Plants in Shandong Province

Table 13. Fuel Efficiency Measures for 16 Studied Cement Plants in Shandong Province Ranked by Cost of Conserved Fuel (CCF)

CCF Rank	Efficiency Measure	Measure No.	Fuel Savings (TJ)	Cost of Conserved Fuel (RMB/GJ-saved)	CO_2 Emission Reduction (kton CO_2)
1	Blended cement (Additives: fly ash, pozzolans, and blast furnace slag)	33	2,011	0.72 [b]	378.1 [a]
2	Limestone Portland cement	34	105	0.76 [b]	20.3 [a]
3	Kiln shell heat loss reduction (Improved refractories)	12	2,177	1.98	206.0
4	Use of alternative fuels	30	1,749	3.78	165.4
5	Optimize heat recovery/upgrade clinker cooler	15	231	4.71 [b]	22.0
6	Energy management and process control systems in clinker making	13	1,676	12.55	157.8

[a]: CO_2 emission reduction from reduced energy use as well as reduced calcination in clinker making process.

[b]: For this measure, primary energy savings was used to calculate CCF based on both the electricity and fuel savings. However, since the share of fuel saving is more than that of electricity saving, this measure is included between fuel saving measures.

As can be seen in Table 13, production of blended cement have the largest contribution to CO_2 emission reductions, accounting for about 40% of the CO_2 emission reduction potential from fuel saving measures. The reasons are: first, the energy saving potential of measure number 1 (blended cement) is high, therefore, the CO_2 emission reduction associated with reduced energy consumption is high. Secondly, since blended cement has much lower clinker per cement ratio compared with ordinary Portland cement, it needs less clinker for the production of one unit of final product. As a result, CO_2 emissions due to the calcination reaction, which is the source of almost half of CO_2 emissions in a cement plant, are reduced for this type of cement. Therefore, CO_2 emission reductions are achieved from both reduced energy use and reduced calcination reaction for this measure.

The total annual fuel efficiency improvement potential for the studied cement plants in 2008 is equal to 7,949 TJ which represents about 8% of the total fuel use in all the sixteen plants in 2008. The interesting result is that all the total fuel efficiency potential is cost-effective. The annual CO_2 emission reductions associated with total fuel saving potential is 950 ktCO_2 (Table 14). The share of technical potential for CO_2 emission reductions from total CO_2 emissions of the sixteen studied plants in 2008 is 4%.

Table 14. Cost-Effective and Technical Potential for Annual Fuel Saving and CO_2 Emission Reduction in the 16 Studied Cement Plants in Shandong Province in 2008

	Annual Fuel Saving Potential (TJ)		Annual Carbon Dioxide Emission Reduction (ktCO_2)	
	Cost-Effective	Technical	Cost-Effective	Technical
Saving potentials for 2008	7,949	7,949	950	950
Share of total fuel used in / CO_2 emission from all studied plants in 2008	8%	8%	4%	4%

By converting the electricity saving potentials to primary energy using the conversion factors and taking into account the average efficiency of power generation and transmission, and distribution losses in China, Table 15 shows the total primary energy saving potentials as well as the total CO_2 emission reduction potential for the sixteen studied cement plants in Shandong Province achieved from all the applicable electricity and fuel saving measures presented above. It can be seen that two thirds of the total technical primary energy saving potential is cost effective, but have not been adopted up by the cement plants included in this study for various financial and technical reasons. These reasons are very important to be investigated, understood, and addressed.

Table 15. Cost-Effective and Technical Potential for Annual Primary Energy Saving and CO_2 Emission Reduction in 16 Studied Cement Plants in Shandong Province in 2008

	Annual Primary Energy Saving Potential (TJ)		Annual Carbon Dioxide Emission Reduction (ktCO_2)	
	Cost-Effective	Technical	Cost-Effective	Technical
Saving potentials for 2008	12,122	18,191	1,333	1,890
Share of total primary energy used in / CO_2 emission from all studied plants in 2008	10%	15%	5%	8%

The results obtained from this study are also in agreement with the results of a similar study conducted for the Thai cement industry using energy conservation supply curves (Hasanbeigi, 2009a). Almost all of the energy-efficiency technologies and measures that are cost-effective for the 16 studied cement plants in Shandong Province were also cost-effective when they were applied to the Thai cement industry. Using the bottom-up electricity conservation supply curve model, the cost-effective electricity efficiency potential for the Thai cement industry in 2008 was estimated to be about 265 GWh, whereas the total technical electricity saving potential was 1,697 GWh. When the revenue from CERs of CDM projects for the implementation of low temperature waste heat recovery power generation was taken into account for the calculation of CCE, then this measure became cost effective and increased the cost-effective electricity saving potential in Thai cement industry to 911 GWh. The fuel conservation supply curve model showed the cost-effective fuel efficiency potential of 17,214 TJ and total technical fuel efficiency potential equal to 21,202 TJ for Thai cement industry, respectively (Hasanbeigi, 2009a).

The results of CSCs presented above, are limited to the 16 studied cement plants in Shandong Province which together have the clinker production capacity of 29.144 Mt. Total clinker production capacity of Shandong Province's NSP kiln cement plants was 49.31 Mt in 2007 (Liao, 2008b). A rough estimation of the provincial level energy-efficiency improvement opportunity for NSP kilns cement plants in Shandong Province is calculated using the 2007 clinker production capacity for NSP kilns in Shandong Province. The results of the provincial-level energy efficiency improvement potential are presented in Table 16.

Table 16. Estimation of the Cost-Effective and Technical Potential for Annual Energy Savings and CO_2 Emission Reduction in Shandong's Cement Industry in 2007

	Annual Energy Saving Potential		Annual Carbon Dioxide Emission Reduction ($ktCO_2$)	
	Cost-Effective	Technical	Cost-Effective	Technical
Annual Electricity Saving Potential (GWh)	631	1,548	648	1,591
Annual Fuel Saving Potential (TJ)	13,450	13,450	1,607	1,607
Annual Primary Energy Saving Potential (TJ)	20,510	30,779	2,255	3,198

Sensitivity Analyses

In the previous sections, the cost-effective and technical energy-efficiency improvement potentials for the studied cement plants in Shandong Province were presented and discussed. Since several parameters play important roles in the analysis and results of energy-efficiency potentials, it is important and relevant to see how changes in those parameters can influence the cost effectiveness of the potentials. Hence, a sensitivity analysis was performed for four important parameters: discount rate and electricity, fuel prices, investment cost of the measures, and energy saving of the measures. The results are discussed below.

In general, the cost of conserved energy is directly related to the discount rate. In other words, a reduction in the discount rate will reduce the cost of conserved energy which may or may not increase the cost-effective energy-saving potential, depending on the energy price. Table 17 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 35% to 15% will increase the cost-effective electricity savings from 317 GWh to 631 GWh. The cost-effective fuel savings, however, will not change by a reduction in the discount rate from 35% to 15% and it will remain equal to 7,949 TJ. 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 15 to 35% will not affect its cost effectiveness.

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 energy price also plays a role in cost-effectiveness (as is the case for cost-effective fuel saving when the discount rate changes from 35% to 15%). However, the fact is that the cumulative cost of conserved electricity (CCE) and cost of conserved fuel (CCF) will decrease with the decline in discount rate regardless of the cost effectiveness. That means although the cost effectiveness of fuel saving potential will not change by the changes in the discount rate from 35% to 15%, its CCF will decrease by the decrease in the discount rate. That is, the total fuel saving potential can be achieved with lower investment cost. The total technical energy saving and CO_2 emission potentials do not change with the variation of the discount rate.

Table 17. Sensitivity Analysis for the Cost-Effective Electricity and Fuel Saving Potentials and CO2 Emission Reductions in 16 Studied Cement plants in 2008 with Different Discount Rates Keeping Other Parameters Constant

Discount Rate (%)	Electricity			Fuel		
	Cost-effective saving (GWh)	Cost-effective CO_2 emission reduction ($ktCO_2$)	Cumulative CCE * (RMB/MWh saved)	Cost-effective saving (TJ)	Cost-effective CO_2 emission reduction ($ktCO_2$)	Cumulative CCF * (RMB/GJ saved)
d.r. = 15	631	649	8,850	7,949	950	13.9
d.r. = 20	625	642	11,085	7,949	950	17.3
d.r. = 25	441	453	13,434	7,949	950	20.8
d.r. = 30 **	373	383	15,858	7,949	950	24.5
d.r. = 35	317	325	18,331	7,949	950	28.3

*: Cumulative CCE (the sum of CCE of all 23 applicable electricity saving measures) and CCF (the sum of CCF for all 6 applicable fuel saving measures) are just presented as the indicators to show that although the change in discount rate may not result in the change in cost effective savings and CO_2 emission reduction, it will change the CCE and CCF in general.

**: The discount rate = 30% is the base scenario which is used in the main analysis presented in this report.

The energy price can also directly influence the cost-effectiveness of energy-saving potentials. A higher energy price would result in more energy-efficiency measures being cost effective, as it would cause the cost of conserved energy to fall below the energy price line in more cases. Table 18 shows how the cost-effective energy savings and their associated CO_2 emission reductions change with the variation of energy prices, keeping the other parameters (i.e. the discount rate, investment cost of the measures, and energy saving of the measures). It shows that a 30% increase in the 2008 electricity price will increase the cost-effective electricity savings from 545 GWh to 709 GWh, whereas a 10% decrease in the 2008 electricity price will decrease the cost-effective electricity savings from 545 GWh to 491 GWh.

Since energy prices are more likely to increase rather than decreasing, there are more increased cases of energy price in the sensitivity analysis. All of the fuel-saving measures are already cost-effective given the 2008 fuel price. Thus, an increase in the fuel price will not change the cost-effective fuel-saving potential. A 60% reduction in the average fuel price for cement plants will not change the cost-effective fuel-saving potential because the change in the average fuel price in the mentioned range will not change the position of the CCF of the measures compared to the fuel price line. In other words, no additional measures will move up to the average fuel price line. Technical energy saving and CO_2 emission potentials do not change with the variation of energy prices.

Table 18. Sensitivity Analysis for the Cost-Effective Electricity and Fuel-Saving Potentials and CO_2 Emission Reductions in 16 Studied Cement Plants in 2008 with Different Electricity and Fuel Prices Keeping Other Parameters Constant

Scenario	Electricity			Fuel		
	Electricity Price (RMB /MWh)	Cost-Effective Saving (GWh)	Cost-Effective CO_2 Emission Reduction (ktCO2)	Average Fuel Price (RMB /GJ)	Cost-Effective Saving (TJ)	Cost-Effective CO_2 Emission Reduction (ktCO2)
Energy prices for cement plants in 2008 - 10%	491	317	325	28.7	7,949	950
Energy prices for cement plants in 2008 *	545	373	383	31.9	7,949	950
Energy prices for cement plants in 2008 + 5%	572	373	383	33.5	7,949	950
Energy prices for cement plants in 2008 + 10%	600	373	383	35.1	7,949	950
Energy prices for cement plants in 2008 + 20%	654	441	453	38.3	7,949	950
Energy prices for cement plants in 2008 + 30%	709	622	640	41.5	7,949	950

*: The base case energy prices which are used in the main analysis presented in this report.

As mentioned before, in reality, the energy-saving potential and investment cost of each energy-efficiency measure and technology may vary and will depend on various conditions such as raw material quality (e.g. moisture content of raw materials and hardness of the limestone), the technology provider, production capacity, size of the kiln, fineness of the final product and byproducts, time of the analysis, etc. Thus, a sensitivity analysis was conducted to assess the effect of the changes in investment cost and/or energy savings of the energy-efficiency measures on the final results.

From the CCE formula (equation 2) it is noted that the cost of conserved energy is directly related to the investment cost and has an inverse relation with the energy savings of a measure. However, only if the change in the investment cost or/and the energy savings is large enough to change the position of the CCE of any energy-efficiency measure against the energy price line in the conservation supply curve (bring it below the line, while it was above the energy price line before the change or vice versa), then the cost-effective energy saving potential will change. In addition, the change in the energy saving of any energy-efficiency measure will change the total amount of energy saving potential regardless of its cost-effectiveness.

Tables 19 and 20 below show how changes in the investment cost or energy saving of the measures can affect the cost-effective energy-saving potentials and their associated CO_2 emission reduction potentials, keeping constant the other parameters.

Table 19. Sensitivity Analysis for the Cost-Effective Electricity and Fuel Saving Potentials and CO2 Emission Reductions in 16 Studied Cement Plants in 2008 with Different Investment Costs Keeping Other Parameters Constant

Investment Cost (IC)	Electricity			Fuel		
	Cost-Effective Saving (GWh)	Cost-Effective CO_2 Emission Reduction ($ktCO_2$)	Cumulative CCE * (RMB/MWh saved)	Cost-Effective Saving (TJ)	Cost-Effective CO_2 Emission Reduction ($ktCO_2$)	Cumulative CCF * (RMB/GJ Saved)
Base case IC – 20%	622	640	12,723	7,949	950	19.5
Base case IC – 10%	441	453	14,290	7,949	950	22.0
Base case IC	373	383	15,858	7,949	950	24.5
Base case IC + 10%	317	325	17,426	7,949	950	27.0
Base case IC + 20%	317	325	18.993	7,949	950	29.5

*: Cumulative CCE (the sum of CCE of all 23 applicable electricity saving measures) and CCF (the sum of CCF for all 6 applicable fuel saving measures) are just presented as the indicators to show that although the change in the investment cost may not result in the change in cost effective savings and CO_2 emission reduction, it will change the CCE and CCF in general.

Table 19 shows that the cost-effective electricity saving potential increases from 317 GWh to 622 GWh if the investment cost of the energy-efficiency technologies is decreased from the base case+20% to base case-20%. However, the cost-effective fuel saving potential and its associated CO_2 emission reductions will not change by the changes in the investment cost in the range of ±20%. The reason for this is that the total fuel saving potential in Fuel CSC is by far cost-effective and changes in the investment cost in that range will not affect the cost-effectiveness. Nevertheless, Table 19 shows that although the cost-effective fuel saving potential does not change, the cumulative Cost of Conserved Fuel declines by the decrease in the investment cost of the technologies. That is to say that the fuel savings potential can be achieved with the lower cost if the investment cost of the technologies decreases.

Table 20. Sensitivity Analysis for the Cost-Effective Electricity and Fuel Saving Potentials and CO2 Emission Reductions in 16 Studied Cement Plants in 2008 with Different Energy Savings Keeping Other Parameters Constant

Energy Saving (ES)	Electricity				Fuel			
	Cost-Effective Saving (GWh)	**Cost-Effective CO_2 Emission Reduction ($ktCO_2$)**	**Cumulative CCE * (RMB/MWh Saved)**	**Total Electricity Saving Potential (GWh) ****	**Cost-Effective Saving (TJ)**	**Cost-Effective CO_2 Emission Reduction ($ktCO_2$)**	**Cumulative CCF * (RMB/GJ Saved)**	**Total Fuel Saving Potential (TJ) ****
Base case ES – 20%	253	260	19,716	732	6,359	799	30.6	6,359
Base case ES – 10%	285	293	7,573	823	7,154	874	27.2	7,154
Base case ES	373	383	15,858	915	7,949	950	24.5	7,949
Base case ES + 10%	410	421	14,455	1,006	8,744	1,025	22.3	8,744
Base case ES + 20%	529	544	13,286	1,098	9,539	1,100	20.4	9,539

*: Cumulative CCE (the sum of CCE of all 23 applicable electricity saving measures) and CCF (the sum of CCF for all 6 applicable fuel saving measures) are presented as indicators to show that although the change in the energy savings may not result in the change in cost-effective savings and CO_2 emission reduction, it will change the CCE and CCF in general.

**: The cumulative electricity saving and fuel saving is presented in the table to show that the change in the energy saving of the energy efficiency measures will change the total cumulative amount of energy saving potential regardless of its cost-effectiveness.

Table 20 shows how the cost-effective electricity saving potential increases from 253 GWh to 529 GWh and the cost-effective fuel saving potential increases from 6,359 TJ to 9,539 TJ by the increase in the energy saving of the energy efficiency technologies from the Base case-20% to base case+20%. The total electricity saving potential and fuel saving potential also increase by the increase in energy saving potential of each measure as shown in the Table 20. That is to say that even higher energy saving can be achieved in the studied cement plants depending on the current efficiency of the facilities and the level of the efficiency that can be achieved with a specific energy efficiency technology. Furthermore, the cumulative CCE and CCF decrease by the increase in the energy saving potential of the technologies.

D. Identified Opportunities for Improvement of Energy-Efficiency of the Cement Industry in Shandong Province

This study identified a number of cost-effective energy-efficiency technologies and measures that have not been fully adopted in the 16 surveyed cement plants in Shandong Province. In addition, a few energy-efficiency technologies and measures that are not cost-effective, but that are very close to being cost-effective at the current price of energy, and that have large energy savings were also identified.

Electricity-Saving Technologies and Measures

Table 21 lists 13 cost-effective electricity-saving technologies and measures identified in this study that have not been fully adopted in the 16 surveyed cement plants. These technologies and measures can be grouped into those that are related to improving the efficiency of motors and fans, fuel preparation, and finish grinding. In addition, Table 21 lists two measures that were nearly cost-effective and that had large electricity-saving potential.

Table 21. Identified Electricity-Saving Opportunities for the 16 Surveyed Cement Plants in Shandong Province

CCE Rank	Measure	Measure No.	Electricity Saving (GWh)
	Motor and Fans		
11	Adjustable Speed Drives	32	147.85
2	Adjustable speed drive for kiln fan	14	26.68
5	High efficiency motors	31	52.97
6	Variable Frequency Drive (VFD) in raw mill vent fan	9	6.12
9	Variable Frequency Drive in cooler fan of grate cooler	21	1.83
12	Installation of Variable Frequency Drive & replacement of coal mill bag dust collector's fan	3	1.53
4	Replacement of Cement Mill vent fan with high efficiency fan	29	1.37
7	High efficiency fan for raw mill vent fan with inverter	11	7.23
8	Replacement of Preheater fan with high efficiency fan	23	4.97
	Fuel Preparation		
3	Efficient coal separator for fuel preparation	1	2.20
1	Efficient roller mills for coal grinding	2	17.18
	Finish Grinding		
10	Energy management & process control in grinding	24	34.98
13	Improved grinding media for ball mills	27	11.72
15	Replacing a ball mill with vertical roller mill	25	68.46
16	High pressure roller press as pre-grinding to ball mill	26	181.20
	Power Generation		
14	Low temperature waste heat recovery power generation	16	56.06

Note: measures shaded in grey are not cost-effective, but are very close to being cost-effective and have high energy savings

Motor and Fans

Nine cost-effective measures are related to improving the energy efficiency of motors and fans in the cement plants. The largest savings in this category are from the use of variable frequency drives (VFDs, also called adjustable speed drives, ASDs). The analysis identified electricity savings of nearly 150 GWh from implementation of this measure. The second largest savings in this area are from implementation of high efficiency motors. This measure was found to have the potential to save over 50 GWh in the surveyed plants that had not fully adopted such motors. In addition to the energy and cost savings from efficient drives and motors, further savings can be realized through the adoption of energy-efficient fans. Each of these measures is described more fully below.

High Efficiency Motors. Motors and drives are used throughout a 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 from a few kW to MW-size (Vleuten, 1994). Power use in the kiln (excluding grinding) is roughly estimated to be 40-50 kWh/tonne clinker (Heijningen et al., 1992). Variable speed drives, improved control strategies and high-efficiency motors can help to 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.

Power savings may vary considerably on a plant-by-plant basis, ranging from 3 to 8% (Fujimoto, 1994; Vleuten, 1994). Based on an analysis of motors in the U.S. Department of Energy's MotorMaster+ software, and a breakdown of motors in a 5,000 tpd cement plant given in Bösche (1993), it is assumed that high-efficiency motors replace existing motors in all plant fan systems with an average cost of $0.22/annual tonne cement capacity.

Variable Frequency Drives (Adjustable Speed Drives). Drives are the largest power consumers in cement making. The energy efficiency of a drive system can be improved by reducing the energy losses or by increasing the efficiency of the motor. Most motors are fixed speed AC models. However, motor systems are often operated at partial or variable load (Nadel et al., 1992). Also, in cement plants large variations in load occur (Bösche, 1993). 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 (Bösche, 1993; Fujimoto, 1993), 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 reason for installing ASDs (Holderbank Consulting, 1993). An overview of savings achieved with ASD in a wide array of applications is provided in Worrell et al. (1997). Savings depend on the flow pattern and loads. Savings can be significant but strongly depend on the application and flow pattern of the system on which the ASD is installed, varying between 7 and 60% (Holderbank Consulting, 1993). They estimate that the potential savings are

15% for 44% of the installed power, or roughly equivalent to 8 kWh/t cement. The specific costs depend strongly on the size of the system. For systems over 300 kW the costs are estimated to be 70 ECU/kW (75 US$/kW) or less and for the range of 30-300 kW at 115-130 ECU/kW (120-140 US$/kW) (Worrell et al,. 1997). Using these cost estimates, the specific costs for a modern cement plant, as studied by Bösche (1993), can be estimated to be roughly $0.9 to 1.0/annual tonne cement capacity. Other estimates vary between $0.4 and $3/annual tonne cement (Holland et al., 1997; Holderbank Consulting, 1993).

Some specific applications, which are modeled separately in the electricity conservation supply curves, are provided below.

Adjustable Speed Drives for Kiln Fan. Adjustable or variable speed drives (ASDs) for the kiln fan result in reduced power use and reduced maintenance costs. ASDs are currently being made in China, although many of the parts and instrumentation are still being imported from Germany and/or Japan (Cui, 2004; Cui, 2006).

Variable Frequency Drive (VFD) in Raw Mill Vent Fan. In the Birla Cement Works, Chittorgarh Company. India, the raw mill vent fan damper was only partially open for the required airflow. Since the damper opening was reduced, there was high-pressure loss across the damper resulting in higher power consumption. Keeping the damper opened fully and reducing the fan speed (rpm) could save on power consumption. Hence, VFDs were installed in raw mill vent fans which have resulted in power savings of 0.25 - 0.41 kWh/ton clinker. The capital cost for the measure was around $ 0.023 - 0.026 / annual ton clinker capacity (UNFCCC, 2007b).

VFD in Cooler Fan of Grate Cooler. In the Chittor Cement Works, Chittorgarh Company, India, the cooler fan damper was only partially open for the required airflow. Since the damper opening was reduced, there was high-pressure loss across the damper resulting in higher power consumption. Thus, keeping the damper opened fully and reducing the fan rpm could save power. Hence, VFD had been proposed to be installed in various cooler fans and has resulted in a power savings of 0.044 - 0.173 kWh/ton clinker. The capital cost for the measure was around $ 0.012 /annual ton clinker capacity (UNFCCC, 2007b).

Installation of Variable Frequency Drive and Replacement of Coal Mill Bag Dust Collector Fan. In the Birla Cement Works, Chittorgarh Company, India, the coal mill # 1 and 2 bag dust collector's fan was replaced and VFDs were installed resulting in the power savings of 0.11 kWh/t of clinker for coal mill #1 and 0.21 kWh/t of clinker for coal mill #2. The capital cost for the measure was around $ 0.024 - 0.030 / annual ton clinker capacity (UNFCCC, 2007b).

High-Efficiency Fans. *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 of 0.13 kWh/ton clinker. The capital cost for the measure was around $0.009 /annual ton clinker capacity (UNFCCC, 2007b).

High Efficiency Fan for Raw Mill Vent Fan With Inverter. In the Birla Vikas Cement Works (SCW), 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. These reduced the energy consumption by 0.36 kWh/ton clinker. The capital cost for the measure was around $ 0.033 / annual ton clinker capacity (UNFCCC, 2007c).

Replacement of Preheater Fan with High Efficiency Fan. The preheater fan at the Birla Vikas Cement Works, Birla Corporation Limited, India, was an older generation, low-efficiency, high energy-consuming fan. Therefore, it was replaced with a high efficiency fan resulting in the power savings of 0.7 kWh/ton clinker. The capital cost for the measure was around $0.068 /annual ton clinker (UNFCCC, 2007c).

Fuel Preparation

Two cost-effective measures were identified related to improving the energy-efficiency of the fuel preparation phase of cement manufacturing in the 16 surveyed cement plants. The largest savings can be realizes from adoption of efficient roller mills for coal grinding. Additional savings can be obtained using a more efficient coal separator. These two measures are described below.

Efficient Roller Mills for Coal Grinding. Coal is the most used fuel in the cement industry. Fuel preparation is most often performed on-site. Fuel preparation may include crushing, grinding and drying of coal. Coal is shipped wet to prevent dust formation and fire during transport. Passing hot gasses through the mill combines the grinding and drying. Coal roller mills are available for throughputs of 5.5 to 220 t/hour. Coal grinding roller mills can be found in many countries around the world, for example, Brazil, Canada, China, Denmark, Germany, Japan and Thailand. Vertical roller mills have been developed for coal grinding. An impact mill consumes around 45 to 60 kWh/t and a tube mill around 25 to 26 kWh/t (total system requirements). Waste heat of the kiln system (for example the clinker cooler) can be used to dry the coal if needed. Advantages of a roller mill are its ability to handle larger sizes of coal (no pre-crushing needed) and coal types with a higher humidity and to manage larger variations in throughput. However, tube mills are preferred for more abrasive coal types. Electricity consumption for a vertical roller mill is estimated to be 16 to 18 kWh/t coal (Cembureau, 1997). Electricity consumption for a bowl mill is 10 to 18 kWh/t coal (Bhatty et al., 2004), and for a ball mill 30 to 50 kWh/t coal (Cembureau, 1997). The investment costs for a roller mill are typically higher than that of a tube mill or an impact mill, but the operation costs are also lower; roughly 20% compared to a tube mill and over 50% compared to an impact mill (Cembureau, 1997), estimating savings at 7 to 10 kWh/t coal.

Efficient Coal Separator. Earlier, the pressure drop across the original coal mill separator in the Birla Vikas Cement Works, Birla Corporation Ltd, was 200-250 mmWG, as compared to 100-125 mmWG for the Coal mill separator in Satna Cement Works (SCW) which is the other cement plants of the company, resulting in higher power consumption of bag dust collector's fan. It was replaced with a modified separator of similar design of SCW, to reduce pressure drop across separator by approx.120 mmWG. The earlier motor of 300 Kw/1500 rpm was replaced with available 200 Kw/1000 rpm, due to change in reduced inlet draft of BDC Fan, thus saving in Fan power equal to 0.26 kWh/ton clinker. The capital cost for the measure was around $ 0.011 / annual ton clinker capacity (UNFCCC 2007 c).

Finish Grinding

Energy management and the use of process control systems for finish grinding could cost-effectively save nearly 35 GWh if adopted in the 16 surveyed plants that currently do not have such systems. In addition, the use of improved grinding media for ball mills was also found to be a cost-effective efficiency measure for these plants.

In addition to these two cost-effective measures, two measures with high electricity savings were identified to improve the energy efficiency of finish grinding that were not quite cost-effective, but that had high potential energy savings. These measures are to replace an existing ball mill with a vertical roller mill and to use a high pressure roller press for pre-grinding in a ball mill.

These measures are described below.

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.

Typical energy savings are 3 to 3.5 kWh/t (reduction in power consumption by 2%-3%) and simple payback periods are typically between 6 months and 2 years (Martin et al., 2001; Albert, 1993). Other benefits include reduced process and quality variability as well as improved throughput/production increases.

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. 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 (Venkateswaran and Lowitt, 1988). 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. Improved grinding media have the potential to reduce grinding energy use by 5-10% in some mills, which is equivalent to estimated savings of 3-5 kWh/t cement (Venkateswaran and Lowitt, 1988).

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 (Cembureau, 1997). The raw material is ground on a surface by rollers that are pressed down using spring or hydraulic pressure, with hot gas used for drying during the grinding process (Bhatty et al., 2004). Typical energy use is between 18.3 and 20.3 kWh/t clinker compared to 30-42 kWh/t clinker for a ball mill, depending on the fineness of the cement. A vertical roller mill can accept raw materials with up to 20% moisture content and there is less variability in product consistency.

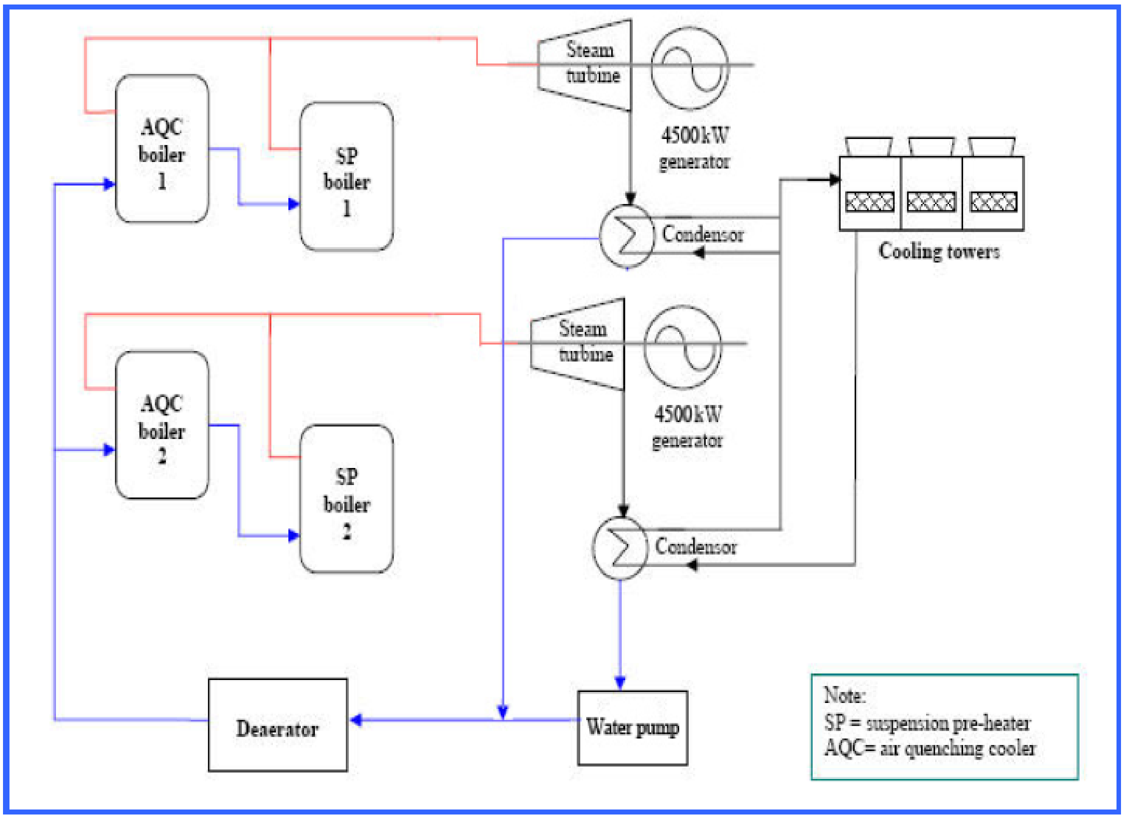
High Pressure Roller Press and Pre-Grinding to Ball Mill. A high pressure roller press, in which two rollers pressurize the material up to 3,500 bar, can replace ball mills for finish grinding, improving the grinding efficiency dramatically (Seebach et al., 1996). A roller press with a V-separator uses 15.6 kWh/t clinker for finish grinding (Bhatty et al., 2004). Capital cost estimates for installing a new roller press vary widely in the literature, ranging from low estimates of $2.5/annual tonne cement capacity (Holderbank Consulting, 1993) or $3.6/annual tonne cement capacity (Kreisberg, 1993) to high estimates of $8/annual tonne cement capacity (COWIconsult, 1993). The capital costs of roller press systems are lower than those for other systems (Kreisberg, 1993) or at least comparable (Patzelt, 1993). This technology can achieve an increase in throughput of about 20% and energy savings of about 7 to 15% (Bhatty et al., 2004).

Power Generation

Another energy-efficiency measure that was identified as having high energy savings and was cost-effective is the use of low temperature waste heat recovery for on-site power generation.

Low Temperature Waste Heat Recovery for Power Generation. A large amount of energy consumption for the production of cement 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 clinker production process, a significant amount of heat is typically vented to the atmosphere without utilization. This situation wastes natural resources and causes serious heat pollution in the workplace. 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. A design schematic of the Quzhai 9000 kW waste-heat utilization project in China is provided below (UNFCCC 2007 d).



Design schematic of the Quzhai 9000 kW waste-heat utilization project in China (UNFCCC 2007 d)

Pan (2005) estimates a cost for imported (Japanese) technology of 18,000 to 22,000 RMB ($2,250 to $2,750) per kW with an installation capacity over 6 MW. Chinese domestic technology was developed in 1996 and is currently available from three Chinese companies: Tianjin Cement Industry Design & Research Institute Co., Ltd., Zhongxin Heavy Machine Company, and Huaxiao Resource Co. Ltd. All three companies have on-going demonstration programs in Chinese cement plants. Installation cost of domestic technology and equipment is currently about 10,000 RMB ($1,250) per kW. The installation cost would be a bit lower if kilns and generation system are constructed simultaneously. For a 2000 tonne per day (730,000 annual tonne) kiln capacity, about 20 kWh/t clinker of electricity could be generated for an investment of 20 to 30 million RMB (ITIBMIC, 2004). Generating capacity of domestic technology is approximated to be 24 to 32 kWh and foreign technology about 28 to 36 kWh (ITIBMIC, 2004). Domestic technology could produce 35kWh/t of clinker while Japanese technology now produces 45 kWh/t of clinker. German technology is even better but no data is available (Cui, 2004; Cui, 2006). Running time and required labor are approximately the same for foreign and domestic equipment.

Fuel-Saving Technologies and Measures

Table 22 lists six cost-effective fuel-saving technologies and measures identified in this study that have not been fully adopted in the 16 surveyed cement plants. These technologies and measures are described below. For both blended cement and limestone Portland cement, the energy savings depend on the efficiency of current facilities. Furthermore, the increase in the production of blended cements highly depends on the market and its acceptance. Thus, the market could be targeted for the promotion of these types of cement. For the limestone Portland cement, however, the cement plant personnel are uncertain about the reliability of this type of cement, although it is being produced in used in other countries. Thus, further research work may be needed to prove the reliability of this type of cement probably for some applications.

None of the studied cement plants in Shandong Province use alternative fuels. This is a key opportunity for China's cement industry which has not been tapped so far. The reason stated by some cement plant personnel and cement experts is the lack of alternative fuels and as a result its high cost. More supportive policy and applied research work can help the increase in the use of alternative fuels in cement plants in Shandong.

Table 22. Identified Fuel-Saving Opportunities for the 16 Surveyed Cement Plants in Shandong Province

CCE Rank	Measure	Measure No.	Fuel Saving (TJ)
1	Blended cement	33	2,011
2	Limestone Portland cement	34	105
3	Kiln shell heat loss reduction (Improved refractories)	12	2,177
4	Use of alternative fuels	30	1,749
5	Optimize heat recovery/upgrade clinker cooler	15	231
6	Energy management and process control systems in clinker making	13	1,676

Blended Cement. The production of blended cements involves the intergrinding of clinker with one or more additives (fly ash, pozzolans, blast furnace slag, volcanic ash) in various proportions. Blended cements demonstrate 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 cements 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% (Cembureau, 1997). Blended cements were introduced in the U.S. to reduce production costs for cement (especially energy costs), to expand capacity without extensive capital costs, to reduce emissions from the kiln. The use and production of blended cement is still limited in the U.S. However, Portland ordinary cement and Portland slag cement are used widely in cement produced in China. In addition, due to technical advancement and market development allowing the production of different kinds and grades of cement, some industrial byproducts like blast furnace slag, fly ash, coal gangue, limestone, zeolite, pozzolana as well as natural minerals are widely used in cement production. The average percentage of admixtures in Chinese cement products stands at 24% to 26% (ITIBMIC, 2005).

China produces 25 Mt of blast furnace slag per year and has a long history of using this type of waste. Where utilized, about 20 to 25% of clinker is replaced; the country's highest slag ratio is 50%. In addition, blast furnace slag is added into concrete as well as clinker. Fly ash is also increasingly being used in China (Cui, 2004; Cui, 2006).

Prices for different additives vary greatly. Prices change with location, output, market need, produce type and ways of handling. Fuel savings of at least 10% is estimated with a similar increase in production (ITIBMIC, 2005). The use of blended cements is a particularly attractive efficiency option since the intergrinding of clinker with other additives not only allows for a reduction in the energy used (and carbon emissions) in clinker production, but also corresponds to a reduction in carbon dioxide emissions in calcination as well. For blended cement with, on average, a clinker/cement ratio of 65%, the reduction in clinker production corresponds to a specific fuel savings of 1.42 GJ/t cement (48.5 kgce/t cement). There is an increase in fuel use of 0.09 GJ/t cement (3.1 kgce/t cement) for drying of the blast furnace slags but a corresponding energy savings of 0.2 GJ/t cement (7 kgce/t cement) for reducing the need to use energy to bypass kiln exit gases to remove alkali-rich dust. Energy savings are estimated to be 9 to 23 MJ/t cement (0.3 to 7.1 kgce/t cement) per percent bypass (Alsop and Post, 1995). The bypass savings are due to the fact that blended cements offer an additional advantage in that the inter-ground materials also lower alkali-silica reactivity (ASR), thereby allowing a reduction in energy consumption needed to remove the high alkali content kiln dusts. In practice, bypass savings may be minimal to avoid plugging of the preheaters, requiring a minimum amount of bypass volume. This measure therefore results in total fuel savings of 1.4 GJ/t blended cement (48 kgce/t blended cement) (0.9 GJ/t clinker or 31 kgce/t clinker for 0.65 clinker to cement ratio). However, electricity consumption is expected to increase, due to the added electricity consumption associated with grinding blast furnace slag (as other materials are more or less fine enough).

The costs of applying additives in cement production may vary. Capital costs are limited to extra storage capacity for the additives. However, blast furnace slag may need to be dried before use in cement production. This can be done in the grinding mill, using exhaust from the kiln, or supplemental firing, either from a gas turbine used to generate power or a supplemental air heater. The operational cost savings will depend on the purchase (including transport) costs of the additives, [11] the increased electricity costs for (finer) grinding, the reduced fuel costs for clinker production and electricity costs for raw material grinding and kiln drives, as well as the reduced handling and mining costs. These costs will vary by location, and would need to be assessed on the basis of individual plants. An increase in electricity consumption of 16.5 kWh/t cement (11 kWh/t clinker) (Buzzi, 1997) is estimated while an investment cost of \$0.72/t cement capacity (\$0.5/t clinker), which reflects the cost of new delivery and storage capacity (bin and weigh-feeder) is assumed.

Portland Limestone Cement. Similar to blended cement, ground limestone is interground with clinker to produce cement, reducing the needs for clinker-making and calcination. This measure reduces energy use in the kiln and clinker grinding as well as CO_2 emissions from calcination and energy use. The addition of up to 5% limestone has shown to have no negative impacts on the performance of Portland cement, while optimized limestone cement would improve the workability slightly (Detwiler and Tennis, 1996).

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 (Venkateswaran and Lowitt, 1988). Refractory choice is the function of insulating qualities of the brick and the ability to develop and maintain a coating. The coating helps to reduce heat losses and to protect the burning zone refractory bricks. Refractories protect the steel kiln shell against heat, chemical and mechanical stress. The choice of refractory material depends on the combination of raw materials, fuels and operating conditions.

Extended lifetime of the higher quality refractories will lead to longer operating periods and reduced lost production time between relining of the kiln, and, hence, offset their higher costs (Schmidt, 1998). The use of improved kiln-refractories may also lead to improved reliability of the kiln and reduced downtime, reducing production costs considerably, and reducing energy needs during start-ups. Estimates suggest that the development of high-temperature insulating linings for the kiln refractories can reduce fuel use by 0.12 to 0.4 GJ/t (4.1 to 13 kgce/t) of clinker (Lowes and Bezant, 1990; COWIconsult, 1993; Venkateswaran and Lowitt, 1988). Costs for insulation systems are estimated to be \$0.25/annual tonne clinker capacity (Lesnikoff, 1999). Structural considerations may limit the use of new insulation materials.

Use of Alternative Fuels. Alternative, or waste, fuels can be substituted for traditional commercial fuels in a cement kiln. In North America, many of the alternative fuels are focused on the use of tires or tire-derived fuel. Since 1990 more than 30 cement plants have gained approval to use tire-derived fuels, burning around 35 million tires per year (CKRC, 2002). Other plants have experience injecting solid and fluid wastes, as well as

[11] To avoid disclosing proprietary data, the USGS does not report separate value of shipments data for "cement-quality" fly ash or granulated blast furnace slag, making it impossible to estimate an average cost of the additives.

ground plastic wastes. Tires accounted for almost 5% of total fuel inputs in the U.S. cement industry in 1999 and all wastes total about 17% of all fuel inputs. New waste streams include carpet and plastic wastes, filter cake, paint residue and (dewatered) sewage sludge (Hendriks et al,. 1999). Cement kilns also burn hazardous wastes; since the early 1990's cement kilns burn annually almost 1 Mt of hazardous waste (CKRC, 2002).

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). 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 (Hendriks et al., 1999).

Currently, in China only three cement plants are burning waste fuels. Beijing Cement Plant has the capacity to dispose of 10 kt per year of 25 types of waste; the plant is burning solid waste from the chemical industry, some paints, solvents and waste sludge from water treatment Shanghai Jinshan Cement Plant disposes of sludge dredged from the Huangpu River which runs through Shanghai (Cui, 2004; Cuil, 2006). Hong Kong Cement Plant purchases waste from other provinces to utilize in its kilns. Other plants are utilizing wastes but the amounts are very small (Wang, X. 2006).

The revenues from waste intake have helped to reduce the production costs of all waste-burning cement kilns, and especially of wet process kilns. Waste-derived fuels may replace the use of commercial fuels, and may result in net energy savings and reduced CO_2 emissions, depending on the alternative use of the wastes (for example. incineration with or without energy recovery). A net reduction in operating costs by injecting solid and fluid wastes, as well as ground plastic wastes is assumed (CADDET, 1996; Gomes, 1990; Venkateswaran and Lowitt, 1988). Investment costs are estimated to be $1.1/annual tonne clinker for a storage facility for the waste-derived fuels and retrofit of the burner (if needed).

Optimize Heat Recovery/Update Clinker Cooler. The clinker cooler drops the clinker temperature from 1200°C down to 100°C. The most common cooler designs are of 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 (Alsop and Post, 1995). 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 highest temperature portion of the remaining air can be used as tertiary air for the precalciner. Rotary coolers (used for approximately 5% of the world clinker capacity for plants up to 2200 to 5000 tpd) and planetary coolers (used for 10% of the world capacity 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 (Buzzi and Sassone, 1993; Vleuten, 1994).

Grate coolers may recover between 1.3 and 1.6 GJ/t (44 to 55 kgce/t) clinker sensible heat (Buzzi and Sassone, 1993). Heat recovery can be improved through reduction of excess air volume, control of clinker bed depth and new grates such as ring grates (Alsop and Post, 1995; Buzzi and Sassone, 1993). Improving heat recovery efficiency in the cooler results in fuel savings, but may also influence product quality and emission levels. Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. Additional heat recovery results in reduced energy use in the kiln and precalciner, due to higher combustion air temperatures. Birch, (1990) notes a savings of 0.05 to 0.08 GJ/t (2 to 3 kgce/t) clinker through the improved operation of the grate cooler, while Holderbank, (1993) notes savings of 0.16 GJ/t (5.4 kgce/t) clinker for retrofitting a grate cooler. COWIconsult et al. (1993) note savings of 0.08 GJ/t (3 kgce/t) clinker but an increase in electricity use of 2.0 kWh/t clinker. The costs of this measure are assumed to be half the costs of the replacement of the planetary with a grate cooler, or $0.22/annual tonne clinker capacity. A recent innovation in clinker coolers is the installation of a static grate section at the hot end of the clinker cooler. This has resulted in improved heat recovery and reduced maintenance of the cooler. Modification of the cooler would result in improved heat recovery rates of 2 to 5% over a conventional grate cooler. Investments are estimated to be $0.11 to $0.33/annual tonne clinker capacity (Young, 2002).

Energy Management and Process Control Systems in Clinker Making. Heat from the kiln may be lost through non-optimal process conditions or process management. Automated computer control systems help to optimize the combustion process and conditions. Improved process control will also improve product quality and grindability, for example reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding. A uniform feed allows for steadier kiln operation, saving on fuel requirements. In cement plants across the world, different systems are used, marketed by different manufacturers. Most modern systems use so-called "fuzzy logic" or expert control, or rule-based control strategies. If automatic controls are going to be successfully implemented, they must link all processes from mine management to raw materials input into the kiln to kiln fuel input in order to realize stable production; none should be done manually (ITIBMIC, 2004).

Expert control systems do not use a modeled process to control process conditions, but try to simulate the best human operator, using information from various stages in the process. One such system, called ABB LINKman, was originally developed in the United Kingdom by Blue Circle Industries and SIRA (ETSU, 1988). Other developers also market "fuzzy logic" control systems, for example, F.L. Smidth (Denmark) Krupp Polysius (Germany) and Mitsui Mining (Japan). 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. Several companies in China provide optimized information technology for energy management and process control, such as the ABB or the Chinese software company Yun Tian (Wang, 2006). Most technologies for this measure are made by international companies such as Siemens and ABB; few if any are made by domestic companies (Cui, 2004; Cui, 2006).

Energy savings from process control systems vary between 2.5% and 10% (ETSU, 1988), and the typical savings are estimated to be 2.5 to 5%. All control systems described here report typical energy savings of 3 to 8%, while improving productivity of the kiln. For example, Krupp Polysius reports typical savings of 2.5 – 5%, with similar increased throughput and increased refractory life of 25 –100%. The economics of advanced process control systems are very good and payback periods can be as short as 3 months (ETSU, 1988). A payback period of 2 years or less is typical for kiln control systems, while often much lower payback periods are achieved (ETSU, 1988). Process control of the clinker cooler can help to improve heat recovery, material throughput and improved control of free lime content in the clinker, and to reduce NOx emissions (Martin et al., 2000). Installing a Process Perfecter® (of Pavilion Technologies Inc.) has increased cooler throughput by 10%, reduced free lime by 30% and reduced energy by 5%, while reducing NOx emissions by 20% (Martin et al., 1999; Martin et al., 2001). The installation costs equal $0.35/annual tonne of clinker, with an estimated payback period of 1 year (Martin et al., 1999). 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 each, and by automating the weighing process and the pellet production (water content and raw feed mixtures), the blending process, the kiln operation (optimizing air flow, temperature distribution, and the speed of feeding and discharging).

E. Barriers to the Adoption of Energy-Efficiency Technologies and Measures in the Cement Industry in Shandong Province

There are various reasons cited by cement plant personnel and Chinese cement experts regarding why the plants have not adopted even the cost-effective measures identified in this study. Some of the common reasons are 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, plant-specific operational conditions (e.g., in one of the studied plants, due to the low cooling performance of the grate cooler, fans are on full speed so installing a VFD in the cooler fan of grate cooler is not possible), investors preferences, and high initial cost despite the fact that the payback period of the technology is short.

Most of the NSP production lines surveyed in this study were built in the period 2004-2008. Even so, they did not always install the most energy-efficient equipment for various reasons. Now that the new plants are operating, it may be difficult to convince the top management to retrofit the equipment to improve energy efficiency except in the cases where the investment cost is very low or the payback is very short.

Some of the surveyed plants indicated that they are planning to implement some of the measures which were identified as cost effective, but they have not yet realized these plans for various reasons. For example, in the case of high efficiency motors, some plants may be waiting for the end of the lifetime of the existing motors to substitute them with high efficiency ones. Other reasons could be organizational issues, bureaucracy issues, long approval process in the company, lack of knowledge or confidence about certain technologies, etc. Also, many of the plants indicated that they have plans for the installation of high efficiency motors and VFD, yet those plans might not cover all of the identified energy-saving potential.

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

- ***Management concerns about the investment costs of energy efficiency measures***: Some of the energy efficiency measures have high capital cost. Even though the payback period of the measure might be short, some cement plants have difficulty acquiring the high initial investment funds.

- ***Management considers production more important***: In many industrial plants, the focus of the top management is the production, the quality of final products, and the market. Thus, energy efficiency might not get the due attention. This is also the case in some cement plants, although it might be less severe compared to some other less-energy intensive industries, as energy cost is a substantial part of the production cost in a cement plant.

- ***Management concerns about time required to improve energy efficiency***: In the cement industry, the cost of production disruption could be high which is why the time required for the implementation of some energy efficiency measures is of high importance in this sector.

- ***Lack of coordination between external organizations***: Different ministries and government institutions responsible for energy and environmental issues are not well-coordinated with each other, thus the implementation of energy and environmental regulation lacks the efficient execution and enforcement.

- ***Current installations are considered sufficiently efficient***: This especially the case in the newly-installed cement production lines, although they may not be as efficient as the best commercially available technologies.

Based on the preliminary information available regarding the barriers to adoption of cost-effective energy-efficient technologies and measures in Shandong Province, it is recommended that further research related to the implementation barriers for the identified cost-effective technologies and measures be undertaken in order to more thoroughly understand the types of interventions that may be effective at barrier removal.

V. Findings and Recommendations

A. Findings

The 16 surveyed cement plants in Shandong Province were compared to international and domestic (Chinese) best practice in terms of energy efficiency using BEST-Cement. Such a comparison provides an initial assessment of the technical potential for energy-efficiency improvement by comparing a plant to an identical model of itself using the most energy-efficient technologies and measures available.

This assessment found that when compared to international best practice, none of the surveyed cement plants were at or near this benchmark. Using an energy efficiency index to compare the plants resulted in scores ranging from 117 to 159, indicating potential savings of 15% to 37% in terms of primary energy. The average identified technical potential based on international best practice was 24%.

When compared to domestic (Chinese) best practice, however, 5 of the 16 surveyed plants were quite close to best practice, with scores ranging from 102 to 107. Overall the range of scores was from 102 to 133, indicating potential savings of 2% to 25% in terms of primary energy. The average identified technical potential based on domestic best practice was 12%.

Bottom-up Energy Conservation Supply Curves (i.e. ECSC and FCSC) constructed in this study for the 16 cement plants in Shandong Province determine the potentials and costs of energy-efficiency improvements by taking into account the costs and energy savings of different technologies. Many cost-effective opportunities for energy efficiency improvement in the studied plants were identified which have not been adopted, leading to what is called an "efficiency gap" (Jaffe and Stavins, 1994). This is explained by the existence of various obstacles especially non-monetary barriers to energy-efficiency improvement in cement industry.

Thirty-four energy-efficiency technologies and measures for cement industry were analyzed. Using the bottom-up electricity conservation supply curve model, the cost-effective electricity efficiency potential for the studied cement plants in 2008 is estimated to be 373 GWh, which accounts for 16% of total electricity use in the 16 surveyed cement plants in 2008. Total technical electricity-saving potential is 915 GWh, which accounts for 40% of total electricity use in the studied plants in 2008. CO_2 emission reduction potential associated with cost-effective electricity saving is 373 kiloton $ktCO_2$, while total technical potential for CO_2 emission reduction is 915 $ktCO_2$. The fuel conservation supply curve model shows the total technical fuel efficiency potential equal to 7,949 TJ, accounting for 8% of total fuel used in the studied cement plants in 2008. All the fuel efficiency potential is shown to be cost effective. CO_2 emission reduction potentials associated with fuel saving potentials is 950 $ktCO_2$.

A sensitivity analysis was conducted for four key parameters which are involved in the analysis, i.e. discount rate, electricity and fuel prices, investment cost of the measures, and energy saving of the measures. For this study, the reduction of discount rate from 35% to 15% will increase the cost effective electricity saving from 317 GWh to 631 GWh. The cost effective fuel saving, however, will not change by the change in the discount rate from 35% to 15% and it will remain equal to 7,949 TJ. The 30% increase in 2008 electricity price will increase the cost effective electricity saving from 545 GWh to 709 GWh, whereas 10% decrease in 2008 electricity price will decrease the cost effective electricity saving from 545 GWh to 491 GWh. The increase in the fuel price will not change the cost effective fuel saving potential. Moreover, the change in the fuel price for cement plants down to -60% decrease will not change the cost effective fuel saving potential. Technical energy saving and CO_2 emission potentials do not change with the variation of discount rate and energy prices.

The cost-effective electricity saving potential increases from 317 GWh to 622 GWh if the investment costs of the energy-efficiency technologies are decreased from the base case+20% to base case-20%. However, the cost-effective fuel saving potential and its associated CO_2 emission reductions does not change if the investment costs change in the range of ±20%. Nevertheless, although the cost-effective fuel-saving potential does not change, the cumulative Cost of Conserved Fuel declines by the decrease in the investment cost of the technologies. The cost-effective electricity savings potential increases from 253 GWh to 529 GWh and the cost-effective fuel savings potential increases from 6,359 TJ to 9,539 TJ with the increase in the energy-saving potential of the energy-efficiency technologies from the base case-20% to base case+20%. The total electricity savings potential and fuel savings potential also increase by the increase in energy saving potential of each measure regardless of the cost-effectiveness. Furthermore, the cumulative CCE and CCF decreases by the increase in the energy-saving potential of the technologies.

B. Recommendations

A number of recommendations can be made based on the findings of this study as presented above.

First, it is recommended that the BEST-Cement tool be further utilized by the 16 surveyed cement plants. The findings presented in this study indicate that there are a number of cost-effective energy-efficiency technologies and measures that can still be implemented in these plants. Now that the input data has been acquired and entered into BEST-Cement for each plant, the tool is ready for application at the plant-level. Such application involves working with the plant engineers to identify packages of energy-efficiency technologies and measures that they would like to install at the plant. BEST-Cement allows the plant engineers to develop various packages and provides them with information on the individual measure and total package implementation costs, O&M costs, energy savings, simple payback time, and CO_2 emissions reductions. Such packages can be developed in order to meet a specific energy-saving or CO_2 emissions reduction target or to meet a specific energy-saving financial budget.

Second, it is recommended that further research related to the implementation barriers for the identified cost-effective technologies and measures be undertaken. Now that a number of cost-effective technologies and measures have been identified, it is important to understand why they haven't been adopted by the 16 surveyed cement plants. An understanding of the barriers is an important first step in developing programs and policies to promote further implementation of energy-efficiency opportunities.

Third, once the barriers have been identified and are understood, it is important to develop effective programs and policies to overcome the barriers to adoption. Such programs and policies could include development of energy-efficiency information resources, technical assistance in identifying and implementing energy-efficiency measures, and financing programs for the identified technologies and measures.

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Acronyms

AAGR	average annual growth rate
APP	Asia Pacific Partnership on Clean Energy and Climate
AQC	air quenching chamber
ASD	adjustable speed drive
ASTAE	Asia Alternative Energy Unit
BEST-Cement	Benchmarking and Energy Saving Tool for Cement
CBMA	China Building Materials Academy
CCA	China Cement Association
CCAP	Center for Clean Air Policy
CCATC	China Cement Association's Technology Center
CCE	Cost of Conserved Energy
CCE	Cost of Conserved Electricity
CCF	Cost of Conserved Fuel
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CO_2	carbon dioxide
CSC	Conservation Supply Curve
ECSC	Electricity Conservation Supply Curve
EII	energy intensity index
ERI	Energy Research Institute
ETC	Economic and Trade Commission
FCSC	Fuel Conservation Supply Curve
GGBS	ground granulated blast-furnace slag
GHG	greenhouse gas
GJ	gigajoule
GWh	gigawatt-hour
HPRP	high pressure roller press
IPCC	Intergovernmental Panel on Climate Change
ITIBMIC	Institute of Technical Information for the Building Materials Industry of China
kgce	kilograms of coal equivalent
$kgCO_2$	kilograms carbon dioxide
kt	kiloton
$ktCO_2$	kilotons carbon dioxide
kWh	kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
LHV	lower heating value
Mt	metric tons
mtce	million tons of coal equivalent
MWh	megawatt-hour
N/A	not available
NBS	National Bureau of Statistics

NDRC	National Development and Reform Commission
NSP	new suspension pre-heater and pre-calciner
O&M	operations & maintenance
PDD	Project Design Document
RMB	Reminbi
RP	roller press
SP	suspension pre-heater
tce	ton coal equivalent
TJ	terajoules
tpd	tons per day
TWh	terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
U.S.	United States
USGS	United States Geological Society
VFD	variable frequency drive
VRM	vertical roller mill
VSK	vertical shaft kiln
WBCSD	World Business Council on Sustainable Development
WHR	waste heat recovery
WWF	World Wide Fund for Nature

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Appendix A. Phase II Data Collection Form

Survey of Energy-Saving Potentials and Investment Returns of Major Cement Enterprises in Shandong Province

I. Enterprise's Contact Information

Enterprise Name:

Address: Zip code:

	Name	Position	Tel	Cell	E-Mail
Contact Person 1					
Contact Person 2					

II. Enterprise's Basic Information

Enterprise Superior Unit	
Enterprise Attribute	□ SOE
Percentage of Shares	
Date Production Began **Line 1** **Line 2** **Line 3**	
Current Clinker Production Capacity (ton/year) **Line 1** **Line 2** **Line 3**	
Current Cement Production Capacity (ton/year) **Line 1** **Line 2** **Line 3**	

III. Enterprise's Production Information

Yearly Actual Clinker Production (ton)

	2007	2008
1st Production Line		
2nd Production Line		
3rd Production Line		
Purchased Clinker		
Sold Clinker		
Total		

Yearly Actual Cement Production: Line 1 (ton)

	% Cementitious Materials	2007	2008
Pure Portland Cement			
Common Portland Cement			
Slag Cement			
Pozzolana Cement			
Fly Ash Cement			
Blended Cement			
Others			
Total			
Please explain if you do not use the maximum allowable % of supplementary cementitious materials			

Yearly Actual Cement Production: Line 2 (ton)

	% Cementitious Materials	2007	2008
Pure Portland Cement			
Common Portland Cement			
Slag Cement			
Pozzolana Cement			
Fly Ash Cement			
Blended Cement			
Others			
Total			
Please explain if you do not use the maximum allowable % of supplementary cementitious materials			

Yearly Actual Cement Production: Line 3 (ton)

	% Cementitious Materials	2007	2008
Pure Portland Cement			
Common Portland Cement			
Slag Cement			
Pozzolana Cement			
Fly Ash Cement			
Blended Cement			
Others			
Total			
Please explain if you do not use the maximum allowable % of supplementary cementitious materials			

Yearly Actual Raw Materials Usage (ton)

	2007	2008
Calcareous materials		
Aluminum silicon raw materials		
Other (sulfuric acid residue)		
Other (fly ash)		
Other (please specify)		

Yearly Additives Usage (ton)

	2007	2008
Slag		
Fly Ash		
Limestone		
Gypsum		
Other (please specify)		
Other (please specify)		
Total		

Yearly Energy Consumption (ton)

		2007	2008
Coal	Usage (ton)		
	Average heat value (kcal/kg)		
Coke	Usage (ton)		
	Average heat value (kcal/kg)		
Biomass	Usage (ton)		
	Average heat value （kcal/kg）		
Other (please specify)	Usage (ton)		
	Average heat value (kcal/kg)		
Purchased Electricity（kWh）			
Total Electricity Generated Onsite (kWh)			
Electricity Generated onsite and Sold to Grid or Offsite (kWh)			
Electricity Generated onsite and Used at Cement Plant (kWh)			
Diesel (ton)			
Gasoline (ton)			
Waste Heat Power Generation (kWh)			
Waste Heat Used to Generate Electricity (kgce)			
Fuels used to Generate Electricity (coal) (kcal)			
Fuels used to Generate Electricity (please specify) (kgce)			
Fuels used to Generate Electricity (please specify) (kgce)			

IV. Enterprise's Process and Equipment Information

Production Line 1		2007	2008
Yearly Operation Rate（%）			
Detailed Explanation			

Production Line 2		2007	2008
Yearly Operation Rate（%）			
Detailed Explanation			

Production Line 3		2007	2008
Yearly Operation Rate（%）			
Detailed Explanation			

（1） Raw Meal Preparation

Raw Meal Preparation		
	2007	2008
Total amount of raw meal (ton)		
Electricity consumption of raw meal preparation (kWh)		
Fuel consumption for raw meal preparation (please identify the fuel)		

（2） Clinker Making

Clinker Making		
	2007	2008
Total amount of clinker produced (ton)		
Electricity consumption for clinker making (kWh)		
Coal consumption for clinker making (ton)		
Other fuel (identify) consumption for clinker making (ton)		
Other fuel (identify) consumption for clinker making (ton)		
Heat consumption per unit of clinker produced (kJ/kg)		

（3） Cement Grinding and Distribution

Cement Grinding and Distribution		
	2007	2008
Total amount of cement ground (ton)		
Electricity consumption of grinding cement (kWh)		
Electricity consumption per unit of cement ground (kWh/ton)		
Total amount of packaged and distributed cement (ton)		
Electricity consumption of packaging and		

distributing cement (kWh)		

V. Enterprise's Financial Conditions and Operation Results

	2007	2008
Production Costs (RMB)		
Output Value (RMB)		
National Taxation (Central) (RMB)		
Provincial Taxation (Local) (RMB)		
Fixed-assets (RMB)		

	2007	2008
Production Costs (RMB)		
Salaries		
Costs of Materials		
Total costs of coal		
Cost of coal per unit		
Total costs of coke		
Total costs of biomass		
Total costs of other fuel (diesel)		
Total costs of purchased electricity		
Electricity cost per unit		
Other costs		
Output Value (RMB)		
Total amount of sold Clinker (ton)		
Average price of Clinker (yuan/ton)		
Total amount of sold cement (ton)		
Average price of cement (yuan/ton)		
Other output value		

VI. Recent Major Technical Transformation Plans, Investment Returns Analysis and Financing Demands

a. **Does the enterprise have major technical energy-saving transformation plans in recent years (2009-2010)**

b. **Which projects does the energy-saving transformation plans include?**

c. **Does the corporation have CDM projects (waste heat recovery technologies for power generation or alternative raw materials) under development?**

d. **Does the corporation apply for major energy-saving-award projects from NDRC?**

e. **Does this energy-saving transformation plan need external financing (e.g., loans, investment subsidy)? If so, what would be the financing amount?**

f. **What are the expected energy-savings results from these energy-saving transformation plans? How about cost-effectiveness analysis on its investment returns?**

VII. <u>Others</u>

a. **Does each production line have maintenance overhaul plans?**

b. **Is there energy management training for managers and staff? At which level?**

c. **Does computer automatic control system apply to kiln calcination? Is it using fuzzy control or rule-based control?**

d. **Does online analyzer apply to raw material analysis?**

e. **How many motors in each production line? How many of them are normal motors, adjustable speed motors, and high efficiency motors, respectively?**

f. **Does the plant produce blended cement? What is the ratio of fly ash and slag?**

g.

	Energy Efficiency Technologies – Production Line (Please Fill In for Each Production Line)			
	Measures	**Description**	**Is this already installed or used in your plant?**	**If "No", please give a short explanation why it is not implemented.**
NO.	***Raw Materials Preparation***			
1	Raw meal process control for vertical mills	The main difficulty with existing vertical roller mills are vibration trips. Operation at high throughput makes manual vibration control difficult. When the raw mill trips, it cannot be started up for one hour, until the motor windings cool. A model predictive multivariable controller maximizes total feed while maintaining a target residue and enforcing a safe range for trip-level vibration.		
2	High-efficiency classifiers/separators	Standard classifiers may have low separation efficiency, leading to the recycling of fine particles and resulting in to extra power use in the grinding mill. In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing over-grinding.		
3	Raw materials grinding	Do you use ball mill or vertical roller mill or Ball mills combined with high pressure roller presses?		
4	Efficient transport systems for raw materials preparation	Do you use Mechanical conveyor or Pneumatic transport system in the raw material preparation process?		
5	Raw meal blending (homogenizing) systems	Do you use Air-fluidized bed system or Gravity-type homogenizing system for homogenizing?		
6	Variable Frequency Drive (VFD) in raw mill vent fan			
7	Bucket elevator for raw meal transport from raw mill to homogenizing silos			
8	High efficiency fan for Raw Mill vent fan with inverter			
	Fuels Preparation			
9	New efficient coal separator for fuel preparation	In a closed circuit system, larger coal particles are separated from gas and finer coal particles in a classifier or separator. There are static classifiers with a fixed geometry, classifiers with adjustable geometry, and dynamic high efficiency classifiers. Replacing the separator in the coal mill circuit with an efficient grit separator can save energy.		
10	Efficient roller mills			

11	Installation of variable frequency drive & replacement of coal mill bag dust collector's fan			
	Kilns			
12	Improved refractories	The use of better insulating refractories (for example Lytherm) can reduce heat losses. Do you use the energy efficient refractories or the conventional ones? Is it manufactured in Chinese or other countries?		
13	Energy management and process control systems	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. Do you have any of these expert systems?		
14	Adjustable speed drive for kiln's fan			
15	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. Have you done this measure before?		
16	Low temperature heat recovery for power generation			
17	Efficient kiln's drives	A substantial amount of power is used to rotate the kiln. The highest efficiencies are achieved using a single pinion drive with an air clutch and a synchronous motor. Do you have this system for your kiln's drives?		
18	Upgrading the preheater from 5 to 6 stages	If your preheater has less than 5 stages please mention.		
19	Upgrading of a preheater to a preheater/ precalciner kiln			
20	Low pressure drop cyclones	The installation of **newer** cyclones in a plant with lower pressure losses will reduce the power consumption of the kiln exhaust gas fan system.		
21	VFD in cooler fan of grate cooler			
22	Bucket elevators for kiln feed			
23	Replacement of Preheater fan with high efficiency fan			
	Cement Grinding			
24	Energy management and process control	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.		
25	Vertical roller mill			
26	High pressure roller press			
27	Improved grinding media (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.		
28	High efficiency classifiers	Standard classifiers may have low separation efficiency, leading to the recycling of fine particles and resulting in to extra power use in the grinding mill. In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing over-grinding.		
29	Replacement of Cement Mill vent fan with high efficiency fan			
	General measures			
30	Use of alternative fuels	Do you use any alternative fuels? If "Yes", what kind of fuels?		
31	High efficiency motors	Do you use high efficiency motor for the large motors?		
32	Variable speed drives	Do you use Variable speed drives for the large motors and fans?		

Appendix B. Description of Domestic (Chinese) and International Best Practice Values

Domestic (Chinese) Best Practice Values

To determine domestic (Chinese) best practice values, four modern Chinese cement plants were audited and best practices determined at each plant by the Energy Research Institute (ERI) and the China Cement Association. Two of these plants were 2000 tonnes per day (tpd) and two were 4000 tpd.

Chinese best practices for each stage of production were determined from these plants. Where no data was available (for example, non-production energy use), international best practices were used.

International Best Practice Values

For the international best practices at each stage of production, data were gathered from public literature sources, plants, and vendors of equipment. These data and calculations are described below.

Raw Materials and Fuel Preparation

Energy used in preparing the raw material consists of pre-blending (pre-homogenization and proportioning), crushing, grinding and drying (if necessary) the raw meal which is mostly limestone. All materials are then homogenized before entering the kiln. Solid fuels input to the kiln must also be crushed, ground, and dried. Best practice for raw materials preparation is based on the use of a longitudinal pre-blending store with either bridge scraper or bucket wheel re-claimer or a circular pre-blending store with bridge scraper re-claimer for pre-blending (pre-homogenization and proportioning) at 0.5 kWh/t raw meal (Cembureau, 1997) a gyratory crusher at 0.38 kWh/t raw meal (PCA, 2004), an integrated vertical roller mill system with four grinding rollers and a high-efficiency separator at 11.45 kWh/t raw meal for grinding (Schneider, 1999), and a gravity (multi-outlet silo) dry system at 0.10 kWh/t raw meal for homogenization (PCA, 2004). Based on the above values, the overall best practice value for raw materials preparation is 12.05 kWh/t raw material. Ideally this value should take into account the differences in moisture content of the raw materials as well as the hardness of the limestone. Higher moisture content requires more energy for drying and harder limestone requires more crushing and grinding energy. If drying is required, best practice is to install a pre-heater to dry the raw materials, which decreases the efficiency of the kiln. For BEST-Cement, it is assumed that pre-heating of wet raw materials is negligible and does not decrease the efficiency of the kiln.

Solid fuel preparation also depends on the moisture content of the fuel. It is assumed that only coal needs to be dried and ground and that the energy required for drying or grinding of other materials is insignificant or unnecessary. Best practice is to use the waste heat from the kiln system, for example, the clinker cooler (if available) to dry the coal (Worrell and Galitsky, 2004). Best practice using an MPS vertical roller mill is 10-36 kWh/t anthracite, 6-12 kWh/t pit coal, 8-19 kWh/t lignite, and 7-17 kWh/t petcoke (Kraft, B. and Reichardt, Y., 2005) or using a bowl mill is 10-18 kWh/t product (PCA, 2004). Based on the above, it is assumed that best practice for solid fuel preparation is 10 kWh/t product.

Additives Preparation

In addition to clinker, some plants use additives in the final cement product. While this reduces the most energy intensive stage of production (clinker making), as well as the carbonation process which produces additional CO_2 as a product of the reaction, some additives require additional electricity for blending and grinding (such as fly ash, slags and pozzolans) and/or additional fuel for drying (such as blast furnace and other slags).

Additional requirements from use of additives are based on the differences between blending and grinding Portland cement (5% additives) and other types of cement (up to 65% additives). Portland Cement typically requires about 55 kWh/t for clinker grinding, while fly ash cement (with 25% fly ash) typically requires 60 kWh/t and blast furnace slag cement (with 65% slag) 80 kWh/t (these are typical grinding numbers only used to determine the additional grinding energy required by additives, not best practice; for best practice refer to data below in cement grinding section). It is assumed that only fly ash, blast furnace and other slags and natural pozzolans need additional energy. Based on the data above, fly ash will require an additional 20 kWh/t of fly ash and slags will require an additional 38 kWh/t of slag. It is assumed that natural pozzolans have requirements similar to fly ash. These data are used to calculate cement grinding requirements. For additives which are dried, best practice requires 0.75 GJ/t (26 kgce/t) of additive. Generally, only blast furnace and other slags are dried. Those additives that need to be dried (the default is all slags, although the user can enter this data as well in the production input sheet) best practice requires an additional 0.75 GJ/t (26 kgce/t) of additive.

Kiln

Clinker production can be split into the electricity required to run the machinery, including the fans, the kiln drive, the cooler and the transport of materials to the top of the pre-heater tower ("kiln pre-heaters" and "cooler system"), and the fuel needed to dry, to calcine and to clinkerize the raw materials ("pre-calcination", if applicable, and the "kiln"). Best practice for clinker making mechanical requirements is estimated to be 22.5 kWh/t clinker (COWIconsult, 1993), while fuel use has been reported as low as 2.85 GJ/t (97.3 kgce/t) clinker (Park, 1998).

Final Grinding

Best practice for cement grinding depends on the cement being produced, measured as fineness or Blaine (cm^2/g). In 1997, it was reported that the Horomill required 25 kWh/tonne of cement for 3200 Blaine and 30 kWh/tonne cement for 4000 Blaine (Buzzi, 1997). The following assumptions are made regarding Chinese cement types: 325 = a

Blaine of less than or equal to 3200; 425 = a Blaine of approximately 3500; 525 = a Blaine of about 4000; and, 625 = a Blaine of approximately 4200. More recent estimates of Horomill energy consumption range between 16 and 19 kWh/tonne (Hendriks et al., 2004). Best practice values for the Horomill for 3200 and 4000 Blaine were used and interpolated and extrapolated values based on an assumed linear distribution for 3500 and 4200 Blaine. It was estimated that the lowest quality cement requires 16 kWh/tonne and that 3500 Blaine is 8% more than 3200 Blaine (17.3 kWh/tonne), 4000 Blaine is 20% more than 3200 Blaine (19.2 kWh/tonne), and 4200 Blaine is 24% more than 3200 Blaine (19.8 kWh/tonne). These values were then used to estimate the values of other types of cement, based on more or less grinding that would be needed for any additives. Common Portland cement grinding is assumed to require similar energy as pure Portland cement. It was also assumed that blended slag and fly ash cements were on average 65% slag and 35% fly ash and that grinding pozzolans required similar energy as grinding slags (at a similar ratio of 65%) and that limestone cement contained 5% extra limestone with grinding requirements similar to grinding slag.

Other Production Energy Uses

Some cement facilities have quarries on-site, and those generally use both trucks and conveyors to move raw materials. If applicable to the cement facility, quarrying is estimated to use about 1% of the total electricity at the facility (Warshawsky, 1996).

Other production energy includes power for auxiliaries and conveyors within the facility. (Packaging is excluded from the analysis). Total power use for auxiliaries is estimated to require about 10 kWh/t of clinker at a cement facility. Power use for conveyors is estimated to require about 1 to 2 kWh/t of cement (Worrell and Galitsky, 2004). Lighting, office equipment, and other miscellaneous electricity uses are estimated to use about 1.2% of the total electricity at the facility (Warshawsky, 1996).

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Appendix C. Description of Energy-Efficiency Technologies and Measures[1]

Fuel Preparation

1. New Efficient Coal Separator

An external, high efficiency fan provides airflow through the material that is falling from the distribution plate into a cage rotor with a variable speed drive. Gravity and centrifugal force cause the heavy particles to separate while the fines are carried away as dust-laden air. This type of coal separator improves the capacity of the grinding system and also improves product quality because of the more uniform particle size.

2. Efficient Roller Mills 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. Coal is shipped wet to prevent dust formation and fire during transport. Passing hot gasses through the mill combines the grinding and drying (Cembureau, 1997).

3. Installation of Variable Frequency Drive and Replacement of Coal Mill Bag Dust Collector Fan

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

Raw Materials Preparation

4. Raw Meal Process Control for Vertical Mill

Raw meal process control, such as a model predictive multivariable controller, eliminates avoidable vibration trips, and reduces down-time while the mill cools (Cembureau, 1997).

5. High Efficiency Classifiers/Separators

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 and resulting in to extra power use in the grinding mill. In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing over-grinding.

6. High Efficiency Roller Mill for Raw Materials Grinding

Traditional ball mills used for grinding certain raw materials (mainly hard limestone) can be replaced by high-efficiency roller mills, by ball mills combined with high-pressure roller presses, or by horizontal roller mills. The use of these advanced mills saves energy without compromising product quality (Holderbank Consulting, 1993). An additional advantage of the inline vertical roller mills is that they can combine raw material drying with the

[1] Excerpted from Worrell, et al., (2008) and LBNL and ERI, (2008) and UNFCCC (2007a,b,c,d).

grinding process by using large quantities of low grade waste heat from the kilns or clinker coolers (Venkateswaran and Lowitt, 1988).

7. Efficient Transport System for Raw Materials Preparation

Transport systems are required to convey powdered materials such as kiln feed, kiln dust, and finished cement throughout the plant. These materials are usually transported by means of either pneumatic or mechanical conveyors. Mechanical conveyors use less power than pneumatic systems. Conversion to mechanical conveyors is cost-effective when replacement of conveyor systems is needed to increase reliability and reduce downtime.

8. 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) reducing 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 (Gerbec, 1999).

9. Variable Frequency Drive (VFD) in Raw Mill Vent Fan

Variable frequency drives (VFDs) can be installed in raw mill vent fans to reduce the fan speed and keep the damper open to meet airflow requirements, thus avoiding high-pressure loss across the damper with leads to high power consumption (UNFCCC, 2007b).

10. Bucket Elevator for Raw Meal Transport from Raw Mill to Homogenizing Silos

In the Birla Cement Works, Chittorgarh Company, India, the pneumatic transport system from raw mill # 1 & 2 to homo silos in kiln # 1 & 2 was replaced with mechanical transport system resulting in the power savings of 2.35 kWh/t of clinker. The capital cost for the measure was around $ 0.228 / annual ton clinker capacity (UNFCCC, 2007b).

11. 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. These reduced the energy consumption by 0.36 kWh/ton clinker. The capital cost for the measure was around $ 0.033 / annual ton clinker capacity (UNFCCC, 2007c).

Clinker Making

12. 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 (Venkateswaran and Lowitt, 1988). Extended lifetime of the higher quality refractories will lead to longer operating periods and reduced lost production time between relining of the kiln, and, hence, offset their higher costs (Schmidt, 1998). The use of improved kiln-refractories may also lead to improved reliability of the kiln and reduced downtime, reducing production costs considerably, and reducing energy needs during start-ups. Structural considerations may limit the use of new insulation materials.

13. Energy Management and Process Control Systems in Clinker Making

Automated computer control systems help to optimize the combustion process and conditions. Improved process control will also improve product quality and grindability, for example reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding. A uniform feed allows for steadier kiln operation, saving on fuel requirements. Expert control systems simulate the best human operator, using information from various stages in 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 to improve heat recovery, material throughput and improved control of free lime content in the clinker, and to reduce NOx emissions (Martin et al., 2000). 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 each, and by automating the weighing process and the pellet production (water content and raw feed mixtures), the blending process, the kiln operation (optimizing air flow, temperature distribution, and the speed of feeding and discharging).

14. Adjustable Speed Drives for Kiln Fan

Adjustable or variable speed drives (ASDs) for the kiln fan result in reduced power use and reduced maintenance costs.

15. Optimize Heat Recovery/Update Clinker Cooler

The clinker cooler drops the clinker temperature from 1200°C down to 100°C. The most common cooler designs are of 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 (Alsop and Post, 1995). 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 highest temperature portion of the remaining air 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 (Buzzi and Sassone, 1993; Vleuten, 1994). Heat recovery can be improved through reduction of excess air volume, control of clinker bed depth and new grates such as ring grates (Alsop and Post, 1995; Buzzi and Sassone, 1993). Improving heat recovery efficiency in the cooler results in fuel savings, but may also influence product quality and emission levels. Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. Additional heat recovery results in reduced energy use in the kiln and precalciner, due to higher combustion air temperatures.

16. Low Temperature Waste Heat Recovery for Power Generation

A large amount of energy consumption for the production of cement 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 clinker production process, a significant amount of heat is typically vented to the atmosphere without utilization. This situation wastes natural resources and causes serious heat pollution in the workplace. 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.

17. Efficient Kiln Drives

A substantial amount of power is used to rotate the kiln. The highest efficiencies are achieved using a single pinion drive with an air clutch and a synchronous motor (Regitz, 1996). The system would reduce power use for kiln drives by a few percent, or roughly 0.55 kWh/t clinker at slightly higher capital costs (+6%). More recently, the use of alternate current (AC) motors is advocated to replace the traditionally used direct current (DC) drive. The AC motor system may result in slightly higher efficiencies (0.5 – 1% reduction in electricity use of the kiln drive) and has lower investment costs (Holland, 2001). Replacing older motors with high-efficiency ones may reduce power costs by 2 to 8%.

18. Upgrade Preheater from 5 Stages to 6 Stages

A preheater is a counter-current flow heat exchanger consists of number of cyclones to transfer heat from gases to the material. In the cyclone of a preheater, there are two parts. The upper part called riser duct (raw meal) is meant for heat transfer, whereas the cone and cylindrical part act as a separator. Material falls down and is transferred to another cyclone, whereas gases are sucked by means of preheater fan. At the entry point, raw meal temperature is approx. 70 degree Celsius, but when it reaches kiln inlet its temperature increases up to 1000 degree Celsius. The gas which flows from kiln is at 1100 degree Celsius and when it passes out of the 5th stage of preheater it is approx. 300 degree Celsius and at the outlet of the 6th stage, it is 260 degree Celsius. By adding one extra stage to 5-stage preheater, the preheater exit gas temperature reduces to 260 degree Celsius from 300 degree Celsius. This 40 degree Celsius temperature drop gives further reduction in specific fuel consumption. In practice, by addition of one stage, raw feed, which enters the preheater tower, has sufficient time to absorb temperature from gas and cool down preheater exit gas. By this retrofit measure, it is possible to achieve fossil fuel saving and feed more raw meal through kiln.

19. Upgrade 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, when possible an extra preheater. The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption and reducing thermal NOx 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 NOx emission reduction.

20. 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, if an inline raw mill follows it, the dust carryover problem becomes less of an issue.

21. VFD in Cooler Fan of Grate Cooler

Variable frequency drives (VFDs) can be installed for the cooler fan of the grate cooler to reduce the fan speed and keep the damper open to meet airflow requirements, thus avoiding high-pressure loss across the damper with leads to high power consumption (UNFCCC, 2007b).

22. Bucket Elevator for Kiln Feed

Pneumatic transport systems for kiln feed can be replaced with a mechanical transport system resulting in electricity savings (UNFCCC, 2007b).

23. Replacement of Preheater Fan with High Efficiency Fan

Older generation, low-efficiency, high energy-consuming pre-heater fans can be replaced with a high efficiency fan resulting in electricity savings (UNFCCC, 2007c).

Finish Grinding

24. 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 (Martin et al., 2001; Albert, 1993).

25. 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 (Cembureau, 1997). The raw material is ground on a surface by rollers that are pressed down using spring or hydraulic pressure, with hot gas used for drying during the grinding process (Bhatty et al., 2004). A vertical roller mill can accept raw materials with up to 20% moisture content and there is less variability in product consistency.

26. High Pressure Roller Press and 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 (Seebach et al., 1996).

27. 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. 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 (Venkateswaran and Lowitt, 1988). 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.

28. 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 improved 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), while optimizing the design.

29. 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 of 0.13 kWh/ton clinker. The capital cost for the measure was around $0.009 /annual ton clinker capacity (UNFCCC 2007 b).

General Measures

30. Use of Alternative Fuels
Alternative, or waste, 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). 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 (Hendriks et al., 1999; CKRC, 2002). Waste-derived fuels may replace the use of commercial fuels, and may result in net energy savings and reduced CO_2 emissions, depending on the alternative use of the wastes (for example. incineration with or without energy recovery).

31. 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 from a few kW to MW-size (Vleuten, 1994). Power use in the kiln (excluding grinding) is roughly estimated to be 40-50 kWh/tonne clinker (Heijningen et al., 1992). Variable speed drives, improved control strategies and high-efficiency motors can help to 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.

32. Adjustable Speed Drives
Drives are the largest power consumers in cement making. The energy efficiency of a drive system can be improved by reducing the energy losses or by increasing the efficiency of the motor. Most motors are fixed speed AC models. However, motor systems are often operated at partial or variable load (Nadel et al., 1992). Also, in cement plants large variations in load occur (Bösche, 1993). 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 (Bösche, 1993; Fujimoto, 1993), 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 reason for installing ASDs (Holderbank Consulting, 1993).

Product Change

33. Blended Cement

The production of blended cements involves the intergrinding of clinker with one or more additives (fly ash, pozzolans, blast furnace slag, volcanic ash) in various proportions. Blended cements demonstrate 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 cements 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% (Cembureau, 1997).

34. Portland Limestone Cement

Similar to blended cement, ground limestone is interground with clinker to produce cement, reducing the needs for clinker-making and calcination. This measure reduces energy use in the kiln and clinker grinding as well as CO_2 emissions from calcination and energy use. The addition of up to 5% limestone has shown to have no negative impacts on the performance of Portland cement, while optimized limestone cement would improve the workability slightly (Detwiler and Tennis, 1996).

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