Title

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Executive Summary

China's cement industry accounted for more than half of the world's total cement production in 2010. The cement industry is one of the most energy-intensive and highest carbon dioxide (CO_2)-emitting industries and one of the key industrial contributors to air pollution in China. For example, it is the largest source of particulate matter (PM) emissions in China, accounting for 40 percent of industrial PM emissions and 27 percent of total national PM emissions. Although specific regulations and policies are needed to reduce the pollutant emissions from the cement industry, air pollution can also be reduced as a co-benefit of energy efficiency and climate-change mitigation policies and programs. Quantifying and accounting for these co-benefits when evaluating energy efficiency and climate-change mitigation programs reveals benefits beyond the programs' energy and global warming impacts and adds to their cost effectiveness.

In this study, we quantify the co-benefits of PM_{10} and sulfur dioxide (SO_2) emissions reductions that result from energy-saving measures in China's cement industry. We use a modified form of the cost of conserved energy (CCE) equation to incorporate the value of these co-benefits:

$$CCE_{co\text{-}ben} = \frac{(\text{annualized capital cost + annual change in operations\&maintenance costs - annual co-benefits})}{\text{annual energy savings}} \qquad \textbf{(Equation ES-1)}$$

The annualized capital cost can be calculated as follows:

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

where:
d = discount rate (assumed 30 percent in this study)
n = lifetime of the energy-efficiency measure

We used the following methodology to calculate CCE with co-benefits ($CCE_{co\text{-}ben}$):

1. We established the year 2008 as the base year for energy, materials use, and production in 16 representative cement plants in Shandong Province. We also used 2008 data when modeling air quality and health impacts, as described below.

2. We compiled a list of 34 commercially available technologies Out of the 34 measures, 29 are applicable to the cement plants in our study, 23 are electricity-saving measures, and 6 are fuel-saving measures. To quantify the air pollution emissions (PM and SO_2) reductions associated with the electricity-saving measures, we used relevant average emission factors for the electricity grid. We did not conduct the air quality modeling or analyze health impacts of the electricity-saving measures because the air pollution from electricity generation is emitted by power plants that are dispersed around the region which is beyond the scope of this study, and our goal in this study is in the air pollution effects of the cement plants themselves. Therefore, in quantifying co-benefits to be included in the CCE calculation, we focused only on the six fuel-saving measures because those measures reduce air pollution at the cement plant site.
3. We assessed the potential application of the energy-efficiency technologies and measures in the 16 Shandong cement plants based on information collected from the plants.
4. We calculated energy savings and CO_2 and air pollutant (PM_{10} and SO_2) emissions reductions for each technology at each cement plant.
5. We modeled air quality for PM_{10} and SO_2 separately, to obtain emissions concentrations for the base and efficiency cases. We performed this modeling only for the six fuel-saving measures. (Section 3.4. describes the modeling in detail).
6. Using the emissions concentration data obtained in the previous step, we calculated the health benefits of the fuel-saving measures using the concentration-response function. (Section 3.5 explains the details of this calculation).
7. Calculate the CCE with the co-benefits included (Equation ES-2), using the calculated the monetary value of the co-benefits from PM_{10} and SO_2 reduction associated with each fuel saving measure.

The results show that more than 41 percent of the PM and SO_2 emissions reduction potential of the electricity-saving measures is cost effective even without taking into account the co-benefits for the electricity-saving measures for the reason explained above. (Figure ES-1). The results also show that including health benefits from PM_{10} and SO_2 emissions reductions reduces the CCE of the fuel-saving measures (Table ES-1).

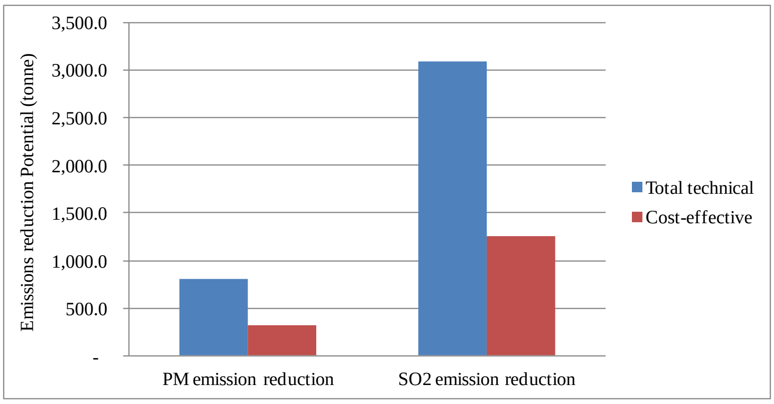

Figure ES-1. Cost-effective and total technical potential in 2008 of PM and SO_2 emissions reductions resulting from electricity-saving measures in 16 cement plants in Shandong Province

Table ES-1. PM_{10} and SO_2 emissions reduction potential and CCE and $CCE_{co\text{-}ben}$ of fuel-saving measures in 2008 for 16 cement plants in Shandong Province

CCE Rank	Efficiency Measure [b]	PM_{10} Emission Reduction (ton PM_{10})	SO_2 Emission Reduction (ton SO_2)	CCE (RMB/GJ-saved)*	$CCE_{co\text{-}ben}$ (RMB/GJ-saved)	Difference (%)
1	Blended cement (additives: fly ash, pozzolans, and blast furnace slag) [a]	2,560	248	0.72	0.25	-65%
2	Limestone Portland cement [a]	850	13	0.76	0.16	-80%
3	Kiln shell heat loss reduction (Improved refractories)	-	270	1.98	1.89	-5%
4	Use of alternative fuels	-	215	3.78	3.76	-1%
5	Optimize heat recovery/upgrade clinker cooler [a]	-	28	4.71	4.56	-3%
6	Energy management and process control systems in clinker making	-	202	12.60	12.4	-1%

*RMB/GJ = Renminbi per gigajoule

[a] For this measure, primary energy savings were used to calculate CCE and $CCE_{co\text{-}ben}$ based on both the electricity and fuel savings. However, because fuel savings have a larger share than electricity savings, this measure is included with the fuel-saving measures.

[b] Brief descriptions of the fuel-saving measures are provided in Appendix A.5.

The two measures that entail changing products (production of blended cement and limestone Portland cement) showed the largest reduction in CCE when co-benefits were included because these measures can reduce both PM_{10} and SO_2 emissions, whereas the other fuel-saving measures do not reduce PM_{10}. This shows the importance of the PM_{10} emissions reduction from the cement industry and how significant the benefits are from reducing this pollutant. The sensitivity analysis showed that the CCE with co-benefits included ($CCE_{co\text{-}ben}$) has an inverse relation with concentration-response coefficients and the unit value of the health outcomes (disease/death) and a direct relation with wind speed.

The report also describes uncertainties relating to the scope, air quality modeling, health benefits assessment, and CCE calculation in this study and identifies the following areas of future research: incorporating other emissions, particularly $PM_{2.5}$, in the analysis; performing similar co-benefits assessments of other industries in China; and studying the policy implications of co-benefits assessment, particularly in developing countries.

Contents

Acronyms

AAGR	average annual growth rate
CCA	China Cement Association
CCE	cost of conserved energy
CI	confidence interval
CMAQ	Community Multiscale Air Quality
CO	carbon monoxide
COI	cost of illness
CO_2	carbon dioxide
C-R	concentration - response
CSC	conservation supply curve
ETC	Economic and Trade Commission
GHG	greenhouse gas
GJ	gigajoule
GWh	gigawatt-hour
kt	kilo tonne
$ktCO_2$	kilo tonnes carbon dioxide
kWh	kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
m/s	meters per second
Mt	metric tonnes
g/m^3	microgram per cubic meter
MWh	megawatt-hour
NH_3	ammonia
NOx	nitrogen oxides
NSP	new suspension pre-heater and pre-calciner
O&M	operations & maintenance
PM	particulate matter
RMB	Reminbi
s	second
SO_2	sulfur dioxide
t	tonne
tce	tonne coal equivalent
TJ	terajoules
USGS	United States Geological Society
VFD	variable frequency drive
VOC	volatile organic compound
WTP	willingness to pay

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1. Introduction

China's cement industry produced 1,868 million metric tonnes (Mt) of cement in 2010, accounting for more than half of the world's total cement production (MIIT 2011). Consistent with the Chinese cement industry's large production volume, total CO_2 emissions from the industry are very high, as are associated air pollutant emissions, including sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), and particulate matter (PM). These emissions cause significant regional and global environmental problems (Lei et al. 2011). The cement industry is the largest source of PM emissions in China, accounting for 40 percent of PM emissions from all industrial sources and 27 percent of total national PM emissions (Lei et al. 2011).

Chinese government policies often focus on reducing energy use, which, in turn, helps to reduce greenhouse gas (GHG) emissions. Other important co-benefits of energy-efficiency policies and programs are reduced harm to human health through reduction in air pollutant emissions, reduced corrosion, and reduction in crop losses caused by surface ozone and regional haze (Aunan et al. 2004). Cost-benefit analysis and energy modeling of the effects of efficiency measures often takes into account only the energy saved, however, and co-benefits of energy efficiency policies and programs, such as reduced harm to human health, are often not included in an impact analysis. There are various reasons for this, including lack of reliable data, uncertainties in co-benefit analysis, and lack of resources. However, it is important for policy makers to understand the overall societal costs and benefits of energy-efficiency technologies, so they can design effective policies with the broader benefits.

This report studies several collateral health and environmental benefits (co-benefits) of energy-saving measures in the cement industry and shows that including co-benefits can significantly affect the cost effectiveness of some energy-efficiency measures. We use a modified cost of conserved energy (CCE) calculation to determine the monetary value of the co-benefits of reduced damage to human health that results from reduced air pollutant emissions.

In 2009, the World Bank's Asia Sustainable and Alternative Energy Unit initiated a study to analyze untapped energy-efficiency opportunities in NSP kiln plants in Shandong Province, China. The study, led by the Lawrence Berkeley National Laboratory (LBNL), evaluated 16 representative cement plants in Shandong Province to identify specific energy-efficiency technology options and evaluate their energy savings and the associated costs for these plants (Price et al. 2009, Hasanbeigi et al. 2010).

The current report aims to quantify the health co-benefits of implementing the energy-efficiency measures analyzed in the prior study of 16 cement plants in Shandong Province. Health co-benefits result from the reduction in air pollutant emissions that in turn results from implementation of the energy-efficiency measures.

For a review of previous research on quantifying the co-benefits of energy-efficiency programs, we refer you to Williams et al. (2012), which contains the results of a literature review performed at the outset of the current study.

This report begins with a brief introduction to the cement industry in China and in Shandong Province. Next, we describe the methodology used in this study, including our data collection efforts, calculation of CCE, air quality modeling, calculation of health benefits, and sensitivity analysis. Finally, we present our results, which include the energy saved by the efficiency measures studied and the associated air pollution emissions reductions, the reduced health impacts resulting from fuel-saving measures, and the CCE including health benefits. We also present an uncertainty and sensitivity analysis.

2. Brief Overview of Cement Industry in China and Shandong Province

The subsections below describe China's national cement industry, the regional cement industry in Shandong Province, and the industry's air pollution sources. A more detailed description of the cement industry in China can be found in Price et al. (2009).

2.1. Cement industry in China

As noted in Section 1, China produces nearly half of the world's cement. The 1,868 million Mt that China produced in 2010 (MIIT 2011) far surpassed the amount manufactured by the two countries with the next-largest production: India (210 Mt) and the U.S. (67 Mt) (USGS 2012). Two types of kilns are used in China to produce clinker, which is the key ingredient in cement: vertical shaft kilns and rotary kilns. Vertical shaft kilns are outdated technologies that use significantly more energy to produce a tonne of clinker than rotary kilns do.

In 2010, nearly 20 percent of China's cement was produced by plants using outdated vertical shaft kilns (VSKs); the remainder was produced in plants using modern rotary kilns, including many plants equipped with new suspension pre-heater and pre-calciner (NSP) kilns (Figure 1). By the end of 2011, the share of cement produced by VSKs decreased to 15 percent (MIIT 2012). The Chinese government had an aggressive policy to phase out VSKs during the 11th Five-Year Plan (FYP) (2006 to 2011); this policy continues in the 12th FYP (2011-2016). During the 11th FYP, the target for phasing out inefficient VSK capacity from the cement industry was 250 million tonnes; by 2010 (4 years into the 11th FYP), the reported actual VSK capacity phased out was 370 million tonnes (CIEE 2011). Figure 1 shows that cement production from rotary kilns grew rapidly in recent years, from 116 Mt in 2000 to 1,494 Mt in 2010 (ITIBMIC 2004, MIIT 2011).

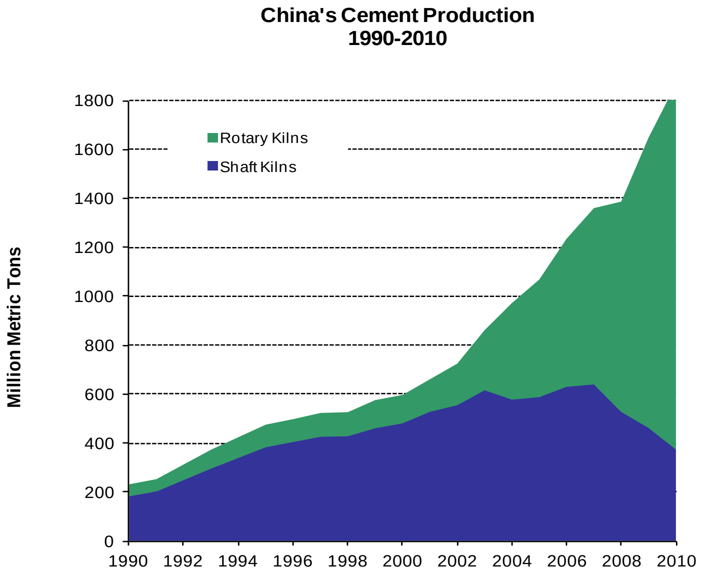

Figure 1. Cement production in China by kiln type, 1990-2010 (ITIBMIC 2004, Kong 2009, CCA 2010, MIIT 2011)

2.2. Cement industry in Shandong Province

Shandong Province produced more cement than any other Chinese province except Jiangsu Province in 2010. Eight percent of China's total cement output in 2010 was manufactured in Shandong Province (NBS 2011). Table 1 shows cement and clinker production 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 percent. This growth was dominated by the increase in rotary kiln production, which was mostly a result of an increased share of NSP kilns. NSP kilns are the most efficient type of cement kilns. Production from rotary kilns has increased at an average of 36 percent per year since 2000, growing from 11 percent of total cement production in 2000 to 58 percent in 2008. Clinker production in Shandong Province was 88 Mt in 2008, and the provincial level clinker-to-cement ratio for that year was 0.63. Shandong Province is also a large cement-exporting province.

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

During the 10th FYP (2000-2005), construction of modern cement plants using NSP kiln technology was promoted. The goal was for 40 percent of cement production capacity to use NSP kilns by the end of the 10th FYP. In 2000, 310 outdated small cement production lines were either banned or closed in Shandong Province, eliminating 8.6 Mt of capacity that relied on obsolete technologies (Shandong ETC and CBMA 2009).

Table 1. Cement and clinker production in Shandong Province, 2000-2008.

	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: When conflicting values were found in different sources, expert judgment was used to determine the values presented in this table.

2.3. Sources of air pollutions in the cement industry

The main emissions from cement manufacturing are PM, NO_x, SO_2, CO, and CO_2. In addition, small quantities of volatile organic compounds (VOCs), ammonia (NH_3), chlorine, hydrogen chloride, and heavy metals (as particulate or vapor) may also be emitted. Residual materials from the fuel and raw materials and other hazardous pollutants that are products of incomplete combustion can also be emitted (U.S. EPA 2009, European Commission 2010).

Producing one tonne of cement releases an estimated 0.73 to 0.99 t CO_2 depending on the clinker-per-cement ratio and other factors. A major difference between the cement industry and most other industries is that fuel consumption is not the dominant driver of CO_2 emissions. More than 50 percent of the CO_2 released during cement manufacture, or approximately 540 kilograms (kg) CO_2 per t of clinker (WBCSD 2009), is from calcination, in which $CaCO_3$ is transformed into lime (CaO) in the following reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

The remainder of the CO_2 emitted during cement manufacture is mostly the result of burning fuel to provide the thermal energy necessary for calcination. An average 100 to 110 kilowatt hours (kWhs) of electricity is consumed per tonne of cement (WWF 2008). The share of CO_2 emissions from electricity use is, on average, 5 percent of the total CO_2 emissions in the cement industry. Depending on the energy source and the efficiency with which it is used in the local electricity mix, this figure can vary from less than 1 percent to more than 10 percent. Roughly 5 percent of CO_2 emissions are associated with quarry mining and transportation (WWF 2008).

In this study, we assess the co-benefits of PM_{10} and SO_2 emissions reductions from implementation of energy- efficiency measures in the cement industry. Exposures to these two pollutants can have serious environmental impacts (e.g., reduced visibility, acid rain, etc.) and human health impacts (disease and death). The discussion below focuses on the sources of these two pollutants in the cement industry. European Commission (2010) provides detailed explanation of emissions sources and specific control technologies for each type of emission in the cement industry.

The main sources of PM (PM_{10} and $PM_{2.5}$) emissions at a cement plant are: 1) quarrying and crushing, 2) raw material storage, 3) grinding and blending (in the dry process only), 4) clinker production, 5) finish grinding, and 6) packaging and loading. The largest PM emission source at cement plants is the pyroprocessing system, which includes the kiln and clinker cooler exhaust stacks. Often, kiln dust is collected and recycled into the kiln where clinker is produced from the dust. However, if the alkali content of the raw materials is too high, some or all of the dust is discarded or leached before being returned to the kiln. Other sources of PM are raw material storage piles, conveyors, storage silos, and unloading facilities (U.S. EPA 2009).

PM emissions from the kiln stack are controlled by fabric filters (reverse air, pulse jet, or pulse plenum) and electrostatic precipitators. PM emissions from clinker cooler systems are most often controlled with pulse-jet or pulse plenum fabric filters (U.S. EPA 2009).

SO_2 can be generated from the sulfur compounds in the raw materials as well as from sulfur in the fuel, which varies from plant to plant and with geographic location. However, the highly alkaline internal environment in the cement kiln system creates good conditions for direct absorption of SO_2 into the product, thereby mitigating the quantity of SO_2 emissions in the exhaust stream. Depending on the process and the source of the sulfur, SO_2 absorption ranges from about 70 percent to more than 95 percent (U.S. EPA 2009).

3. Methodology

The subsections below describe our data collection, energy-efficiency technologies applied to the 16 cement plants, CCE and $CCE_{co\text{-}ben}$ calculation, air quality modeling, health benefit estimation, and sensitivity analyses.

3.1. Data collection

Our 2009 study characterized the energy use and energy-efficiency potential of 16 NSP cement plants in Shandong Province (Price et al. 2009). For that analysis, we used detailed forms to collect data on cement production and energy use from 16 cement plants. These forms requested specific information on the number of production lines at the plants, the plants' age, their clinker and cement-making capacity, their actual clinker and cement production levels in 2007 and 2008, the 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 asked whether the facilities had adopted any of 34 energy-efficiency measures, and the reasons why not if the measures had not been adopted. The data was collected from the plants by LBNL, the China Building Materials Academy, and Shandong Energy Conservation Association staff. Having these detailed plant-level data[1] enabled us to

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[1] The detailed plant-level are considered confidential and are therefore not included in this or the previous

construct an energy conservation supply curve (CSC), which is a bottom-up model showing the energy-saving potential as well as the cost associated with each efficiency measure that might be implemented in the plants we studied (see Price et al. (2009) for more details).

In the current study, we use the same plant-level data collected in 2009 to assess the potential application of each energy-efficiency technology in the 16 plants. Because we are using data from 2009, the year 2008 is the base year for the current study, as it was in the previous report. The new data collected for air quality modeling and determining the health benefits of reduced pollutant emissions are described in the relevant subsections below.

3.2. Energy-efficiency technologies and measures for the cement industry

We studied 34 technologies and measures in our 2009 assessment of the potential for improving the energy efficiency of NSP-kiln cement plants in Shandong Province. Table 2 shows, for each energy-efficiency technology or measure studied, the typical fuel and electricity savings (compared to the fuel and energy consumption of lower-efficiency technologies or measures that are typically in use), as well as capital costs and change in annual operations and maintenance (O&M) costs. Price et al. (2009) briefly describes each of the 34 technologies and measures evaluated.

As noted above, the 16 cement companies in the current study had provided information indicating whether or not they had already applied any of the 34 measures or technologies in their plants. Based on the responses, we applied the measures or technologies to each cement production step in specific portions of the overall production capacity of the plants studied. We applied the efficiency measures that were applicable to the plant’s operation but had not been adopted by the plants at the time of the study. The last column in Table 2 shows the share of production capacity to which each technology or measure could be applied.

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reports.

Table 2. Energy savings, capital costs, and CO_2 emissions reductions for energy-efficient technologies and measures applied to 16 Shandong cement facilities.

No.	Technology/Measure	Production Capacity in 2008 (Mt/year)*	Fuel Savings (GJ/t-cl)*	Electricity Savings (kWh/t-cl)*	Capital Cost (RMB/t-cl)*	Change in annual O&M cost (RMB/t-cl)	Share of clinker production capacity in 2008 to which measure is applied
	Fuel Preparation						
1	New efficient coal separator	[a]		0.26	0.08	0.0	29%
2	Efficient roller mills for coal grinding	[a]		1.47	0.32	0.0	40%
3	Installation of VFD & replacement of coal mill bag dust collector’s fan	[a]		0.16	0.18	0.0	33%
	Raw Materials Preparation						
4	Raw meal process control for vertical mill	45.7		1.41	3.52	0.0	5%
5	High efficiency classifiers/separators	45.7		5.08	23.5	0.0	16%
6	High efficiency roller mill	45.7		10.2	58.8	0.0	54%
7	Efficient transport system	45.7		3.13	32.1	0.0	9%
8	Raw meal blending (homogenizing) systems	45.7		2.66	39.6	0.0	0%
9	VFD in raw mill vent fan	45.7		0.33	0.17	0.0	64%
10	Bucket elevator for raw meal transport	45.7		2.35	1.56	0.0	0%
11	High efficiency raw mill vent fan w/inverter	45.7		0.36	0.23	0.0	69%
	Clinker Making						
12	Kiln shell heat loss reduction (Improved refractories)	29.1	0.26		1.71	0.0	29%
13	Energy management & process control systems	29.1	0.15	2.35	6.84	0.0	33%
14	Adjustable speed drive for kiln fan	29.1		6.10	1.57	0.0	15%
15	Optimize heat recovery/upgrade clinker cooler	29.1	0.11	-2.00 [c]	1.37	0.0	9%
16	Low temperature Waste Heat Recovery for power generation	29.1		30.8	9130 RMB/ kWh-capacity	5.58	6%
17	Efficient kiln drives	29.1		0.55	1.50	0.0	40%
18	Upgrading preheater from 5 stages to 6 stages	29.1	0.11	-1.17 [c]	17.4	0.0	0%
19	Upgrading to a preheater/precalciner Kiln	29.1	0.43		123	-7.52	0%
20	Low pressure drop cyclones for suspension preheater	29.1		2.60	20.5	0.0	52%
21	VFD in cooler fan of grate cooler	29.1		0.11	0.08	0.0	58%
22	Bucket elevators for kiln feed	29.1		1.24	2.41	0.0	0%
23	Use of high efficiency preheater fan	29.1		0.70	0.47	0.0	24%

No.	Technology/Measure	Production Capacity in 2008 (Mt/year)*	Fuel Savings (GJ/t-cl)*	Electricity Savings (kWh/t-cl)*	Capital Cost (RMB/t-cl)*	Change in annual O&M cost (RMB/t-cl)	Share of clinker production capacity in 2008 to which measure is applied
	Finish Grinding						
24	Energy management & process control in grinding	18.5 [b]		4.00	3.21	0.0	30%
25	Replacing a ball mill with vertical roller mill	18.5		25.9	53.5	0.0	9%
26	High pressure roller press for ball mill pre-grinding	18.5		24.4	53.5	0.0	25%
27	Improved grinding media for ball mills	18.5		6.10	7.49	0.0	7%
28	High-Efficiency classifiers (for finish grinding)	18.5		6.10	21.4	0.0	29%
29	High efficiency cement mill vent fan	18.5		0.13	0.06	0.0	36%
	General Measures						
30	Use of alternative fuels	18.5	0.60		7.52	0.0	10%
31	High efficiency motors	18.5		4.58	2.35	0.0	40%
32	Adjustable Speed Drives	18.5		9.15	9.63	0.0	55%
	Product Change [2]	**Production Capacity (Mt/year)**	**Fuel Savings (GJ/t-cement)**	**Electricity Savings (kWh/t-cement)**	**Capital cost (RMB/t-cement)**	**Change in annual O&M cost (RMB/t-cement)**	**Share of cement production capacity to which measure is applied**
33	Blended cement	18.5	1.77	-7.21[c]	4.92	-0.27	6%
34	Portland limestone cement	18.5	0.23	3.30	0.82	-0.04	2%

* Mt = metric tonnes; GJ/t-cl = gigajoules per tonne clinker; kWh/t-cl = gigawatt hours per tonne clinker; RMB/t-cl = Renminbi per tonne clinker

[a] This measure applied based on plant clinker production capacity because the energy savings were given per tonne of clinker production capacity.

[b] Total cement production capacity in the studied plants is less than total clinker production capacity because some plants produce only clinker and do not produce cement.

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

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[2] Because 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, in contrast to the other measures for which the calculations are based on clinker production capacity.

3.3. Cost of conserved energy

In this study, we calculate the CCE with and without co-benefits. The unique contribution of this report is that it quantifies, at the technology level, health co-benefits from the reduction in air pollution emissions that results from implementing energy-efficiency measures and includes these co-benefits in the traditional CCE calculation. This is one of the only (if not the only) studies to quantify the health co-benefits of energy efficiency for the cement industry at this level of detail.

Equation 1 shows the simple calculation of CCE using data from the base year:

$$CCE = \frac{\text{(annualized capital cost + annual change in operations \& maintenance costs)}}{\text{annual energy savings}} \qquad \textbf{(Equation 1)}$$

To include co-benefits in the CCE calculation, we modify Equation 1 as follows:

$$CCE_{co\text{-}ben} = \frac{\text{(annualized capital cost + annual change in operations\&maintenance costs - annual co-benefits)}}{\text{annual energy savings}} \qquad \textbf{(Equation 2)}$$

The annualized capital cost can be calculated from Equation 3:

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

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

In this study, we use a real discount rate of 30 percent 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). This is a rather conservative assumption since the societal discount rate used for climate or environmental analysis could be much lower. In the sensitivity analysis section (section 6), we explain how the change in the discount rate will influence the results.

Figure 2 shows, in schematic form, the data collection and calculation methodology used to produce the CCE with co-benefits incorporated ($CCE_{co\text{-}ben}$) . Each step is explained following the figure.

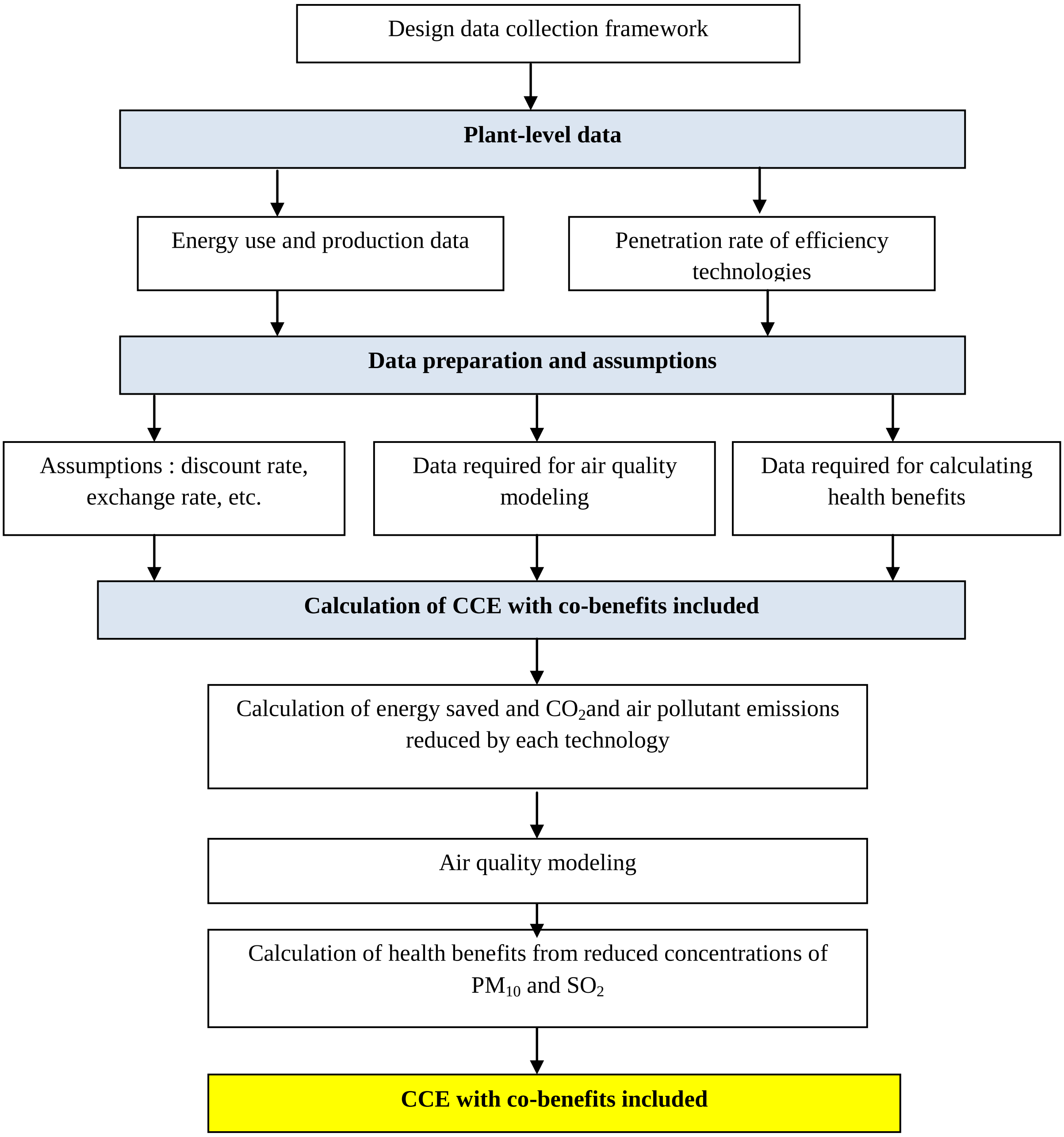

Figure 2. Schematic of the methodology used for this study

The methodology outlined in Figure 2 for calculating the $\mathrm{CCE}_{\text{co-ben}}$ entailed the following detailed steps:

1. Established the year 2008 as the base year for energy, materials use, and production in 16 representative cement plants in Shandong Province. Used 2008 data when modeling air quality and health impacts, as described below.
2. Compiled a list of 34 commercially available technologies Out of the 34 measures, 29 are applicable to the cement plants in our study, 23 are electricity-saving measures, and 6 are fuel-saving measures. To quantify the air pollution emissions (PM and SO_2) reductions associated with the electricity-saving measures, we used relevant average emission factors

for the electricity grid[3]. We did not conduct the air quality modeling or analyze health impacts of the electricity-saving measures because the air pollution from electricity generation is emitted by power plants that are dispersed around the region which is beyond the scope of this study, and our goal in this study is in the air pollution effects of the cement plants themselves. Therefore, in quantifying co-benefits to be included in the CCE calculation, we focused only on the six fuel-saving measures because those measures reduce air pollution at the cement plant site.

3. Assessed the potential application of the energy-efficiency technologies and measures in the 16 Shandong cement plants based on information collected from the plants.
4. Calculated energy savings and CO_2 and air pollutant (PM_{10} and SO_2) emissions reductions for each technology at studied cement plants.
5. Modeled air quality for PM_{10} and SO_2 separately, to obtain emissions concentrations for the base and efficiency cases. We performed this modeling only for the six fuel-saving measures. (Section 3.4. describes the modeling in detail).
6. Calculated the health benefits of the fuel-saving measures using the concentration-response function using the emissions concentration data obtained in the previous step,. (Section 3.5 explains the details of this calculation).
7. Calculated the CCE with the co-benefits included (Equation 3), using the calculated monetary value of the co-benefits from PM_{10} and SO_2 reduction associated with each fuel saving measure.

3.4. Air quality modeling

This subsection summarizes the methods and assumptions used to estimate SO_2 and PM_{10} air pollutant concentrations around the 16 cement plants that we studied in Shandong Province. We briefly describe the study region, the United States Environmental Protection Agency (U.S. EPA)'s AERSCREEN model used in this study, and the inputs and assumptions used to estimate pollutant air concentrations.

3.4.1. Study region

We estimated SO_2 and PM_{10} concentrations within a 10-kilometer (km) radius of the 16 cement plants, which are located in Jinan, Zaozhuang, and Zibo municipalities in Shandong Province. Figure 3 shows the location of Shandong Province in China and the location of Jinan, Zaozhuang, and Zibo municipalities in Shandong Province. Because of the confidentiality agreement, we cannot show the location of the cement plants.

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[3] Average electricity emissions factors are used to reflect the emissions that would occur if electricity savings measures are implemented immediately and does not take into account the emissions associated with prospective power plants whose construction and future operations would be affected by the energy efficiency actions.

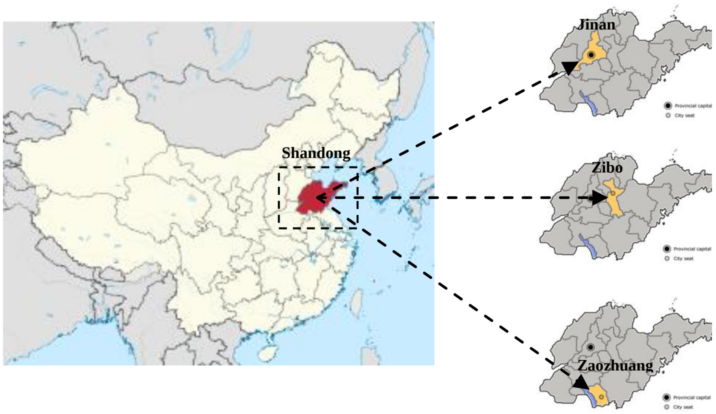

Figure 3. Location of Shandong Province in China and the location of Jinan, Zibo, and Zaozhuang municipalities in Shandong Province. [4]

Table 3 summarizes the annual cement and clinker production in each of these municipalities in 2008. For the purpose of modeling air pollutant concentrations, we aggregated into groups the clinker and cement production plants that are within 10 km of each other, which produced a total of 10 plant groups. The population within a 10-km radial distance of each plant group ranges between 165,939 and 2,019,000 persons (population density of 528 – 4,005 persons/ square km). Appendix A.2 provides more information on how we determined the exposed population.

Table 3. Summary of annual cement and clinker production (tonne / year) in 2008 at 16 plants located in Zaozhuang, Jinan, and Zibo municipalities in Shandong Province.

Municipality	Number of plants	Cement production (t/year)	Clinker production (t/year)
Zaozhuang	8	7,475,699	12,431,802
Jinan	3	3,852,772	6,135,017
Zibo	5	2,060,105	7,294,803
Total	**16**	**13,388,577**	**25,861,621**

3.4.2. AERSCREEN model

We used the U.S. EPA's recently released AERSCREEN screening-level model [5] (U.S. EPA 2011) to estimate PM_{10} and SO_2 concentrations associated with the base-case and energy-efficient scenarios. The base-case scenario is the scenario before the implementation of efficiency measures, and the energy-efficient scenario applies the fuel-saving measures. AERSCREEN is a steady-state, Gaussian-plume model intended to provide "worst-case" time-averaged concentrations of conserved pollutants,[6] such as SO_2 and $PM_{2.5}$, emitted from

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[4] Source: Wikipedia.com (http://en.wikipedia.org/wiki/Shandong ; http://en.wikipedia.org/wiki/Jinan ; http://en.wikipedia.org/wiki/Zibo ; http://en.wikipedia.org/wiki/Zaozhuang)

[5] http://www.epa.gov/scram001/dispersion_screening.htm

[6] By definition, a conserved pollutant does not decay, react, or deposit rapidly over scales of < 50 km. For PM_{10}, we apply a correction term to the results to take deposition into account.

point (vertical uncapped stack, capped stack, or horizontal stack), area (rectangular or circular), flare, or volume sources. AERSCREEN results can be used to screen whether more sophisticated spatially resolved modeling is needed. The U.S. EPA also describes AERSCREEN as a "useful tool to estimate potential impacts during the design and planning stages of a project (USEPA, 2011)." This substantiates the use of AERSCREEN for our purposes of assessing potential health impact of energy efficiency projects in the cement industry.

AERSCREEN is based on the AERMOD regulatory model framework, which was jointly developed by the American Meteorological Society and U.S. EPA as a replacement for previous regulatory models, such as the Industrial Source Complex, version 3 (ISC3) model. AERMOD contains new or revised algorithms that allow for advanced treatment of pollutant transport in the planetary boundary layer. These advances include vertical profiles of wind, turbulence, and temperature. Two U.S. EPA reports (U.S. EPA 2004 and 2007) contain detailed information about AERMOD.

Several large-scale impact studies of industrial point-source emissions have used either AERMOD or the ISC3 to assess co-benefits associated with air quality improvements (Staff-Mestl et al. 2005; Wang and Mauzerall 2006). However, because of time, data, and computational resource limitations, we used AERSCREEN rather than AERMOD to assess the potential health benefits associated with the reduction in PM_{10} and SO_2 emissions from the energy-efficient scenario in this study.[7] Specifically, we rely on the annual average concentrations estimated from a one-sector model configuration of AERSCREEN. The one-sector configuration assumes average meteorology and surface characteristics. In the sections below, we describe the meteorological inputs, and source and surface characteristics to AERSCREEN. We end this section with a description of the output provided by AERSCREEN which is used to estimate the exposure concentrations of the population residing within 10 km of each plant group in this study.

Source characteristics

AERSCREEN requires that the following source characteristics be input:

- Emission rate (grams of pollutant/ second)
- Stack height (m)
- Stack diameter (m)
- Difference between stack and ambient temperature (^oC or K)
- Gas exit velocity from the stack (m/s or feet/s or actual cubic feet per minute)

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[7] The tradeoffs of using AERSCREEN vs. AERMOD are associated with data intensity and meteorological and geospatial specificity. AERSCREEN does not require finely gridded terrain and meteorology data as inputs. AERSCREEN is much less computationally intensive. If the meteorology, terrain, and other characteristics would be available on a finely gridded scale (such as 10 x 10 km) and time and resources to collect such data and use them are available, then AERMOD would be recommended in order to get a higher level of accuracy.

- Source elevation (m)[8]
- Urban population

Clinker production stack PM emissions are mainly associated with the raw material grinding and kiln combined stacks and the clinker cooler stack. For cement production, in addition to these stacks, PM stack emissions from the finish grinding stack should also be added. SO_2 emissions are associated with kiln combustion for clinker production and are released from the raw material grinding and kiln combined stack.

Table 4 summarizes the stack parameters, including the height,[9] temperature, and gas exit velocity of each stack involved in the manufacture of clinker and/or cement. These data are based on 5,000-tonne (t)-per-day cement production line (Al Smadi et al. 2009) and corroborated by a Chinese cement industry expert (Yu 2012). Stack exit velocities were calculated based on the volume of the air flowing through the stack.

Table 4. Clinker and cement stack parameters for a 5,000-tonne-per-day cement production line

	Stack height (m)	**Stack diameter (m)**	**Stack temperature (°C)**	**Stack Exit velocity (m/s)[a]**
Raw material grinding and kiln	93	3.0	90 [b]	14.4
Clinker cooler	30	3.2	192	85
Finish grinding	40	1.5	106	8.6

Source: Based on Al Smadi et al. (2009) and Yu (2012)

[a] calculated based on Yu (2012)

[b] combined operation; 130 °C is the normal operation

Based on Al Smadi et al. (2009)'s study of emissions associated with cement manufacturing, we assume the following share of PM_{10} emissions from different stacks of the cement and clinker manufacturing processes:

- Clinker production:
  - combined raw material grinding and kiln stack = 49 percent
  - clinker cooler stack = 42 percent
  - other = 9 percent [10]

- Cement production:
  - combined raw material grinding and kiln stack = 42 percent
  - clinker cooler stack = 34 percent
  - finish grinding = 6 percent
  - other = 18 percent

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[8] The model default value of 0m is used in our analysis.

[9] Stack height is actual stack height, not effective stack height. AERSCREEN calculates the effective stack height based on the meteorological and stack characteristic inputs.

[10] We assume that the "other" emissions for clinker production are half of the "other" emissions from the complete cement manufacturing process.

SO_2 and PM_{10} are both emitted from point sources except in the case of PM_{10} emissions from “other” sources. We explored options for modeling the “other” sources as a volume source. Volume sources associated with cement and kiln manufacturing are defined as follow: "spaces within the manufacturing building, and the pollutants from these spaces usually exit the building through controlled outlets" (Al Smadi et al. 2009). "Controlled outlets" can include air pollution control equipment such as dust collectors or volume releases from conveyers or packaging processes. There might be several volume sources across the entire production line. Because we did not have information regarding the volume source release height and initial lateral/horizontal and vertical dimensions of the volume source, which is needed to accurately represent the “other” PM_{10} volume source emissions, we only report on the co-benefits associated with point source emissions of PM_{10} and SO_2 in this study. We did not include the “other” sources in our air quality modeling. Therefore, not all the PM_{10} emissions from cement manufacturing are included in the analysis. As a result, the co-benefits results from PM_{10} emissions reduction are likely an underestimate.

Table 5 summarizes the SO_2 and PM_{10} baseline emission factors (kilogram of pollutant / t clinker or cement) associated with clinker and cement manufacturing. We assumed a constant emission rate over the 320 days that the plant operates per year. Based on the annual production of clinker and/or cement for each plant, the emission factors in Table 5 were converted to pollutant emissions rates (g/ s) for the base year as input to AERSCREEN.

Table 5. Base year (2008) PM_{10} and SO_2 emissions factors (kilogram / tonne cement or clinker manufactured) for each point source.

	PM_{10}	SO_2
Clinker manufacturing		
Raw material grinding and kiln combined stack	1.07	0.39 - 0.53[a]
Clinker cooler stack	0.92	
Cement manufacturing		
Raw material grinding and kiln combined stack	1.04	0.39 - 0.53
Clinker cooler stack	0.86	
Finish grinding stack	0.16	

[a] Specific to a given plant group, depending on the coal used for production of 1t clinker (kilogram coal/t clinker)

Using the AERSCREEN model, we separately modeled air concentrations for fuel-efficiency measures, implemented at the plant group level, that reduce SO_2 and PM_{10} emissions. Six fuel-efficiency measures reduce SO_2 emissions, and two (production of Blended Cement and Limestone Portland Cement) reduce PM_{10} emissions. Table 6 summarizes the SO_2 and PM_{10} emissions reductions associated with each fuel- saving measure.

As noted in Section 3.3, we only focus on the six fuel-saving measures because they reduce pollution at the cement plant site, so we modeled the air quality impacts of only these six measures. As can be seen in Table 6, only product-change measures, i.e., shifting to production of blended cement and limestone Portland cement, reduce PM_{10} emissions. The

PM_{10} reduction associated with the other four thermal efficiency measures is minimal. However, all six measures reduce SO_2 emissions because they reduce kiln fuel use (combustion), which is the primary source of SO_2 emissions.

Table 6. SO_2 and PM_{10} emissions reductions (t/year) associated with each energy-efficiency measure for each cement plant group (A-J).

No.	**Efficiency Measure**	**Emissions Reductions by Plant Group (t / year]**										
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**All Plants (A-J)**
1	*Kiln shell heat loss reduction (Improved refractories)*											
	SO_2	75	63		59				73			270
	PM_{10}											
2	*Energy management and process control systems in clinker making*											
	SO_2		22			68		64	49			202
	PM_{10}											
3	*Optimize heat recovery/upgrade clinker cooler*											
	SO_2			13			15					28
	PM_{10}											
4	*Use of alternative fuels*											
	SO_2	32	35	21	14	23	17	26	17	27	3	215
	PM_{10}											
5	*Blended cement (Additives: fly ash, pozzolans, and blast furnace slag)*											
	SO_2	34	71				64	40	39			248
	PM_{10}	362	710				654	424	410			2,560
6	*Limestone Portland cement*											
	SO_2	1.6	3.2	1.4	0.8	0.8	3.1	0.8	1.3		0.1	13
	PM_{10}	109	200	93	48	51	199	54	86		8	850
	All Measures (1-6)											
	SO_2	143	194	36	73	91	99	130	179	27	3	976
	PM_{10}	471	910	93	48	51	853	479	496		8	3,410

* Grey shaded cells indicate that the pollutant reductions are not associated with the efficiency measure or are not applicable.

To account for urban heat island effects and adjust the mixing height, Z_{iuc}, the urban population is required as an input to AERSCREEN (Cimorelli et al. 2004, AERMOD Implementation Workgroup, 2009). Specifically, Z_{iuc} is adjusted as follows:

$$Z_{iuc} = Z_{iuo} (P / Po)^{1/4}$$

where Z_{iuo} is the mixing height (400 m) corresponding to the reference population P_o (which is 2 million), and P is the population of the urban area, which is assumed to be the population estimated to reside within the 10 km radius of the plant groups.

Lastly, for defining source characteristics, we assume the default AERSCREEN source elevations, i.e., that the source and receptors are at the same height (source elevation = 0 m). However, if receptors are at a lower elevation than the source, then the concentrations may be underestimated in our analysis.

Meteorological inputs

AERSCREEN requires inputs for the following meteorological parameters:

- minimum and maximum ambient temperature (K)
- minimum wind speed (m / s)
- anemometer height (m) [default = 10 m]

The one-sector AERSCREEN model configuration assumes annual average meteorology and a wind direction of 270 degrees.[11] We base the minimum and maximum ambient temperatures on monthly average temperatures in 2007 (Shandong Statistical Bureau 2008). For the minimum wind speed, we assumed the minimum monthly average wind speed over the time period 1971-2000 (weather.com). The default AERSCREEN anemometer height of 10 m was assumed. Table 7 summarizes the annual average meteorological inputs to AERSCREEN for the Jinan, Zibo, and Zoazhuang municipalities.

Table 7. Minimum and maximum average monthly temperature and minimum average monthly wind speed in three municipalities of Shandong Province where cement and/or clinker manufacturing plants are located.

Municipality	**Average Monthly Temperature (°C)**		**Wind Speed (m/s)**
	Minimum	Maximum	Minimum
Jinan	0.0	26.6	2.4
Zibo	0.5	27.6	1.9
Zaozhung	0.6	26.3	2.4[a]

[a] Data for Zaozhung were missing, so we used available data from Linyi municipality due to its proximity to Zaozhung [12].

Surface characteristics

AERSCREEN requires the following surface characteristics:

- Albedo
- Bowen ratio
- Surface roughness length

Albedo is a unitless value (between 0 and 1) that characterizes the fraction of incident light that the earth reflects. The Bowen ratio is also unitless (between -10 and 10) and indicates the type of heat transfer through a water body or the ratio of sensible to latent heat; i.e., if the Bowen ratio is < 1, then there is a greater abundance of latent heat relative to sensible heat passed to the atmosphere. The surface roughness length (m) can range between 0.005 for land covered by mud flats or snow and no vegetation to more than 2 in an urban region (U.S. EPA 2011). In the one-sector configuration of the AERSCREEN model, we assumed the annual average surface characteristics shown in Table 8. These characteristics are based on neighboring Taiyun province (Staff-Mestl et al. 2005), which can be considered representative of the Shandong region.

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[11] This is a reasonable assumption considering that the prevailing wind direction appears to be toward the south in the Jinan and Zibo municipalities, but there is no prevailing wind direction in Zaozhuang (see Appendix A.2).

[12] Linyi municipality is around 120km east of Zaozhung municipality.

Table 8. Annual average surface characteristics representative of Shandong Province.

Albedo	Bowen Ratio	Surface Roughness Length
0.25	2.0	0.5

AERSCREEN output

AERSCREEN provides maximum hourly concentrations of conserved (non-reacting, non-depositing) pollutants such as SO_2 released from the point sources described above. We took into account PM_{10} deposition by applying an exponential decay term to the AERSCREEN-modeled PM_{10} concentration. Appendix A.4 provides more information on this adjustment, which effectively attenuates the concentrations of PM_{10} in the exposed population (within 10 km around a plant group).

The maximum hourly pollutant concentrations are along the plume center line and can be converted to annual average concentrations by multiplying by a scaling factor of 0.1 (U.S. EPA 2011). We took the average of the annual average concentrations at each receptor, where receptor indicates a site that is a specific radial distance away from the source. This average of the annual average concentrations at each receptor is considered a reasonable estimate of the exposure concentrations of the population within 10 km of the plant[13].

To evaluate the AERSCREEN-derived air concentration, we made a comparison with a simple box model [14] (over a 10-km radius). This comparison showed general agreement with the AERSCREEN-derived SO_2 and PM_{10} concentrations when we assume the reported minimum monthly average temperature for each municipality, but when we assume default minimum average wind speeds (0.5 m/s), the AERSCREEN-modeled PM_{10} and SO_2 concentrations are up to a factor of 2 greater than box-model-derived concentrations. Because we take into account the stack characteristics (height, diameter, temperature, and plume exit velocity), the AERSCREEN-modeled concentrations can be considered more accurate than the box model.

3.5. Health benefit estimation

The subsections below explain the steps we took to estimate the monetary value of the co-benefits of reduced air pollutant emissions associated with the six fuel-efficiency measures analyzed in this study.

3.5.1. Concentration-response functions

To estimate health benefits from PM_{10} and SO_2 emissions reductions, we used concentration-response (C-R) functions. C-R functions are statistically derived formulas that relate health impacts directly to exposure to concentrations of pollutants and used to estimate health

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[13] Because the maximum annual average concentrations modeled drops by an order of magnitude at 10 km, we limit the assessment to 10-km range around the source.

[14] A box model is a simple, transparent approach to estimating air concentrations by taking the emissions from a region, or in this case the 10-km radial area around the cement plant or plant group, and diluting the emissions based on the area and wind speed of the region.

benefits of emissions reductions in many international studies and some Chinese studies (Aunan et al. 2004, Chen et al. 2007, Kan and Chen 2004, Williams et al. 2012). These functions are based on epidemiological research that statistically correlates health outcomes in large groups of people in geographically limited areas to the level of air pollutants to which the population has been exposed. Because epidemiological studies are more common in developed countries than in developing countries, C-R functions from developed countries are commonly used in studies of developing countries.

In this study, we used C-R coefficient from Chinese studies when available and from international studies when Chinese C-R coefficients are not available. Equation 4 shows the calculation of health effects that correspond to changes in air pollutant concentrations:

$E = \exp(\beta^*(C-C_0))^*E_0$ **(Equation 4)**

Where

β = C-R coefficient (increased risk of mortality or morbidity for each microgram per cubic meter [$\mu g / m^3$] increase in pollutant concentration)

C and C_0 = the pollutant (PM_{10} or SO_2) concentration (g/m^3) under a specific scenario (in this study, the energy-efficient scenario and the baseline scenario, respectively)

E and E_0 = the corresponding number of cases of morbidity or mortality per year per person in the defined population exposed to the defined concentrations of C and C_0.

The potential health benefit of the energy-efficient scenario compared to the baseline scenario is the difference between E and E_0.

The concentrations, C and C_0, are based on the air quality modeling described in Section 3.4. For β and E_0, we used Chinese values when available and international values when Chinese values were not available. Table 9 and Table 10 show the C-R coefficient and baseline values for PM_{10} and SO_2 used in this study for each health outcome along with the sources for each value. The 95 percent confidence interval (CI) of the coefficient is also shown. Later in this report we present a sensitivity analysis using the lower and higher bound of the interval to assess the impact of these changes on the final results.

Health outcomes can be expressed in several ways, including premature mortality, incidence of acute or chronic disease, and hospital visits. The health impacts most commonly evaluated for PM_{10} and SO_2 are the incidence of premature mortality and certain debilitating illnesses such as chronic and acute bronchitis. In this study, we included a number of health outcomes for the PM_{10} analysis for which we could find reliable C-R coefficients (see Table 9). For the SO_2 analysis, however, we only used long-term mortality (all ages), for which we had a reliable C-R coefficient (Table 10). Therefore, the potential health benefits from PM_{10} and SO_2 emissions reduction would likely be greater than estimated here if all of the health outcomes associated with these air pollutants were included.

As mentioned in Section 3.4, we modeled air quality for each efficiency measure and plant group (A-J) separately. Thus, we have the concentrations C and C_0 for each measure and for each plant group. Therefore, the potential health benefit ($E-E_0$) is calculated for measures and at the plant group level.

Table 9. Concentration-response coefficients and baseline rate (per person) used in the PM_{10} analysis.

Health outcome (age group)	β (Mean [95% CI])	β Reference	E_0	E_0 Reference
Long-term mortality (adult≥30) *	0.00024 (0.00010, 0.00047)	Chen, Kan et al. (2012)	0.01077	Shanghai Municipal Bureau of Public Health (2002)
Chronic bronchitis (all ages)	0.00450 (0.00127, 0.00773)	Ma and Hong (1992), Jin et al. (2000)	0.0139	China Ministry of Health (1998)
Respiratory hospital admission (all ages)	0.00130 (0.00010, 0.00250)	Zmirou et al. (1998), Wordley et al. (1997)	0.0124	Shanghai Municipal Bureau of Public Health (2002)
Cardiovascular hospital admission (all ages)	0.00130 (0.00070, 0.00190)	Wordley et al. (1997), Prescott et al. (1998)	0.0085	Shanghai Municipal Bureau of Public Health (2002)
Outpatient visits-internal medicine (all ages)	0.00034 (0.00019, 0.00049)	Xu et al. (1995)	3.26	Shanghai Municipal Bureau of Public Health (2002)
Outpatient visits-pediatrics (all ages)	0.00039 (0.00014, 0.00064)	Xu et al. (1995)	0.3	Shanghai Municipal Bureau of Public Health (2002)
Acute bronchitis (all ages)	0.00550 (0.00189, 0.00911)	Jin et al. (2000)	0.39	Wang et al. (1994)
Asthma attack (children <15 years)	0.00440 (0.00270, 0.00620)	Roemer et al. (1993), Segala et al. (1998), Gielen et al. (1997)	0.0693	Ling et al. (1996)
Asthma attack (adults≥15 years)	0.00390 (0.00190, 0.00590)	Dusseldorp et al. (1995), Hiltermann et al. (1998), Neukirch et al. (1998)	0.0561	Ling et al. (1996)

Source: The values in the table are extracted from Chen et al. (2007) except for the long-term mortality value, which is from Chen, Kan et al. (2012). The original sources of the values are identified above as they were given in Chen et al. (2007).

* The C-R co-efficient for long-term mortality is from Chen, Kan et al. (2012). This value is lower than the one given in Chen et al. (2007) because the value from Chen, Kan et al. (2012) is the co-efficient for PM_{10}, adjusted for SO_2. Because we modeled PM_{10} and SO_2 separately in this study, we use the value from Chen, Kan et al. (2012) to avoid overestimating the health benefit from PM_{10} emissions reduction. The value from Chen, Kan et al. (2012) takes into account the multi-pollutant modeling.

Table 10. Concentration-response coefficients and baseline rate (per person) used in the SO_2 analysis

Health outcome (age group)	β (Mean [95% CI])	β Reference	E_0	E_0 Reference
Long-term mortality (all ages) *	0.00042 (0.00017, 0.00067)	Chen, Huang et al. (2012)	0.01077	Shanghai Municipal Bureau of Public Health (2002)

* The C-R co-efficient for long-term mortality is from Chen, Huang et al. (2012). This value is the co-efficient for SO_2 adjusted for PM_{10}. Because we modeled PM_{10} and SO_2 separately in this study, we use the value from Chen, Kan et al. (2012) to avoid overestimating the health benefit from SO_2 emissions reduction. The value from Chen, Kan et al. (2012) takes into account the multi-pollutant modeling.

3.5.2. Estimation of reduced health impacts

Having calculated the potential health benefit (E-E_0) per person for each energy-efficiency measure and plant group in 2008 and the population within a 10-km radius of each plant group in 2008, we estimate the total health benefit of the adoption of each energy-efficiency measure in terms of reduction in the incidence of each health outcome.

3.5.3. Monetary value of health benefits

Co-benefit impact analysis often entails assigning dollar values to (monetizing) quantifiable health impacts for the purpose of comparing project, policy, or program implementation costs and benefits. Ideally, co-benefits analyses would quantify all potential co-benefits from reductions in energy use. Examples include avoided acidification, eutrophication, other crop damage, visibility losses, pollution clean-up costs, and physical deterioration of buildings and other capital assets. Other benefits include those associated with technology development, structural change, and behavioral change, which are sometimes implicit in energy-efficiency and GHG reduction policies. However, evaluation of some of these co-benefits is more difficult than evaluation of health co-benefits; therefore, the focus of this study is on monetizing human health impacts only.

To monetize the co-benefits, we multiply each avoided health impact by a unit value for that health impact. Table 11 shows the unit value for various health outcomes, calculated for Shandong Province for year 2008 (in US $). Both willingness to pay (WTP) and cost of illness (COI) are used to monetize the health outcomes. The values in Table 11 are based on values given for Shanghai for year 2000 in Chen et al. (2007). We adjusted the WTP values given for Shanghai in Chen et al. (2007) to WTP values for Shandong province based on the differences between average annual income per capita in Shanghai in 2000 and in Shandong Province in 2008 as well as a marginal WTP. It is assumed that with an annual income increase of $145.80, the marginal increase for saving a statistical life was $14,550 (Chen et al. 2007).

Table 11. Unit value for various health outcomes for Shandong Province for the year 2008 (in US $)

Outcome	Unit value	(95% CI)		Approach
	Mean	Low	High	
Premature death	150,797	144,219	157,419	WTP
Chronic bronchitis	8,408	1,142	27,531	WTP
Respiratory hospital admission*	987			COI
Cardiovascular hospital admission*	1,450			COI
Outpatient visits (internal medicine)*	19			COI
Outpatient visits (pediatrics)*	19			COI
Acute bronchitis	10	4	16	WTP
Asthma attack (children <15 years)	7	3	11	WTP
Asthma attack (adults ≥15 years)	7	3	11	WTP

Source: Calculated from Chen et al. (2007)

* The data available for Shanghai did not provide a distribution of the values.

By multiplying the total potential health benefit in 2008 for each measure at each plant group by the unit value of each health outcome, we can calculate the total potential health benefits as a monetary value (US$) in 2008. An example of the results of this calculation is given in Section 4.2.

After calculating the potential health benefits in 2008 for each efficiency measure in each plant group, we can sum the results for the entire plant groups to determine the total potential health benefit in 2008 for each efficiency measure for the 16 cement plants. Then, this number can be used in Equation 2 in order to calculate the CCE with co-benefits included. The results of the calculation are presented in Section 4.3.

3.6. Sensitivity analyses

In the report on the previous phase of this study, Price et al. (2009), we present sensitivity analyses to determine the impact on the analysis results of four key parameters: discount rate, electricity and fuel prices, investment cost of the measures, and energy saving of the measures that affect the energy saving potential and cost-effectiveness.

In this report, we performed sensitivity analysis for several parameters that specifically affect health-benefit analysis results, while keeping all other parameters constant. These parameters are:

a. C-R coefficients (β): Using the lower and higher bound of the 95 percent CI (see Tables 9 and 10)
b. Unit value of health outcomes: Using the lower and higher bound of the 95 percent CI when available (see Table 11)
c. Meteorology, specifically wind speed. We contrast the modeled air concentration assuming the reported minimum average wind speed in Jinan, Zibo, and Zaozhung (Table 7) with the default minimum wind speed in AERSCREEN (0.5 m/s). This sensitivity analysis is important because it assesses the degree to which inversion layers with periods of low wind could worsen the impacts of air pollution. Some regions of China, such as the Taiyun province which neighbors Shandong Province, frequently experience inversion layers; this phenomenon has been incorporated into previous co-benefit studies in China (Staff-Mestl et al., 2005).

The results of the sensitivity analyses are presented in Section 6.

4. Results and Discussion

Based on the methodologies and data explained in Section 3, we calculated the physical values of energy savings and CO_2, PM_{10}, and SO_2 emissions reductions for all 29 energy-efficiency measures applicable to the studied plants. Then, we calculated the health benefits from implementation of the six fuel-saving measures in the 16 cement plants studied. We did not analyze health benefits for the 23 electricity-saving measures because the air pollution reduction from electricity savings takes place upstream at the power generation sites. Quantification of the health benefits from the electricity-saving measures would require more data and sophisticated analysis with a different geographic boundary; thus, this analysis is beyond the scope of this study.

4.1. Energy savings and CO_2, PM_{10}, and SO_2 emissions reductions

The subsections below describe the energy savings and pollutant reductions for all 29 efficiency measures applicable to the studied plants and the health benefits analysis for the six fuel-saving measures.

4.1.1. Electricity efficiency measures

There are 23 electricity-efficiency measures in this study that are applicable to the cement plants we studied. Table 12 shows all of the electricity-efficiency measures, ranked by their CCE which does not include co-benefits. We can see in the table that 14 energy-efficiency measures have CCEs lower than the average unit price of electricity in the plants studied in 2008 (545 RMB/ megawatt-hour [MWh]). In another words, the cost of investing in 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 measures are, therefore, considered cost-effective. The remaining nine electricity-saving measures (measure 15 to 23, which are highlighted gray in Table 12) are not cost-effective using this definition but are technically applicable to the cement plants studied and could save significant energy.

Table 12 also shows the CO_2, PM, and SO_2 emissions reductions from each measure applied tp the 16 cement plants. Figure 4 shows the cost-effective and total technical potential for air pollutant reduction that would be achieved from implementation of electricity-efficiency measures in the plants studied. More than 41 percent of the potential for both PM and SO_2 emissions reduction can be achieved cost effectively. The total pollution emissions reduction from implementing these 23 electricity-efficiency measures in the cement plants studied is significant, equal to 739 kilotons (kt) CO_2, 804 t PM, and 3,086 t SO_2.

Table 12. Electricity savings; CCE (without co-benefits); and CO_2, PM, and SO_2 emissions reductions potential for 16 cement plants in Shandong Province in 2008 (gray rows indicate electricity-saving measures that are not cost effective.)

CCE Rank	**Efficiency Measure**	**Electricity Savings (GWh)**	**CCE (RMB/MWh-saved)**	**CO_2 Emissions Reduction (kt CO_2) [a]**	**PM Emissions Reduction (t PM) [b]**	**SO_2 Emissions Reduction (t SO_2) [c]**
1	Efficient roller mills for coal grinding	15.5	67	12.6	13.7	52.4
2	Adjustable speed drive for kiln fan	26.7	83	21.6	23.5	90.2
3	New efficient coal separator for fuel preparation	2.2	89	1.8	1.9	7.4
4	Replacement of cement mill vent fan with high efficiency fan	1.4	145	1.1	1.2	4.6
5	High efficiency motors	53.0	157	42.9	46.6	179
6	Variable frequency drive (VFD) in raw mill vent fan	6.1	159	4.9	5.4	20.7
7	High efficiency fan for raw mill vent fan with inverter	7.2	192	5.9	6.4	24.5
8	Replacement of Preheater fan with high efficiency fan	5.0	203	4.0	4.4	16.8
9	Variable frequency drive in cooler fan of grate cooler	1.8	230	1.5	1.6	6.2
10	Energy management & process control in grinding	35.0	246	28.3	30.8	118
11	Adjustable Speed Drives	148	322	120	130	500
12	Installation of variable frequency drive & replacement of coal mill bag dust collector’s fan with high efficiency fan	1.5	353	1.2	1.3	5.2
13	Improved grinding media for ball mills	11.7	376	9.5	10.3	39.6
14	Low temperature waste heat recovery power generation	56.1	540	45.3	49.3	189
15	Replacing a ball mill with vertical roller mill in finish grinding	68.5	622	55.4	60.2	231
16	High pressure roller press as pre-grinding to ball mill in finish grinding	181	661	147	159	613
17	Raw meal process control for vertical mill	2.2	765	1.8	1.9	7.4
18	Efficient kiln drives	6.4	883	5.2	5.6	21.6
19	High-efficiency classifiers for finish grinding	51.1	1060	41.3	45.0	173
20	High-efficiency classifiers/separators for raw mill	24.4	1420	19.7	21.5	82.5
21	High-efficiency roller mill for raw materials grinding	160	1770	130	141	543
22	Low pressure drop cyclones for suspension preheater	39.3	2380	31.8	34.6	133
23	Efficient (mechanical) transport system for raw materials preparation	8.5	3140	6.9	7.5	28.8
Total		913	-	739	803	3,086

[a] The average Chinese electric grid CO_2 emissions factor of 0.809 kg CO_2/kWh is used to calculate the CO_2 emissions reduction from electricity savings (calculated based on data from the National Bureau of Statistics (NBS) (2007)).

[a] The average Chinese electric grid PM emissions factor of 1.08 kg PM/MWh is used to calculate the PM emissions reduction from electricity savings (calculated based on data from MEP (2008) and China Electricity Council (2008)).

[a] The average Chinese electric grid SO_2 emissions factor of 3.86 kg SO_2 /MWh is used to calculate the SO_2 emissions reduction from electricity savings (calculated based on data from MEP (2008) and China Electricity Council (2008)).

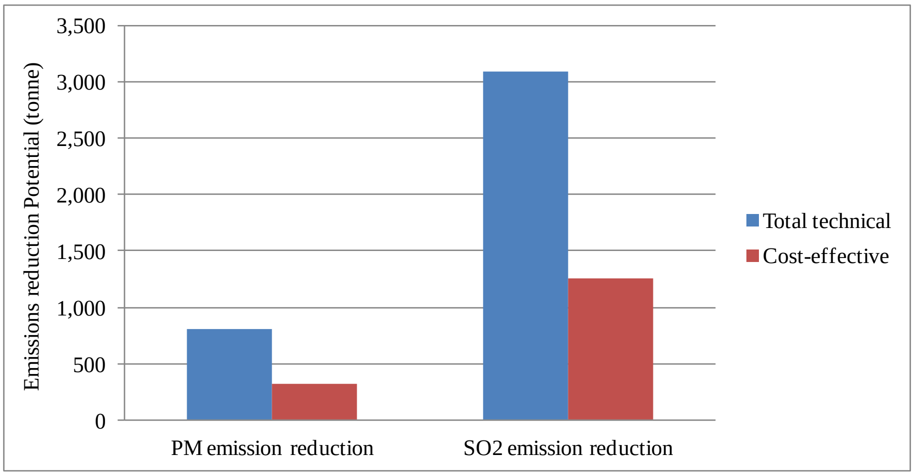

Figure 4. Cost-effective and total technical potential of PM and SO_2 emissions reduction from electricity-efficiency measures in the plants studied in Shandong Province in 2008.

4.1.2. Fuel efficiency measures

Six fuel-efficiency measures were applied to the cement plants studied. Table 13 shows all of the fuel-efficiency measures along with the potential fuel savings and the CO_2, PM_{10}, and SO_2 emissions reductions resulting from applying each measure to the 16 cement plants. Section 4.3 presents the CCE for each fuel-saving measure, calculated with and without health co-benefits.

Table 13. Fuel savings and CO_2, PM_{10}, and SO_2 emissions reductions potential for 16 cement plants in Shandong Province in 2008

$CCE_{co\text{-}ben}$ **Rank**	**Efficiency Measure** [b]	**Fuel Savings (TJ)**	**CO_2 Emissions Reduction (kt CO_2)**	**PM_{10} Emissions Reduction (t PM_{10})**	**SO_2 Emissions Reduction (t SO_2)**
1	Blended cement (additives: fly ash, pozzolans, and blast furnace slag)	2,011	378 [a]	2,560	248
2	Limestone Portland cement	105	20.3 [a]	850	13
3	Kiln shell heat loss reduction (Improved refractories)	2,177	206	-	270
4	Use of alternative fuels	1,749	165	-	215
5	Optimize heat recovery/upgrade clinker cooler	231	22.0	-	28
6	Energy management and process control systems in clinker making	1,676	158	-	202
Total		7,949	948	3,410	976

[a] CO_2 emissions reduction results from reduced energy use as well as reduced calcination in clinker-making process.
[b] Brief descriptions of the fuel-saving measures are provided in Appendix A.5.

The total pollutant emissions reduction associated with implementing the six fuel-efficiency measures in the cement plants is equal to 948 kilotons (kt) CO_2, 3,410 tons PM, and 976 tons SO_2. The greatest potential to reduce CO_2 and SO_2 emissions comes from increased production of blended cement and improved refractory in the kiln. Only product-change measures, i.e., increased production of blended cement and limestone Portland cement instead of ordinary Portland cement, reduce PM_{10} emissions. This is because these two measures substitute alternative materials for clinker and thus eliminate clinker production, which means that fewer raw materials are processed in the kiln to produce these two types of cement. This lowers PM_{10} emissions. The other four measures save fuel by reducing fuel use in the kiln or replacing conventional fuel with alternative fuel; neither of these changes significantly reduces PM_{10} emissions (Lei et al. 2011). Because fuel combustion in the cement kiln contributes only a small fraction of total PM_{10} emissions, reducing or substituting fuel does not significantly reduce PM_{10} emissions.

The energy saved from the two product-change measures depends heavily on plant-specific conditions and the efficiency of current facilities. A number of factors affect a plant's ability to increase the share of blended cement and Portland limestone cement in its production portfolio. These factors include market considerations, government policy, regulations and standards, and public acceptance.

As can be seen in Table 13, shifting to producing blended cement accounts for the largest CO_2 emission reductions, about 40 percent of the total CO_2 emission reduction potential from the six fuel-saving measures analyzed. The reasons for this are: First, the energy-saving potential of this measure is high, and a significant CO_2 emissions reduction results from this significant reduction in energy consumption. Second, because blended cement has a much lower clinker-per-cement ratio compared to ordinary Portland cement, blended cement requires less clinker to produce one unit of final product. As a result, producing this type of cement results in fewer CO_2 emissions from the calcination reaction, which is the source of almost half of CO_2 emissions in a cement plant. Therefore, for this measure, CO_2 emissions are reduced as a result of both reductions in energy use and calcination reaction.

The total fuel efficiency improvement potential for the 16 cement plants in 2008 is equal to 7,949 terajoules (TJ), which represents about 8 percent of the total fuel use in all 16 plants in 2008. The technical potential for CO_2 emission reductions is 4 percent of the total CO_2 emissions of the 16 plants in 2008. The total PM_{10} reduction potential from production of blended cement and limestone Portland cement represents 10 percent of the total PM_{10} emissions from the 16 plants in 2008.

4.2. Health benefits of fuel-saving measures

After calculating the total potential health benefit (in terms of number of health outcomes, i.e., reduced incidence of disease or death) for the population within the 10-km radius of each plant group for each health outcome in 2008 (Section 3.5.2) and by having the unit value for various health outcomes for Shandong Province for the year 2008 (in US $) (Table 11), we can calculate the potential economic benefit in 2008 of the PM_{10} and SO_2 emissions reduction resulting from implementation of each measure.

Tables 14 and 15 show an example of the economic benefits of PM_{10} and SO_2 emissions reductions that result from switching to blended cement. There is no potential benefit for some cement plant groups because the plants within that group produce only clinker and not cement, or because the efficiency measure could not be applied to the plants within that group, or both. Appendix A.1 presents the potential economic benefits of PM_{10} and SO_2

emissions reductions for the other fuel-saving measures analyzed.

Consistent with results from previous studies, the current study shows that the health benefits of PM_{10} emissions reduction are much greater than the benefits of SO_2 emissions reduction.

Table 14. Potential economic benefit from reduction in health effects from PM_{10} emissions as a result of implementing blended cement measure in Shandong Province in 2008 (in US$).

Health outcome (age group)	Group A	Group B	Group C	Group D	Group E	Group F	Group G	Group H	Group I	Group J	Total
Long-term mortality (adult ≥30)	40,481	180,473	-	-	-	401,816	180,150	63,496	-	-	866,415
Chronic bronchitis (all ages)	88,904	396,774	-	-	-	883,174	395,765	139,487	-	-	1,904,103
Respiratory hospital admission (all ages)	2,687	11,982	-	-	-	26,675	11,958	4,215	-	-	57,517
Cardiovascular hospital admission (all ages)	2,706	12,066	-	-	-	26,862	12,042	4,244	-	-	57,919
Outpatient visits internal medicine (all ages)	3,642	16,238	-	-	-	36,152	16,208	5,713	-	-	77,953
Outpatient visits pediatrics (all ages)	384	1,714	-	-	-	3,816	1,711	603	-	-	8,229
Acute bronchitis (all ages)	3,629	16,200	-	-	-	36,058	16,156	5,694	-	-	77,738
Asthma attack (children <15 years)	59	264	-	-	-	588	264	93	-	-	1,268
Asthma attack (adults ≥15 years)	230	1,026	-	-	-	2,283	1,023	361	-	-	4,923

Table 15. Potential economic benefit of reduction of health effects of SO_2 emissions resulting from implementation of blended cement measure in Shandong Province in 2008 (in US$)

Health outcome (age group)	Group A	Group B	Group C	Group D	Group E	Group F	Group G	Group H	Group I	Group J	Total
Long-term mortality (all ages)	12,591	53,956	-	-	-	123,949	60,049	21,912	-	-	272,457

4.3. Cost of conserved energy for fuel-saving measures with health benefits included

To calculate the CCE with health co-benefits included ($CCE_{co\text{-}ben}$), we can use Equation 2 with the total potential economic benefit of PM_{10} and SO_2 emissions reduction for each measure. Table 16 shows the CCE for fuel-efficiency measures, with and without co-benefits. The inclusion of co-benefits in the CCE calculation significantly reduces the CCE for the product-change measures (production of blended cement and limestone Portland cement). This is primarily because these are the only measures that reduce PM_{10} emissions; the other four fuel-saving measures reduce only SO_2 emissions. As mentioned above and reported in previous studies (Aunan et al. 2004, Chen et al. 2007, Kan et al. 2004), the burden of disease associated with PM_{10} is larger than the burden associated with other air pollutants, such as SO_2 and NO_x.

Table 16 also shows that all six fuel-efficiency measures have both CCE and $CCE_{co\text{-}ben}$ lower than the average unit price of coal in the 16 plants in 2008 (31.9 RMB/GJ). In another words, the cost of investing in these six energy-efficiency measures to save one GJ of fuel is less than purchasing one GJ of fuel at the current price of coal. Therefore, these measures are cost effective. However, it should be noted that only the fuel cost savings will benefit the cement plants directly and the other cost savings from health co-benefits are societal. In addition, shifting to blended cement production has the lowest CCE, while shifting to production of limestone Portland cement has the lowest $CCE_{co\text{-}ben}$ and is the most cost-effective measure.

Table 16. CCE and $CCE_{co\text{-}ben}$ of fuel-efficiency measures for 16 cement plants in Shandong Province

CCE Rank	Efficiency Measure [b]	CCE (RMB/GJ-saved)	$CCE_{co\text{-}ben}$ (RMB/GJ-saved)	Difference (%)
1	Blended cement (additives: fly ash, pozzolans, and blast furnace slag) [a]	0.72	0.25	-65%
2	Limestone Portland cement [a]	0.76	0.16	-80%
3	Kiln shell heat loss reduction (Improved refractories)	1.98	1.89	-5%
4	Use of alternative fuels	3.78	3.76	-1%
5	Optimize heat recovery/upgrade clinker cooler [a]	4.71	4.56	-3%
6	Energy management and process control systems in clinker making	12.6	12.40	-1%

[a]: For this measure, primary energy savings were used to calculate CCE and $CCE_{co\text{-}ben}$ based on both the electricity and fuel savings. However, because the share of fuel savings is more than that of electricity savings, this measure is included with the fuel-saving measures.

[b] Brief descriptions of the fuel-saving measures are provided in Appendix A.5.

5. Uncertainties and Limitations

There are number of limitations and sources of uncertainty in this study as is the case with most studies that calculate the health benefits of air pollution reduction. The results of all such studies should, therefore, be interpreted with caution. Some of these uncertainties are discussed below, organized according to the phase of the analysis to which they apply.

5.1. Study scope limitations

Limitations relating to the scope of this study, which was defined based on the purpose of the research as well as on available time and resources, include:

- *Relying on PM_{10} and SO_2 as indicators of outdoor air pollution.* Previous health impact studies in China have assumed that, relative to other air pollutants, PM exposure is the largest contributor to premature mortality (Wang and Mauzerall 2006, Zhang et al. 2010). However, more recent studies based on time-series data, such as the Public Health and Air Pollution in Asia study (HEI 2010 and specifically Qian et al. 2010), report that the estimated mortality effects of NO and SO_2 are greater than the mortality effects of PM_{10}. It is, therefore, likely that there are additional health effects attributable to exposure to other air pollutants, such as nitrogen oxides (NOx, including NO and NO_2), and also due to ozone formation. Thus, our results likely underestimate the health effects attributable to total air pollution in Shandong Province.
- *Assessment of PM_{10} and possible underestimation of total PM health effects.* It is uncertain whether analyzing PM_{10} exposures adequately accounts for $PM_{2.5}$ health impacts. In addition, secondary $PM_{2.5}$ formation from gaseous precursors, including SO_2, NOx, ammonia, and volatile organic compounds, may be a significant contributor to PM health impacts (Chen et al. 2007). For instance, Wang and Mauzerall (2006) report that a business-as-usual approach to managing pollutant emissions in Zaozhuang would result in

secondary PM exposures that would cause one-quarter of all mortalities caused by PM. Because of the scarcity of $PM_{2.5}$ and secondary-PM precursor emission factors and data, as well as the sophisticated modeling framework required to estimate secondary PM air concentrations, we analyzed only directly emitted PM_{10} in this study.

- *Excluding synergistic effects between outdoor air pollutants and co-factors such as environmental tobacco smoke, and pollen and other allergens*. Excluding these synergistic effects could result in an underestimation of health effects.
- *A focus on exposures to ambient air pollution.* We did not consider the health impacts of exposure to indoor air pollution. The Chinese economy is heavily industrialized. Because the industrial sector accounts for around 70 percent of the primary energy consumed in China, and Shandong province is a heavily industrialized province, a considerable portion of indoor air pollution in that province might be caused by outdoor sources (Chen et al. 2007). Therefore, excluding indoor air pollution from our analysis might underestimate the total health benefits of energy-efficiency measures.

5.2. Air quality modeling limitations and uncertainties

Several limitations associated with the AERSCREEN air quality model contribute to uncertainty in our study results. These uncertainties, when combined, likely result in underestimation of the actual concentrations of pollutants attributable to cement manufacturing. This conclusion is substantiated by comparisons between the base-year modeled concentrations and ambient PM_{10} measurements from 2010 (Shandong EPA 2011). These comparisons indicate that we might be under-predicting concentrations. However, the degree to which we might be under-predicting the contribution of cement manufacturing is uncertain because the ambient PM_{10} measurements include PM_{10} from other sources: other industries, power generation, motor vehicles, residential biomass combustion, and dust or soil re-suspension. Nonetheless, we can identify a number of specific factors in the modeling that could lead to an underestimate of air pollutant concentrations, including:

- *"Other" pollutant sources, including volume sources from cement manufacturing, are excluded*.
- *Because of interactions between the plume and surface characteristics, AERSCREEN might predict lower concentrations when receptor elevations are lower than source elevations (i.e., receptors are down-slope of the source), compared to the concentrations when the receptor and source are at the same elevation (AERMOD Implementation Workgroup, 2009)*. In this study, we assumed (reasonably, in the absence of spatial information) a flat terrain, i.e., that source and receptors are at the same elevation (within the radius of up to 10 km around plants). Receptors are points at a radial distance from the source. However, Wang et al. (2006) point out in their analysis of the health damage from industrial air pollutants in China in 2006 that regions of southeast Jinan have hills with an elevation of > 800 m, which would affect the dispersion of conserved pollutants and could lead to "pockets" or regions with much higher concentrations than in other areas. Because we assume a flat terrain, we do not consider the effect of terrain on pollutant plume trajectory.

- *A number of uncertainties are associated with urban topography and meteorology, such as how the effects of building downwash and albedo influence PM concentrations*. The former would be particularly relevant for urban areas with many tall apartment buildings, which could produce an increase in ground-level concentrations downstream of the buildings. Albedo may also vary based on surface characteristics, and for urban regions is typically between 0.15-0,20. Thus, our assumption of 0.25, which is the albedo of the neighboring Taiyun region (Staff-Mestl et al., 2005) may be an overestimate. However, due to time and resource limitations we were unable to conduct sensitivity analyses to assess the degree to which these inputs influence the average annual exposure concentrations. While individually these factors are minor uncertainties, taken together their contribution may rival the uncertainties listed above.

It is likely that a more spatially explicit model, i.e., a more finely gridded or nested modeling framework, would more accurately assess air pollutant concentrations from cement manufacturing plants. For example, the Model-3/Community Multiscale Air Quality (CMAQ) or approaches such as that used by Wang et al. (2006) and Heath et al. (2006) might be applicable. These approaches integrate Gaussian Plume modeling with a geographic information system (GIS) to characterize the impacts of a shift toward distributed electricity generation, but it is possible that they could also be applied to industrial point source emissions in China. However, it is questionable whether adequate GIS data are available, and significant resources would be necessary to conduct such an analysis with CMAQ. Thus, a screening level tool, such as AERSCREEN which requires fewer data and computational resources, combined with a sensitivity analysis of the most influential input parameters, may be sufficient to characterize air concentrations for the purpose of this research and similar studies in the future which is to inform policy makers about the large co-benefits of the energy efficiency and/or GHG emissions reduction programs and policies (Williams et al. 2012).

5.3. Health benefit estimation limitations and uncertainties

The following limitations and uncertainties apply to the calculation of health benefits from air pollution reductions that result from efficiency measures:

- *We only selected the health outcomes that could be quantified and translated those into monetary values.* Therefore, some outcomes that could not be quantified, such as reduced lung function, were not included in this analysis even though there is evidence that they are associated with exposure to air pollution (Zhang et al. 2010, Chen et al. 2007).
- *Because data are scarce on long-term health impacts of air pollution in China, we had in some cases to use C-R coefficients from studies conducted in developed countries.* The C-R coefficients also assume a linear dose-response, and thus a given exposure concentration reductions amount to the same risk of mortality or morbidity regardless of the initial concentration levels. This is likely one of the largest sources of uncertainty because different countries have different levels and components of air pollution as well as differences in population health status, sensitivity, and age distribution (Zhang et al. 2010, Chen et al. 2007). The sensitivity analysis of health benefits in Section 6 addresses this issue by looking at varying C-R coefficients.

- *Because we did not find specific health outcome unit values for Shandong province, we used unit values based on studies in Chongqing and Shanghai, China.* This is a source of uncertainty because characteristics of the affected population, e.g., age distribution, income, health status, and culture, could affect the valuation results (Zhang et al. 2010). To address this issue, Section 6 evaluates how changes in unit value for various health outcomes influences the results of the analysis.
- *To adjust the unit value for various health outcomes that are given for Shanghai, we used the differences between average annual income per capita in Shanghai and in Shandong and the marginal increase for saving a statistical life associated with increase in annual income, which is given in Chen et al. (2007).* This is a reasonable approach that is also used in previous studies, but it can nonetheless be a source of uncertainty.

5.4. Cost of conserved energy calculation limitations and uncertainties

The CCE calculated in this study is a good screening-level indicator to show the cost effectiveness of the efficiency measures. In reality, the energy-saving potential and cost of each energy-efficiency measure and technology could vary and will depend on various conditions such as raw material quality (e.g., moisture content of raw materials and hardness of limestone), the technology provider, the production capacity of the plant, the size of the kiln, the fineness of the final product and byproducts, the time of the analysis, and many other factors). Moreover, some energy-efficiency measures provide productivity and other environmental co-benefits in addition to energy savings and the co-benefits analyzed in this study. However, it is difficult (and sometimes impossible) to quantify those other benefits. Including quantified estimates of other benefits could reduce the CCE for the energy-efficiency measures even further (Worrell et al. 2003, Lung et al. 2005). In addition, the variable discount rate can significantly affect the CCE. Price et al. (2009) presents a sensitivity analysis for the discount rate to show how it changes the CCE and the cost effectiveness of the measures.

6. Sensitivity Analysis

In the previous phase of this study, we found that the CCE is directly related to the discount rate. Therefore, reducing the discount rate will reduce the CCE. A change in energy prices might affect the cost effectiveness of a measure if the change is large enough to change the position of the CCE with respect to the energy price. A change in the investment cost will directly change the CCE, while a change in the energy savings of the measures has an inverse effect on CCE (Equation 2). Furthermore, a change in savings from any energy-efficiency measure will change the total amount of energy-saving potential regardless of the measure’s cost effectiveness. See Price et al. (2009) for further discussion of these four parameters. In the current study, we focused our sensitivity analysis on the parameters that play the most important role in modeling air quality and quantifying health benefits. These parameters are the C-R coefficient, the unit value of health outcomes, and the minimum wind speed used in the AERSCREEN model.

For the C-R coefficients, we conducted the sensitivity analysis using the lower and higher bound of the 95-percent confidence interval (Tables 9 and 10) to determine how this variation affects the final results, i.e. $CCE_{co\text{-}ben}$. This analysis shows that $CCE_{co\text{-}ben}$ has an inverse relation with C-R coefficients (Table 17). In other words, when C-R coefficients decrease, the $CCE_{co\text{-}ben}$ will increase, and vice versa. Also, we can see that the changes in $CCE_{co\text{-}ben}$ are more significant for measure number 1 and 2, which are the product change measures and the only measures resulting in PM_{10} emissions reduction.

Table 17. Sensitivity analysis for $CCE_{co\text{-}ben}$ of fuel-efficiency measures for 16 cement plants with different concentration-response coefficients, and other parameters held constant*

No.	**Efficiency Measure**	**$CCE_{co\text{-}ben}$ (RMB/GJ-saved)**		
		Mean C-R Co-efficient	Low C-R Co-efficient	High C-R Co-efficient
1	Blended cement (additives: fly ash, pozzolans, and blast furnace slag)	0.25	0.56	-0.10
2	Limestone Portland cement	0.16	0.56	-0.31
3	Kiln shell heat loss reduction (Improved refractories)	1.89	1.95	1.84
4	Use of alternative fuels	3.76	3.77	3.75
5	Optimize heat recovery/upgrade clinker cooler	4.56	4.65	4.47
6	Energy management and process control systems in clinker making	12.4	12.5	12.3

* See Table 9 for C-R coefficients

We conducted a sensitivity analysis for another parameter using the lower and higher bound of the 95-percent confidence interval for unit value of health outcomes when this information is available (Table 11). Table 18 shows the result, which is that the $CCE_{co\text{-}ben}$ also has an inverse relation with unit value of health outcomes. For measures 3 to 6, which are the efficiency measures that only reduce SO_2 emissions, the change in $CCE_{co\text{-}ben}$ in this sensitivity analysis is either minimal or zero.

Table 18. Sensitivity analysis for $CCE_{co\text{-}ben}$ of fuel-efficiency measures for 16 cement plants in Shandong Province with different unit value for health outcomes, and other parameters held constant *

No.	**Efficiency Measure**	**$CCE_{co\text{-}ben}$ (RMB/GJ-saved)**		
		Mean unit price of health outcome	Low unit price of health outcome	High unit price of health outcome
1	Blended cement (additives: fly ash, pozzolans, and blast furnace slag)	0.25	0.50	-0.37
2	Limestone Portland cement	0.16	0.50	-0.72
3	Kiln shell heat loss reduction (Improved refractories)	1.89	1.90	1.89
4	Use of alternative fuels	3.76	3.76	3.76
5	Optimize heat recovery/upgrade clinker cooler	4.56	4.56	4.55
6	Energy management and process control systems in clinker making	12.4	12.4	12.4

* See Table 11 for different unit prices of health outcome

In the base-case analysis, we used the minimum monthly average wind speed in the prefectures studied (Jinan, Zibo, and Zaozhung) over the time period 1971-2000 as the minimum wind speed in AERSCREEN. In this sensitivity analysis, we used the default minimum wind speed in AERSCREEN (0.5 m/s) instead of the minimum monthly average wind speed. The result is shown in Table 19. The default minimum wind speed in the AERSCREEN model, which is lower than the minimum monthly average wind speed in the prefectures studied (2.4 m/s for Jinan and Zaozhung and 1.9 m/s for Zibo), results in a lower $CCE_{co\text{-}ben}$. This means that using the default wind speed results in higher health co-benefits for the fuel-saving measures.

The sensitivity analysis of wind speed also demonstrates that at very low wind speed (0.5 m/s), the average exposure concentrations in 10 km around the plant double relative to the exposure concentrations estimated assuming the measured lowest monthly average wind speed between 1971 and 2000 for each prefecture. This highlights the importance of site-specific data to accurately characterize exposure concentrations.

Table 19. Sensitivity analysis for $CCE_{co\text{-}ben}$ of fuel-efficiency measures for 16 cement plants in Shandong Province with different wind speeds, and other parameters held constant

No.	**Efficiency Measure**	**$CCE_{co\text{-}ben}$ (RMB/GJ-saved)**	
		Monthly average wind speed in prefectures studied*	Minimum wind speed in AERMOD model (0.5 m/s)
1	Blended cement (additives: fly ash, pozzolans, and blast furnace slag)	0.25	-0.72
2	Limestone Portland cement	0.16	-1.01
3	Kiln shell heat loss reduction (Improved refractories)	1.89	1.79
4	Use of alternative fuels	3.76	3.74
5	Optimize heat recovery/upgrade clinker cooler	4.56	4.34
6	Energy management and process control systems in clinker making	12.4	12.2

* 2.4 m/s for Jinan and Zaozhung and 1.9 m/s for Zibo

7. Recommendations for Future Work

Based on the research and findings of this study, we recommend the following future research:

1. Assess co-benefits from PM and SO_2 emissions reductions achieved from implementing electricity-saving measures. For this, the pollution concentrations around power plants included in the boundary of the study for the base-case and energy-efficiency scenarios must be calculated. Then, the health benefits from reduction in pollution concentration can be calculated using the similar method presented in this report.

2. Assess co-benefits from $PM_{2.5}$ emission reductions specifically, as well as secondary

PM formation. For this analysis, we would need to obtain stack emission factors for $PM_{2.5}$, as well as NO_x, NH_3, and VOCs (SO_2 is available). We could then incorporate the atmospheric transformation of the gaseous precursors into secondary PM using a modification of the standard Gaussian Plume equation (which only takes into account diffusion and advection of primary pollutants), such as is described by Tsuang (2003). And/or we could use more advanced spatial and chemical transformation modeling, such as the CMAQ model, which is a long-range multi-pollutant dispersion model.

3. There are pollution fees in China for SO_2 and PM emitted by cement plants. We did not include the reduction of such fees that results from SO_2 and PM emissions reduction achieved by the efficiency measures in the analysis. If we had included them in the CCE calculation, the CCE with co-benefits included would have been even lower. This could be included in future studies.

4. Perform similar co-benefits assessment for other industries in China, e.g., the iron and steel industry.

5. Study the use of AERSCREEN or another modeling tool to incorporate “other” emissions, e.g., fugitive dust or volume emissions from cement and clinker production plants. Additional information on characterizing the volume source emissions, e.g., dimensions of the volume source, would be needed (see section 3.4.2 for the discussion on “other” emissions).

8. Summary and Conclusions

This report is a follow-up to an earlier study (Price et al. 2009) on energy-efficiency potentials in 16 cement plants in Shandong Province, China. In the current study, we quantified the potential health co-benefits of energy-saving measures that reduce PM and SO_2 emissions. We conducted a detailed analysis of six fuel-saving measures, estimating the potential health benefits from PM_{10} and SO_2 emissions reduction associated with these measures. The results are presented using the concept of the CCE with co-benefits included. The purpose of this approach is to show how inclusion of co-benefits can affect the cost effectiveness of efficiency measures.

The results show that including the health benefits from PM_{10} and SO_2 emissions reductions reduces the CCE of the fuel-saving measures. However, the reduction in CCE was minimal for the fuel-saving measures that reduce only SO_2 emissions. The two fuel-saving measures that reduce PM_{10} as well as SO_2 emissions, show the largest reduction in CCE when the health co-benefits are included. This demonstrates the importance of PM_{10} emissions in the cement industry and the significant benefits of reducing these emissions. The policy implication of this for China, where energy efficiency policies are sometimes technology-oriented, is that when prioritizing energy efficiency technologies for promotion, in addition to energy savings and CO_2 emissions reductions other benefits especially PM_{10} emissions reduction potential should be taken into account.

Despite the uncertainties associated with this analysis (discussed in Section 5 of this report), we believe this analysis provides valuable information for policy makers on the relative benefits of different future emission scenarios and mitigation strategies. We performed sensitivity analyses to examine the impact of three important parameters on the results. These analyses showed that the $CCE_{co\text{-}ben}$ has an inverse relation with C-R coefficients and the unit value of health outcomes and a direct relation with wind speed. Also, in all three sensitivity analyses, the changes in $CCE_{co\text{-}ben}$ are more significant for measures 1 and 2, which are the product change measures and the only measures resulting in PM_{10} emissions reduction.

Our estimates of exposure concentrations using AERSCREEN and based on available data (prefecture average meteorological data) are conservative. This is because the AERSCREEN results are based on the maximum concentrations along the plume center line, which are averaged (assuming a one-sector model) within a 10-km radial distance of the cement plant groups into which the 16 plants in this study were aggregated based on geographic location. A more sophisticated air quality model using data that have finer spatial and meteorological resolution could more accurately estimate co-benefits. However, for the purpose of informing policy makers of potential co-benefits of energy-efficiency measures, we believe screening models such as AERSCREEN are effective and give reasonable estimates.

As is also highlighted in Williams et al. (2012), co-benefit studies are critical and becoming more common in developing countries such as China. However, data limitations combined with a lack of resources and experience with large-scale CGE or bottom-up models and sophisticated air quality models may present significant barriers. Therefore, the use of a more simplified approach and models, such at the approach and model used in this study, can still provide results with reasonable accuracy for conducting co-benefit studies at a larger scale and scope in developing countries.

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Appendixes

A.1. The potential economic benefit of PM_{10} and SO_2 emissions reduction for fuel-saving measures

Table A.1. The potential economic benefit of PM_{10} emissions reductions based on reduced health impacts resulting from partial switching to production of limestone Portland cement in 2008 (in US$)

Health outcome (age group)	Group A	Group B	Group C	Group D	Group E	Group F	Group G	Group H	Group I	Group J	Total
Long-term mortality (adult ≥30)	36,651	152,092	12,123	-	-	295,720	72,630	30,873	-	-	600,088
Chronic bronchitis (all ages)	80,444	333,938	26,603	-	-	649,185	159,390	67,753	-	-	1,317,313
Respiratory hospital admission (all ages)	811	3,367	268	-	-	6,546	1,608	683	-	-	13,283
Cardiovascular hospital admission (all ages)	817	3,390	270	-	-	6,591	1,619	688	-	-	13,375
Outpatient visits-internal medicine (all ages)	1,100	4,564	364	-	-	8,874	2,179	926	-	-	18,007
Outpatient visits-pediatrics (all ages)	116	482	38	-	-	937	230	98	-	-	1,901
Acute bronchitis (all ages)	3,283	13,631	1,086	-	-	26,497	6,505	2,765	-	-	53,767
Asthma attack (children <15 years)	54	222	18	-	-	432	106	45	-	-	878
Asthma attack (adults ≥15 years)	208	864	69	-	-	1,679	412	175	-	-	3,407

Table A.2. The potential economic benefit of SO_2 emissions reduction based on reduced long-term mortality (all ages) resulting from fuel-saving measures in 2008 (in US$)

Energy-efficiency measure	Group A	Group B	Group C	Group D	Group E	Group F	Group G	Group H	Group I	Group J	Total
Kiln shell heat loss reduction	66,199	116,055	-	28,561	-	-	-	89,773	-	-	300,589
Energy management and process control systems in clinker making	-	38,684	-	-	30,298	-	225,518	59,848	-	-	354,348
Optimize heat recovery/upgrade clinker cooler	-	-	8,523	-	-	65,827	-	-	-	-	74,350
Use of alternative fuels	30,090	64,474	12,784	7,140	10,099	98,741	82,005	22,443	13,526	-	341,302
Blended cement	30,090	128,950	-	-	-	296,226	143,510	52,367	-	-	651,144
Limestone Portland cement	-	-	-	-	-	-	-	-	-	-	-

A.2. Method for estimating populations within 10 km of cement plant groups

We used Google maps and census data for the year 2008 from the *Shandong Statistical Yearbook 2009* to identify cities, districts, and villages within 10 km of each of the cement plants and determine population. To estimate health benefits, we assumed the population for the year 2008 and calculated the potential health benefits from fuel efficiency measures in 2008.

A.3. Prevailing Wind Direction (January 1, 2011 to July 1, 2012)

Municipality	**Wind Direction**	**# of Days**
Jinan	South	190
	North	95
	North - South	58
	South - North	56
	Northeast	51
	East	10
Zibo	South	243
	North	118
	Northeast	46
	North - South	31
	South - North	31
	East	16
	Southeast	14
Zaozhuang	No sustained wind direction	276
	South	66
	North	45

Source: http://lishi.tianqi.com

A.4. Adjustment of modeled concentrations to account for PM_{10} deposition

The AERSCREEN modeled concentrations are adjusted for PM_{10} deposition using the following term:

$\exp(-kx\ U_E^{-1})$

where:
k = the rate constant, in units of s^{-1} and is approximated by the particle deposition velocity (m/s) divided by the atmospheric mixing height (m),U_E = the wind speed (at the effective mixing height; we used the average annual wind speed for each municipality).

For PM_{10}, we assume a particle deposition velocity of 0.14 centimters/s, which is reported by Caffrey et al. (1998) for a 6.9 aerodynamic diameter particle (which is near the midpoint of coarse particles' aerodynamic diameter range).

The atmospheric mixing height refers to the height above ground where the air mass is well mixed as a result of thermal and/or mechanical turbulence. It is also the height at which a pollutant is well mixed over a short time period (1-2 hours). We assumed a mixing height over Shandong Province of 1,150 m, based on figures available for Beijing, see the graphics labeled "Figure 1" and "Figure 3" below, which are reproduced from the Beijing Observatory.

Reference

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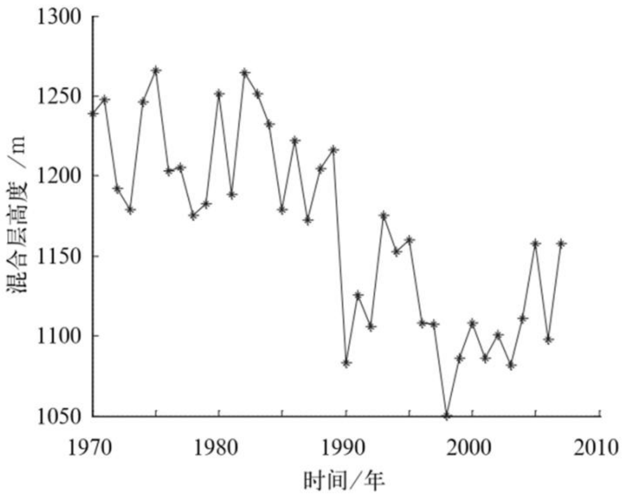

图 1　北京观象台 1970—2007 年年平均最大混合层厚度随时间变化

Fig. 1　Variation of annual maximum mixing depth at Beijing Observatory from 1970 to 2007

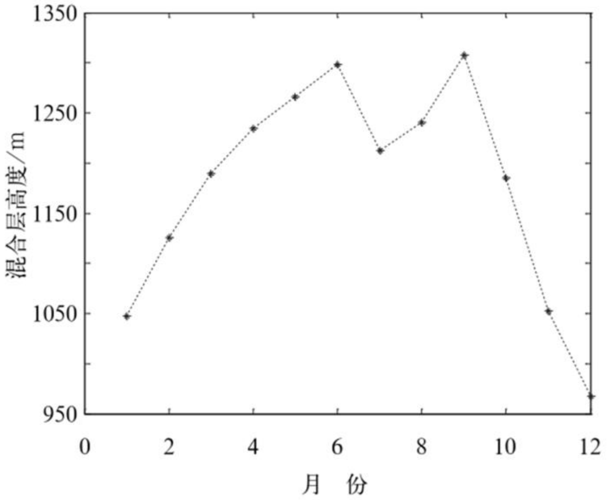

图 3　北京观象台 1970—2007 年逐月平均最大混合层厚度随时间变化

Fig. 3　Variation of monthly maximum mixing depth at Beijing Observatory from 1970 to 2007

A. 5. Description of Fuel-Efficiency Measures[1]

1. 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.

2. Use 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).

3. 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

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[1] Excerpted from Worrell, et al., (2008).

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.

4. 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). In this study we assumed biomass as the alternative fuel, which is carbon neutral.

5. 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).

6. Limestone Portland 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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