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Air Pollutant Emissions Projections for the Cement and Steel Industry in China and the Impact of Emissions Control Technologies

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Abstract

China's cement and steel industry accounts for approximately half of the world's total cement and steel production. These two industries are two of the most energy-intensive and highest carbon dioxide (CO_2)-emitting industries and two of the key industrial contributors to air pollution in China. For example, the cement industry is the largest source of particulate matter (PM) emissions in China, accounting for 40 percent of its industrial PM emissions and 27 percent of its total national PM emissions. The Chinese steel industry contributed to approximately 20 percent of sulfur dioxide (SO_2) emissions and 27 percent of PM emissions for all key manufacturing industries in China in 2013.

In this study, we analyzed and projected the total PM and SO_2 emissions from the Chinese cement and steel industry from 2010–2050 under three different scenarios: a Base Case scenario, an Advanced scenario, and an Advanced EOP (end-of-pipe) scenario. We used bottom-up emissions control technologies data and assumptions to project the emissions. In addition, we conducted an economic analysis to estimate the cost for PM emissions reductions in the Chinese cement industry using EOP control technologies, energy efficiency measures, and product change measures.

The results of the emissions projection showed that there is not a substantial difference in PM emissions between the Base Case and Advanced scenarios, for both the cement and steel industries. This is mainly because PM emissions in the cement industry caused mainly by production process and not the fuel use. Since our forecast for the cement production in the Base Case and Advanced scenarios are not too different from each other, this results in only a slight difference in PM emissions forecast for these two scenarios. Also, we assumed a similar share and penetration rate of control technologies from 2010 up to 2050 for these two scenarios for the cement and steel industry. However, the Advanced EOP scenario showed significantly lower PM emissions for the cement industry, reaching to 1.7 million tons of PM in 2050, which is less than half of that in the other two scenarios. The Advanced EOP scenario also has the lowest SO_2 emissions for the cement industry in China, reaching to 212,000 tons of SO_2 in 2050, which is equal to 40 percent of the SO_2 emissions in the Advanced scenario and 30 percent of the emissions in the Base Case scenario. The SO_2 emission is mainly caused by fuel (coal) burning in cement kiln or steel processes. For the steel industry, the SO_2 emissions of the Advanced EOP scenario are significantly lower than the other scenarios,

with emissions declining to 323,000 tons in 2050, which is equal to 21 percent and 17 percent of the emissions of Advanced and Base Case scenarios in 2050, respectively.

Results of the economic analysis show that for the Chinese cement industry, end-of-pipe PM control technologies have the lowest abatement cost per ton of PM reduced, followed by product change measures and energy efficiency measures, respectively.

In summary, in order to meet Chinese national and regional air quality standards, best practice end-of-pipe emissions control technologies must be installed in both cement and steel industry and it must be supplemented by implementation of energy efficiency technologies and reduction of cement and steel production through structural change in industry.

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1. Introduction

China's cement industry produced 2,360 million metric tons (MMt) of cement in 2015, accounting for 57 percent of the world's totalF cement production (NBS 2015a; USGS 2016). Consistent with the Chinese cement industry's large production volume, total carbon dioxide (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. 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).

China's steel production in 2015 was 804 MMt (worldsteel, 2016), representing 49.5 percent of the world production that year. The Chinese steel industry contributed to about 20 percent of SO_2 emissions, and 27 percent of dust and PM emissions for all key manufacturing industries in China in 2013 (Wang et al. 2016). In addition to setting emissions standards and adoption of end-of-pipe emissions control technologies, Chinese government policies also 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).

In this study, we analyzed and projected the total PM and SO_2 emissions from the Chinese cement and steel industry from 2010–2050 under three different scenarios. We used bottom-up emissions control technologies data to project the emissions. In addition, we conducted an economic analysis to estimate the cost for PM emissions reduction in the Chinese cement industry using end-of-pipe emissions control technologies[1], energy efficiency measures, and product change measures.

This report begins with a brief introduction to the cement and steel industry in China and sources of air pollution from these two industries. Next, we describe the

[1] End-of-pipe emissions control technologies are used to remove already formed contaminants from an exhaust stream. These technologies are normally implemented as a last stage of a process before air pollutants are released to the air.

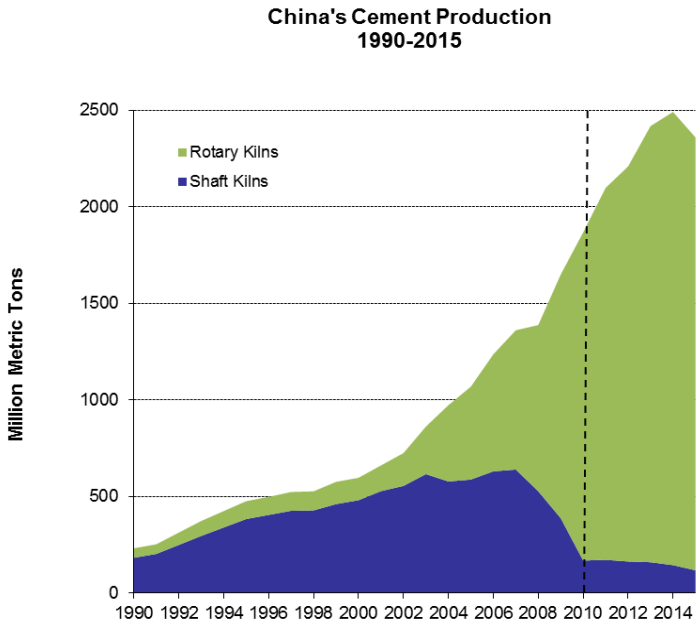
methodology used in this study, including the calculation and forecast for PM and SO_2 emissions for the Chinese cement and steel industries and the economic analysis for PM abatement options for the cement industry as a case-study. Finally, we present our results, which include the PM and SO_2 emissions forecasts for both industries and the PM abatement costs for different abatement options in the cement industry in China.

2. A Brief Overview of the Cement and Steel Industries in China

2.1. Cement industry in China

China produces over half of the world's cement, with 2,360 MMt produced in China in 2015 (NBS 2015a). Two types of kilns—vertical shaft kilns (VSKs) and rotary kilns—are used in China to produce clinker, which is the key ingredient in cement. Vertical shaft kilns are outdated technologies that use significantly more energy to produce a ton of clinker than rotary kilns do.

In 2010, nearly 20 percent of China's cement was produced by plants using outdated vertical shaft kilns; 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 2011). The Chinese government had an aggressive policy to phase out VSKs during the 11th Five-Year Plan (FYP) (2006–2011); this policy continues in the 12th FYP (2011–2016 (CIEE 2011). Figure 1 shows that cement production from rotary kilns grew rapidly in recent years, from 116 MMt in 2000 to 1,494 MMt in 2010 (ITIBMIC 2004; MIIT 2011).



Note: 2011–2015 production shares are based on our model projections
Sources: ITIBMIC 2004; MIIT 2011; NBS 2015a.

Figure 1. Cement production in China by kiln type, 1990–2015

2.2. Sources of air pollution 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 2009a; European Commission 2010).

Producing one ton of cement releases an estimated 0.73 to 0.99 ton (t) of 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) of CO_2 per ton of clinker (WBCSD 2009) is from calcination, in which calcium carbonate ($CaCO_3$) is transformed into lime (CaO) in the following reaction (Equation 1):

$$CaCO_3 \rightarrow CaO + CO_2 \qquad \text{(Eq. 1)}$$

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 (kWh) of electricity is consumed per ton 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 focus on PM_{10} (particulate matter 10 microns or smaller in size) and SO_2 emissions reductions. Exposures to these two pollutants can have serious environmental impacts (e.g., reduced visibility, acid rain) and human health impacts (disease and death). The discussion below focuses on the sources of these two pollutants in the cement industry. The European Commission (2010) has provided a detailed explanation of emissions sources and specific control technologies for each type of emissions 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,

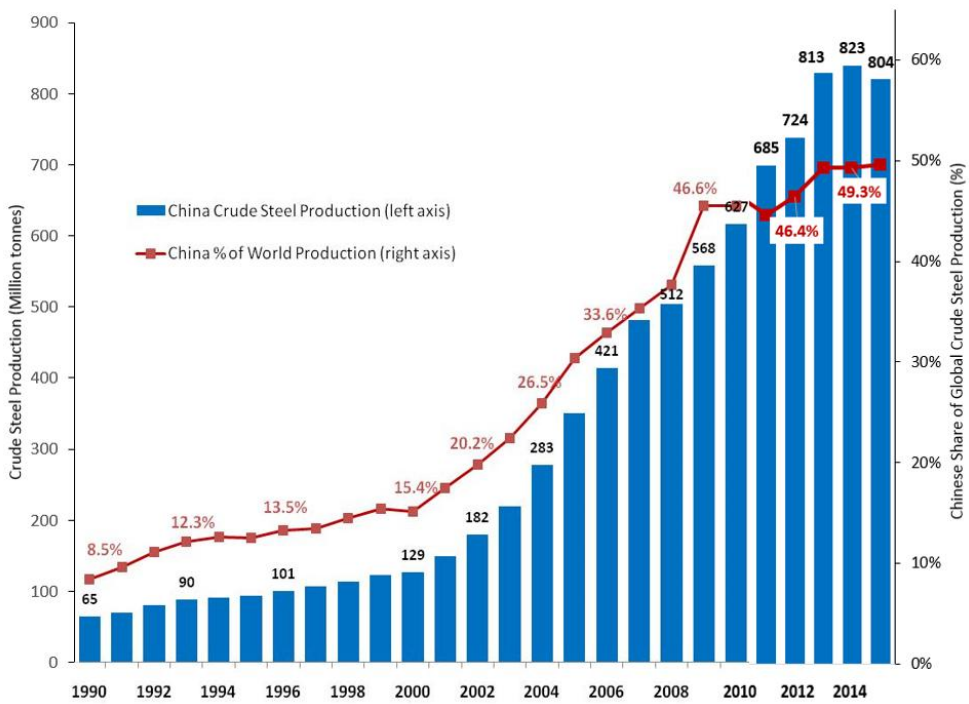
conveyors, storage silos, and unloading facilities (U.S. EPA 2009a).

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

Sulfur dioxide 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 2009a).

2.3. Iron and steel industry in China

Production of iron and steel is an energy-intensive and air polluting manufacturing process. In 2014, the iron and steel industry accounted for approximately 28 percent of the primary energy consumption of Chinese manufacturing[2] (NBS 2015b). Steel production in 2015 was 804 MMt (worldsteel 2016), representing 49.5 percent of the world production that year (Figure 2)



Sources: EBCISIY, various years; NBS 2015a; worldsteel 2016.

Figure 2. China's crude steel production and share of global production (1990–2015)

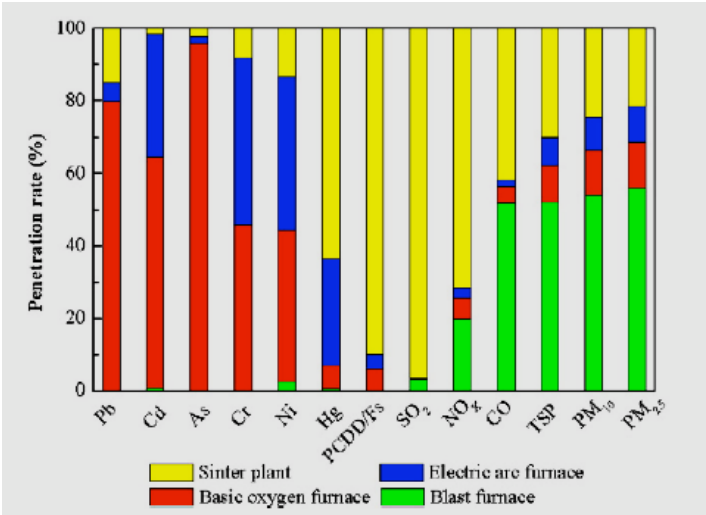
[2] The manufacturing sector does not include mining, oil and gas extraction, power generation, and construction.

China is a developing country, and the iron and steel industry, as a pillar industry for Chinese economic development, has grown rapidly along with the national economy. The average annual growth rate of crude steel production was around 18 percent between 2000 and 2010. China's steel production in 2014 consumed around 580 terawatt-hours (TWh) of electricity and 18,013 petajoules (PJ) of fuel (NBS 2015b). The Chinese iron and steel industry has made much progress in reducing energy use, starting from energy saving of individual equipment and process energy conservation in the 1980s to systematic energy conservation via process optimization in the 1990s and 2000s. China's energy consumption per ton of steel has declined significantly, especially since the 1990s, largely due to process restructuring and optimization and by phasing out inefficient outdated technologies.

The promotion and application of energy-saving technologies has become an important step for increasing energy efficiency and reducing energy consumption of steel enterprises, especially during the 11th FYP (2006–2010) and 12th FYP (2011–2015). During this time, energy efficiency technologies adopted in China's steel industry included: Coke Dry Quenching (CDQ), Top-pressure Recovery Turbine (TRT), recycling converter gas, continuous casting, slab hot charging and hot delivery, Coal Moisture Control (CMC), and recycling waste heat from sintering. The penetration level of energy efficiency technologies in the steel industry has improved greatly in China, improving its energy efficiency and emissions reductions (Hasanbeigi et al. 2011).

2.4. Sources of air pollution in the iron and steel industry

The Chinese steel industry contributed to about 20 percent of SO_2 emissions, and 27 percent of dust and PM emissions for all key manufacturing industries in China in 2013 (Wang et al. 2016). Figure 3 shows the contribution of different processes in the iron and steel industry to emissions of different pollutants in China.



Source: Wang et al. 2016.

Figure 3. Emissions contributions of different iron and steel industry processes in China in 2011 to air pollutants

Sinter plants account for more than 90 percent of the SO_2 emissions in the steel industry. Blast furnaces (BFs) account for approximately half of the PM emissions from the steel plant, followed by the sintering process, basic oxygen furnace (BOF), and electric arc furnace (EAF). The emissions from each of these processes are discussed briefly below. It should be noted that since most of the coke production in China happens outside of the iron and steel industry, coking is not included in this analysis.

2.4.1 Emissions from sintering

Emissions from sinter plants are generated from the raw material handling, windbox exhaust, discharge end (associated sinter crushers and hot screens), cooler, and cold screen processes. The windbox exhaust is the primary source of particulate emissions, mainly iron oxides, sulfur oxides, carbonaceous compounds, aliphatic hydrocarbons, and chlorides. At the discharge end, emissions are mainly iron and calcium oxides. Sinter strand windbox emissions commonly are controlled by cyclone cleaners followed by a dry or wet electrostatic precipitator, high pressure drop wet scrubber, or bag filters (U.S. EPA 2009b).

2.4.2 Emissions from a blast furnace

Significant emissions to all media occur from the blast furnace process. Because of the high input of reducing agents (mainly coke and coal), this process consumes most of the overall energy input of an integrated steelworks (European Commission 2013). The primary source of blast furnace emissions is the casting operation. Particulate emissions are generated when the molten iron and slag contact air above their surface. Casting emissions also are generated by drilling and plugging the taphole. The occasional use of an oxygen lance to open a clogged taphole can cause heavy emissions. During the casting operation, iron oxides, magnesium oxide, and carbonaceous compounds are generated as particulate. Casting emissions at existing blast furnaces are controlled by evacuation through retrofitted capture hoods to a gas cleaner, or by suppression techniques. Emissions controlled by hoods and an evacuation system are usually vented to a bag filters. Another potential source of emissions is the blast furnace top (U.S. EPA 2009b).

2.4.3 Emissions from a basic oxygen furnace

Emissions to air from various sources such as primary and secondary dedusting, hot metal pretreatment and secondary steelmaking, and various solid process residues are the main environmental issues in BOF steelmaking (European Commission 2013). The most significant emissions from the BOF process occur during the oxygen blow period. The predominant compounds emitted are iron oxides, although heavy metals and fluorides are usually present. Charging emissions will vary with the quality and quantity of scrap metal charged to the furnace and with the pour rate. Tapping emissions include iron oxides, sulfur oxides, and other metallic oxides, depending on the grade of scrap used. Hot metal transfer emissions are mostly iron oxides. Basic oxygen furnaces are equipped with a primary hood capture system located directly over the open mouth of the furnaces to control emissions during oxygen blow periods (U.S. EPA 2009b).

2.4.4 Emissions from an electric arc furnace

The emissions to air from the EAF furnace consist of a wide range of inorganic compounds (iron oxide dust and heavy metals) and organic compounds such as persistent organic pollutants, such as polychlorinated biphenyls (PCBs) and dibenzofurans (PCDD/F) (European Commission 2013). The operations which generate emissions during the electric arc furnace steelmaking process are melting and refining, charging scrap, tapping steel, and dumping slag. Iron oxide is the predominant constituent of the particulate emitted during melting. During refining, the primary particulate compound emitted is calcium oxide from the slag. Emissions from charging scrap are difficult to quantify, because they depend on the grade of scrap utilized. Scrap emissions usually contain iron and other metallic oxides from alloys in the scrap metal. Iron oxides and oxides from the fluxes are the primary constituents of the slag emissions. During tapping, iron oxide is the major particulate compound emitted. Emissions control techniques involve an emissions capture system and a gas cleaning system (U.S. EPA 2009b).

3. Methodology

The three scenarios we used to project the PM and SO_2 emissions from the cement and steel industries in China from 2010–2050 are described in the subsection below. We used the China 2050 Demand, Resources and Energy Analysis Model (DREAM) model, which is developed by the China Energy Group at Lawrence Berkeley National Laboratory, to forecast both the cement and steel industry production and the energy use from 2010–2050. The China 2050 DREAM model structure, as well as the methodology to forecast cement and steel production, is detailed in the following subsections.

3.1. Scenarios

This study consisted of three distinct scenarios:

1. **Base Case Scenario**: The baseline scenario assumes that only policies in place in 2010 will continue to have an effect, and that autonomous technological improvement (including efficiency improvement and fuel switching) occurs. The end-of-pipe emissions control technologies share and penetration remain at the 2010 level through the study period up to 2050.
2. **Advanced scenario**: In this scenario, China meets its energy needs and improves its energy security and environmental quality by deploying the maximum feasible share of currently cost-effective energy efficiency and renewable supply technologies by 2050. The end-of-pipe emissions control technologies share and penetration remain at the 2010 level through the study period up to 2050.
3. **Advanced scenario with Improved End-of-Pipe (EOP) Emissions Control (Advanced EOP)**: This scenario is similar to the Advanced scenario above, with the only difference being that the end-of-pipe emissions control technologies

share and penetration rate improves through the study period up to 2050.

In all three scenarios, only technologies that are commercialized or piloted at scale were considered.

3.2. China 2050 DREAM model

Building on the China Energy Group's long-term experience working with Chinese collaborators and our understanding of Chinese data, we have developed and continually refined our detailed, bottom-up China 2050 DREAM model to evaluate potential future low-emissions pathways for China. We initiated the development of this model in 2005 in response to a growing Chinese government policy focus on energy efficiency and the need for a tool capable of modeling and evaluating energy efficiency policies, programs, and targets, such as those set out in the recent 11th and 12th Five-Year Plans.

The foundation for the China 2050 DREAM model is an accounting framework of China's energy and economic structure using the LEAP (Long-Range Energy Alternatives Planning) software platform developed by Stockholm Environmental Institute. LEAP is a medium- to long-term integrated modeling tool that can be used to track energy consumption, production, and resource extraction in all sectors of an economy, as well as to conduct long-range scenario analysis.

The China 2050 DREAM model includes a demand module consisting of five demand subsectors (residential buildings, commercial buildings, industry, transport, and agriculture) and a transformation module consisting of the energy production, transmission, and distribution subsectors. Using LEAP, the model captures diffusion of end-use technologies and macroeconomic and sector-specific drivers of energy demand, as well as the energy required to extract fossil fuels and produce energy and a power sector with distinct generation dispatch algorithms. This model enables detailed consideration of technological development—industrial production, equipment efficiency, residential appliance usage, vehicle ownership, power sector efficiency, lighting, and heating usage—as a way to evaluate China's energy and emissions reduction development path at a more granular level below the level of its macro-relationship to economic development.

3.2.1 Macroeconomic drivers

Key drivers of energy use in the model include activity drivers (total population growth, urbanization, building and vehicle stock, commodity production); economic drivers (total gross domestic product [GDP], value-added [VA] GDP, income); energy intensity trends (energy intensity of energy-using equipment and appliances); and carbon intensity trends. These factors are in turn driven by changes in consumer preferences, settlement and infrastructure patterns, technical change, and overall economic conditions. Key macroeconomic parameters such as economic growth, population, and urbanization are aligned with international sources (e.g., the United Nations World

Population Prospects) as well as Chinese sources (e.g., China Energy Research Institute reports).

These macroeconomic drivers in turn have important linkages to the energy demand subsectors, as shown in Figure 4.

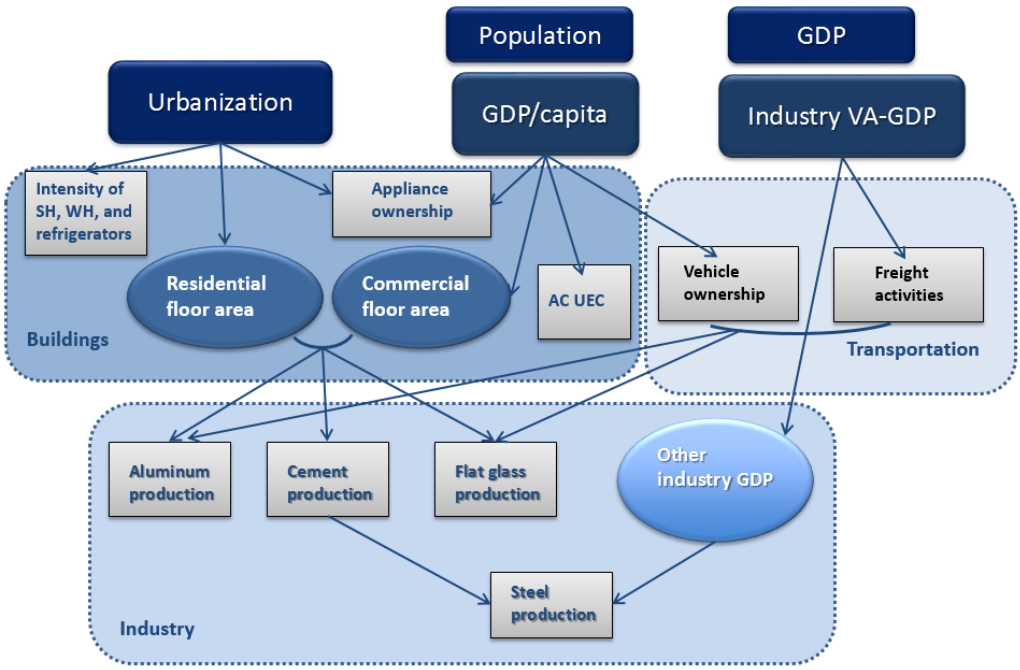


Figure 4. Linkages between macroeconomic drivers and energy end uses in the China 2050 DREAM model

3.2.2 Demand module

The demand module includes the five main economic sectors of residential buildings, commercial buildings, industry, transportation and agriculture. Because of the marginal and decreasing role of economic activity from agriculture, the agricultural sector is included in the model but generally not used. Within the energy demand module, the model is able to address sectoral patterns of energy consumption in terms of end-use, technology and fuel shares, including trends in saturation and usage of energy-using equipment, technological change (including efficiency improvements and complex linkages between economic growth), urban development, and energy demand. The industry sector modeling approach is explain below in more detail.

3.2.3 Industry model

The industry sector is divided into 12 specific energy-intensive industrial subsectors with physical activity drivers, including cement, iron and steel, aluminum, ammonia, ethylene, paper, glass, copper, alumina, caustic soda, soda ash, and calcium carbide. For cement, steel, and aluminum production, the main production drivers are based on the requirements of the built environment that reflects China's growing urban population, with floor space construction area, highway and paved road area, and railway length

combined with material intensity values and ratios between cement, steel, and aluminum used to determine the resulting demand. Ammonia production, in contrast, was modeled as a function of sown area and fertilizer intensity, while ethylene production was based on population and per capita demand for plastics. Exports of these major energy-intensive industrial products are held constant at the base year level to reflect the policy emphasis on shifting away from energy-intensive industrial production to higher value-added production. Physical energy intensities in terms of energy use per ton (or other unit) of industrial product produced for each industrial sector are used. Physical production values are multiplied by industry average physical intensities and then summed to derive energy consumption values for the energy-intensive industries.

In addition to the 12 energy-intensive industrial subsectors, there are also 18 value-added driven industrial subsectors that include manufacturing, chemicals, light industry, and all other small industrial subsectors. As a conglomerate of various industries, production activity in these value-added sectors is characterized by value-added GDP, the annual growth of which is expected to slow down over time. Projections of the value-added GDP output of each of these subsectors are derived from China's Energy Research Institute's (ERI's) computable general equilibrium (CGE) model for China. At the same time, the economic energy intensity of these value-added industries (as measured in kilograms of coal equivalent per unit of value-added GDP) is expected to decline significantly over time following international experiences with a shift towards higher value-added activity and market-driven pace of efficiency gains over time.

3.2.4 Cement production forecast methodology

Cement production is linked to construction of new urban and rural buildings, urban paved roads, expressways and Class I and II highways, and railway bed construction. Cement demand for these end uses is based upon two variables: the area of construction and the amount of cement used per construction unit. The formula for modeling cement production is shown below (Equation 2):

$$P_c = [(CFSr \times CI1) + (RFSu \times CI2) + (RFSr \times CI3)] + (PA \times CI4) + (H \times CI5) + (R \times CI6) + (InI \times CI7) + Others + Ex \qquad \text{(Eq. 2)}$$

Where:

P_c	= Annual cement production
CFS	= Commercial floor space (three-year rolling average)
RFSu	= Urban residential floor space (three-year rolling average)
RSFr	= Rural residential floor space (three-year rolling average)
CI1	= Commercial building cement material intensity
CI2	= Urban residential building cement material intensity
CI3	= Rural residential building cement material intensity
PA	= Urban paved area
CI4	= Paved area cement material intensity
H	= Highways, specifically expressways, and Class 1 and 2 highways (three-year rolling average)
CI5	= Highway cement material intensity

R	= Railroad track length, three-year rolling average
CI6	= Railroad track cement material intensity
InI	= Industrial Investment
CI7	= Cement material intensity for industrial construction
Ex	= Net exports of cement

Buildings Construction Linkages

Cement production for both commercial and residential buildings is calculated as annual newly constructed floor space in square meters (m^2) multiplied by the amount of cement required per m^2 (the cement intensity).

Annual newly constructed urban and rural commercial and residential floor space is calculated from a building stock turnover model, which quantifies average building lifetime by different construction years and by urban and rural areas. Residential building construction growth is modeled based upon population expansion (accounting for the effects of urbanization) and increasing demand for building space per person, as well as rebuild demands as a function of building turnover.[3] Commercial building construction is modeled based upon tertiary workforce size and growing floor space per tertiary worker, in addition to rebuild demands as a function of building turnover.

In the Base Case scenario, average building lifetimes are assumed to be 30 years, 40 years, and 50 years for urban residential and commercial buildings built in 1980–1999, 2000–2019, and 2020–2050, respectively. The building lifetimes are assumed to increase because of more strict building codes and higher quality of building materials.

Cement use per square meter of building (cement intensity) is assumed to be 0.15 ton/m^2 floor area for rural residential buildings (Liu 2010) and 0.22 ton/m^2 floor area for commercial buildings (Liu 2014). For urban residential buildings, the cement intensity is expected to increase over time, as China's buildings are projected to become taller on average and require more cement for structural support. The share of six-story masonry-concrete buildings as a percentage of total buildings is expected to fall from 40 percent to about 10 percent between 2000 and 2020; while the share of seven-story or higher steel-concrete buildings is expected to continue to rise, eventually reaching 100 percent by 2030 (McKinsey 2009; Hu et al. 2010). As a result, the average cement intensity of urban residential buildings is expected to increase from 0.212 ton/m^2 floor area in 2008 to 0.247 ton/m^2 floor area in 2030 and remain constant thereafter (Hu et al. 2010).

Transport Sector and Paved Area Construction Linkages

The area of urban paved area is projected based on total population and an average per capita urban paved roads area. In 2009, China's average per capita urban paved areas was 7.75 m^2/capita (NBS 2010). This value is assumed to double by 2030 in China,

[3] Building turnover is projected to continue to occur every 30 years per building through 2030 due to the generally shorter lifespans of buildings in China.

reaching the per capita urban paved roads area of Japan and the UK (WRI 2009). The expansion of urban paved areas and highways are modeled after Japan's experience of infrastructure development.

The area of primary roads, including expressways and Class I and II highways, is projected based on the total number of vehicles and an average value of vehicles per kilometer of primary road. China's vehicle per kilometer (km)of primary road value is assumed to reach Japan's level of 360 vehicles/km by 2040 and 400 vehicles/km by 2050 (Nambu 2008). The average material intensity of cement use for urban paved roads and Class I and II highways is 1,080 kg/m^2 based on the design standard for highways (MOT 1997).[4] In 2012, 72 percent of paved roads in China were concrete, and 38 percent of the country's total roads were concrete (Prospective Consultant Company 2014).

The railway track area forecast for China assumes that the accelerated 2015 target of 120,000 km set forth in the 12th FYP railway development plan and a potential target of 220,000 km by 2050 (Ministry of Railways 2011; Personal Communication, Dave Mullaney 2014) will be met. The material intensity of cement use for the railway is 14,203 ton/km (UNEP 2013).[5]

In 2007, buildings and infrastructure (roads, railway beds) accounted for 55 percent of the total cement use in China (NBS, 2008). The remaining 45 percent of cement use lies in industrial construction, urban infrastructure, and agriculture construction. Urban infrastructure includes energy facilities such as electricity and heat distribution network and natural gas supply pipelines; water supply and wastewater treatment facilities; transport facilities such as road, bridge, metro, and light rail; telecommunication facilities; and waste treatment facilities. Cement use in industrial construction refers to those used to build industrial facilities such as industrial plants, power plants, and so on.

Industrial investment driver

Other infrastructure (comprised of industrial construction, agriculture construction, and urban utilities in NBS statistics) is driven by industrial investment. Industrial investment projections used in the model are based on ERI's CGE model for China.

3.2.5 Iron and Steel Production Forecast Methodology

The production of iron and steel is divided into structural steel for infrastructural and

[4] The average material intensity of cement use per m^2 is calculated based on the design requirements for number of lanes, lane width, and average thickness for expressways, Class I and II highways. We assume an average cement intensity of concrete at 12.5 percent and a concrete density of 2.4 tons/m^3.

[5] The Beijing-Shanghai high-speed elevated railway line has 1,318 km of viaduct, manufactured from 16.52 million tons of cement. There are twenty-two stations along the line, which required an estimated 2.2 million tons of cement, assuming 100,000 tons of cement per station. Therefore, the material intensity of the Beijing-Shanghai high-speed railway line is calculated as 14,203 ton/km.

construction demand and product steel used in appliances, machinery, and other products for final consumption, as well as exports. The formula for projecting steel production is as follows (Equation 3):

$$P_S = [(CFS \times SI1) + (RFSu \times SI2) + (RSFr \times SI3)] + (Rail \times SIRa) + [(PassCar \times SI\ PasCar) + (Truck \times SITrk)] + (ProdStR \times Industrial\ VAGDP) + (Infra\&Oth\ St\ R \times IFA) + Others + Ex$$
(Eq.3)

Where:

CFS	= Commercial floor space (three-year rolling average)
RFSu	= Urban residential floor space (three-year rolling average)
RSFr	= Rural residential floor space (three-year rolling average)
SI1	= Commercial building steel material intensity
SI2	= Urban residential building steel material intensity
SI3	= Rural residential building steel material intensity
Rail	= New railroad construction, km
SIRa	= Steel intensity of new railroad, ton steel/km
PassCar	= Number of new passenger cars, 1,000 cars
SIPasCar	= Steel intensity of new passenger cars, ton steel per 1,000 cars
Truck	= Number of new trucks, 1,000 trucks
SITrk	= Steel intensity of new trucks, ton steel per 1,000 trucks
ProdStR	= Product steel ratio to sum of machinery, metal product, and electric industry value added, ton steel per million renminbi (RMB)
Industrial VA GDP	= Industrial value-added GDP, US$
Infra&Oth St R	= sum of infrastructure and other steel demand ratio to total industrial fix assets investment, ton steel per million 2005 RMB
IFA	= Industrial fix assets investment, 2005 million RMB
Ex	= Net exports

Building Construction Linkages

Structural steel accounted for 56 percent of total steel use in China in 2010. Structural steel has the same drivers as cement consumption (i.e., floor space demand per person, population size, and building turnover) and is therefore projected using the steel consumption of urban residential, rural residential, and commercial buildings. It is projected that as China's buildings become taller and shift to entirely steel-concrete structure, more steel will be consumed to construct new buildings. Specifically, as with the cement projections, we assume the share of seven-story or higher steel-concrete structures in urban residential buildings will rise from 60 percent in 2000 to 90 percent in 2020, and 100 percent in 2030 (McKinsey 2009; Hu et al. 2010). The steel intensities for masonry-concrete and steel-concrete buildings are assumed to stay constant at current levels of 25 kg/m^2 and 59 kg/m^2, respectively (Hu et al. 2010). From 2010 to 2050, the average steel intensity of urban residential buildings will therefore increase from 49 kg/m^2 in 2010 to 59 kg/m^2 in 2030 and thereafter. Rural residential buildings also consume a small share of total structural steel, and its material intensity is assumed to grow slowly as well, from 5 kg/m^2 in 2000 to 7.7 kg/m^2 in 2050 (Hu et al. 2010). Commercial buildings are assumed to be all high-rise steel-concrete buildings with the same constant steel intensity of 59 kg/m^2 as steel-concrete residential buildings.

Manufacturer Value-Added (MVA)-Based Calculations

Product steel was approximately 44 percent of total steel consumption in 2010. Product steel is projected based upon macroeconomic activity. In our previous modeling, a product steel to "Other Industry" value-added ratio of 198 tons of product steel per million US$ of "Other Industry" value-added is used for 2010. Following Japan's trend of declining ratio between steel production and manufacturing GDP from 1970 to 1988, the model assumed that the 2010 ratio will be lowered by 40 percent to 119 in 2030 as production shifts to higher value-added steel products (Japan Statistics Bureau 2010).

We organized the "Other Industry" category into a number of subsectors. Thus, we calculated the product steel production based on the MVA of only the few subsectors that produce products that require steel instead of all the "Other Industry" subsectors. Product steel production would then be calculated as 198 tons per million US$ of the machinery, transport equipment, and electric product manufacturing subsectors in 2010, dropping to 119 tons per million US$ in 2030, and assumed to further decline to 60 tons per million US$ in 2050, or 30 percent of the 2010 level (Japan Statistics Bureau 2010).

3.3. PM and SO_2 Emissions calculation method for the cement and steel industry

In this analysis, we calculated total suspended PM and SO_2 emissions from the cement and iron and steel industry in China. The year 2010 was chosen as the base year and 2010–2050 as the time frame for the analysis. We calculated only the direct emissions from cement and steel plants. The indirect emissions from electricity use and the transportation of raw materials and end products are not in the analysis. We used a series of PM and SO_2 emissions factors for the cement and steel production, as well as the share and penetration rate of end-of-pipe emissions control technologies, to calculate the total emissions of these pollutants from the cement and steel industry in China from 2010–2050.

3.3.1. PM emissions calculation for the cement industry

To calculate the PM emissions for the cement industry, we used the unabated PM emissions factor of 105 kg PM/ton cement for NSP rotary kilns and 30 kg PM/ton cement for vertical shaft kilns in the Chinese cement industry in 2010 provided by Lei et al. (2011). Having the cement production of each type of kiln in China in 2010, we calculated the total unabated PM emissions for the Chinese cement industry in 2010. Using the bottom-up methodology explained in previous sections, the DREAM model calculated and forecasted the cement production in China from 2010–2050 for different scenarios (Table 1).

Table 1. Cement production in China under different scenarios from 2010–2050 (in million tons)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base Case	1,882	2,394	2,229	1,936	1,795	1,815	1,784	1,691	1,647
Advanced	1,882	2,393	2,228	1,932	1,784	1,792	1,747	1,640	1,590
Advanced EOP	1,882	2,393	2,228	1,932	1,784	1,792	1,747	1,640	1,590

Government regulation requires all cement plants to have PM control technologies. However, the efficiency of the control technologies depends on the type of technology and the size distribution of PM in the raw flue gas. Although more efficient PM control technologies require higher investment and have higher operational costs, improving emissions standards by the government is driving the promotion of these technologies within the industry. The standard value for the PM concentration in cement kiln flue gas has dropped from 800 to 50 mg m^{-3} in 20 years (Lei et al. 2011).

There are three main commercial PM emissions control technologies for the cement industry:

1. Electrostatic precipitator: 96 percent PM reduction efficiency
2. Fabric filter: 99 percent PM reduction efficiency
3. Wet scrubber: 99 percent PM reduction efficiency

We assumed 100 percent of the cement plants have some type of end-of-pipe PM control technology. Lei et al. (2011) gives the penetration share of each of these control technologies in the Chinese cement industry in 2010. For the Base Case and Advanced scenarios, we assumed no changes in the share and penetration rate of control technologies from 2010 to 2050. For the Advanced EOP scenario, we assumed improvement in the control technologies share based on projections given in Wang et al. (2014) up to 2030 and expert judgment for 2030–2050. Table 2 and Table 3 show the share of each of the control technologies assumed from 2010–2050 under different scenarios.

Table 2. Share of PM control technologies in the Chinese cement industry assumed under Base Case and Advanced scenarios, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Electrostatic precipitator	40	40	40	40	40	40	40	40	40
Fabric filter	50	50	50	50	50	50	50	50	50
Wet scrubber	10	10	10	10	10	10	10	10	10

Table 3. Share of PM control technologies in the Chinese cement industry assumed under the Advanced EOP scenario, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Electrostatic precipitator	40	30	20	13	5	0	0	0	0
Fabric filter	50	65	80	88	95	100	100	100	100
Wet scrubber	10	5	0	0	0	0	0	0	0

Using the total unabated PM emissions calculated above, and the adoption share and emissions reduction efficiency of PM control technologies, we calculated the final total

PM emissions from the Chinese cement industry from 2010–2050.

3.3.2. SO_2 emissions calculation for the cement industry

Sulfur dioxide mainly comes from the oxidation of sulfur in coal. In precalciner kilns, approximately 70 percent of SO_2 is absorbed by reaction with calcium oxide (CaO), while much less is absorbed in other rotary kilns and in shaft kilns. Utilization of baghouse filters, as required with new precalciner kilns, can further reduce SO_2 emissions (Lei et al. 2011). Lei et al. (2011) provides the SO_2 emissions factors for precalciner kiln, other rotary kilns, and vertical shaft kilns for the Chinese cement industry (Table 4).

Table 4. SO_2 emissions factor for cement kilns (kg/ton of coal combusted in kilns)

Kiln Type	SO_2 Emissions Factor (kg/ton of coal combusted)
Precalciner kiln	2.9
Other rotary kilns	12.3
Vertical shaft kilns	12.3

We assumed in 2010, 80 percent of Chinese cement plants have precalciner kilns, and the other 20 percent have either other rotary kilns or vertical shaft kilns. Based on that assumption, we calculated the weighted average SO_2 emissions factor of 4.8 (kg/ton of coal combusted). By multiplying this SO_2 emissions factor by total coal consumption in the Chinese cement industry in 2010, we calculated the total SO_2 emissions for the Chinese cement industry before application of end-of-pipe control technologies in 2010.

Using the bottom-up methodology explained in previous sections, the DREAM model calculated and forecasted the coal use in the cement industry in China from 2010–2050 for different scenarios (Table 5).

Table 5. Coal use in the Chinese cement industry under different scenarios from 2010–2050 (in million tons)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base Case	251	297	261	216	190	184	174	158	148
Advanced	251	282	239	194	167	156	141	122	109
Advanced EOP	251	282	239	194	167	156	141	122	109

In China, SO_2 control technologies have rarely been installed in the industrial sector. In recent years, flue gas desulfurization (FGD) units for controlling SO_2 have been installed at a small number of coal-fired boilers and sintering plants in selected regions (Wang et al. 2014). Chinese cement plants usually do not have an FGD unit to reduce SO_2 emissions, mostly because approximately 70 percent of the SO_2 is absorbed by reaction with calcium oxide in the precalciner kilns. However, recently, because the quality of raw materials has decreased and there is more sulfur in the raw meal, sulfur content in the exhaust gas of many cement plants exceeded the standard limit. As of late 2016, there are approximately nine production lines that are using end-of-pipe SO_2 control

technologies. Therefore, we assumed that in our base year of 2010, there were only a few cement plants with end-of-pipe SO_2 control technologies. This would be less than 1 percent of the total cement production capacity in China.

There are three main commercial SO_2 emissions control technologies for the cement industry:

1. Absorbent addition: 70 percent SO_2 reduction efficiency
2. Wet scrubber: 90 percent SO_2 reduction efficiency
3. Activated carbon: 95 percent SO_2 reduction efficiency

The adoption rate of each of these control technologies in the Chinese cement industry in 2010 was assumed to be zero. For the Base Case and Advanced scenarios, we assumed no changes in the share and penetration rate of control technologies up to 2050. For the Advanced EOP scenario, we assumed improvement in the penetration of control technologies. We assumed slow growth up to 2030 and accelerated growth for 2030–2050. Table 6 and Table 7 show the adoption rate of each of the SO_2 control technologies from 2010–2050 under the three different scenarios.

Table 6. Adoption rate of SO_2 control technologies in the Chinese cement industry assumed under the Base Case and Advanced scenarios, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Absorbent addition	0	0	0	0	0	0	0	0	0
Wet scrubber	0	0	0	0	0	0	0	0	0
Activated carbon	0	0	0	0	0	0	0	0	0

Table 7. Adoption rate of SO_2 control technologies in the Chinese cement industry assumed under the Advanced EOP scenario, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Absorbent addition	0	0	0	0	0	0	0	0	0
Wet scrubber	0	0	2	7	12	17	27	37	47
Activated carbon	0	0	0	3	6	9	12	15	18

Using the total SO_2 emissions before application of end-of-pipe control technologies calculated above, and the penetration rate and emissions reduction efficiency of SO_2 control technologies, we calculated the final total SO_2 emissions from the Chinese cement industry from 2010–2050.

3.3.3. PM emissions calculation for the steel industry

In the steel industry, blast furnaces and sinter plants account for approximately

90 percent of the total PM emissions, while basic oxygen furnaces and electric arc furnaces account for the remainder of PM emissions from the steel production process (Wang et al. 2016). To calculate the PM emissions for the Chinese steel industry, we used the PM emissions factors for sinter plants, BF, BOF, and EAF of the Chinese steel industry provided separately by Wang et al. (2016) based on 2010 end-of-pipe PM control technologies adoption rate (Table 8). By multiplying the PM emissions factor of each production process by the total production of that process in China in 2010, we calculated the total PM emissions for each process and for the Chinese steel industry in 2010.

Table 8. Total PM emissions factors for sinter plants, BF, BOF, and EAF of the Chinese steel industry in 2010

Process	PM emissions factor (kg/ton product)
Sinter	1.0
BF	2.0
BOF	0.4
EAF	2.1

Source: Wang et al. 2016.

Using the bottom-up methodology explained in previous sections and the China 2050 DREAM model, we calculated and forecasted the production of sinter, pig iron by BF, and crude steel by BOF and EAF, in China from 2010–2050 for different scenarios (Tables 9–12).

Table 9. Sinter production in China under different scenarios from 2010–2050 (in million tons)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base Case	712	848	835	813	730	680	576	540	520
Advanced	712	798	795	752	654	596	491	455	435
Advanced EOP	712	798	795	752	654	596	491	455	435

Table 10. BF pig iron production in China under different scenarios from 2010–2050 (in million tons)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base Case	558	665	655	638	573	533	452	423	408
Advanced	558	626	623	590	513	467	385	357	341
Advanced EOP	558	626	623	590	513	467	385	357	341

Table 11. BOF steel production in China under different scenarios from 2010–2050 (in million tons)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base Case	558	665	655	638	573	533	452	423	408
Advanced	558	626	623	590	513	467	385	357	341
Advanced EOP	558	626	623	590	513	467	385	357	341

Table 12. EAF steel production in China under different scenarios from 2010–2050 (in million tons)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Base Case	79	116	144	155	152	159	151	161	175
Advanced	79	155	176	202	209	220	207	214	227
Advanced EOP	79	155	176	202	209	220	207	214	227

There are three main commercial PM emissions control technologies for the processes in the steel industry:

1. Electrostatic precipitator: 96 percent PM reduction efficiency
2. Fabric filter: 99 percent PM reduction efficiency
3. Wet scrubber: 99 percent PM reduction efficiency

We assumed 100 percent of the processes in Chinese steel plants have some type of end-of-pipe PM control technology in all scenarios (Wang et al. 2014; Wu et al. 2015). Wang et al. (2014) gives the penetration share of each of these control technologies in the sinter plants, BFs, BOFs, and EAFs in the Chinese steel industry in 2010. For the Base Case and Advanced scenarios, we assumed no changes in the share and penetration rate of control technologies up to 2050. Therefore, by multiplying the 2010 emissions factors by production values from 2010–2050 in the Base Case and Advanced scenarios, we calculated the total PM emissions for the Chinese steel industry from 2010–2050 in these two scenarios.

For the Advanced EOP scenario, we assumed improvement in the adoption of control technologies based on projections given in Wang et al. (2014) up to 2030 and expert judgment for 2030–2050. Tables 13–16 show the assumed changes in the share of each of the control technologies from 2010–2050 under the Advanced EOP scenario for each of the production processes (i.e., sinter, BF, BOF, EAF) separately.

Table 13. Share of PM control technologies in the Chinese sinter plants assumed under the Advanced EOP scenario, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Electrostatic precipitator	75	73	70	65	60	55	50	40	30
Fabric filter	20	25	30	35	40	45	50	60	70
Wet scrubber	5	3	0	0	0	0	0	0	0

Table 14. Share of PM control technologies in the Chinese BFs assumed under the Advanced EOP scenario, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Electrostatic precipitator *	100	100	100	100	100	100	100	100	100
Fabric filter	0	0	0	0	0	0	0	0	0
Wet scrubber *	100	100	100	100	100	100	100	100	100

* Blast furnaces in China are usually equipped with washing towers and double venturi scrubbers, which have approximately the same removal efficiency as the combination of an electrostatic precipitator and a wet scrubber (Wang et al. 2014).

Table 15. Share of PM control technologies in the Chinese BOFs assumed under the Advanced EOP scenario, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Electrostatic precipitator	30	20	10	5	0	0	0	0	0
Fabric filter	70	80	90	95	100	100	100	100	100
Wet scrubber	0	0	0	0	0	0	0	0	0

Table 16. Share of PM control technologies in the Chinese EAFs assumed under the Advanced EOP scenario, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Electrostatic precipitator	50	45	40	30	20	10	0	0	0
Fabric filter	20	40	60	70	80	90	100	100	100
Wet scrubber	30	15	0	0	0	0	0	0	0

Using the total PM emissions calculated above for the Advanced scenario, and average PM emissions reduction efficiency of control technologies calculated based on their share of adoption in each year, we calculated the unabated PM emissions in each year under the Advanced scenario. Then, using the adoption share and emissions reduction efficiency of PM control technologies in the Advanced EOP scenario, we calculated the final total PM emissions for each production process and the Chinese steel industry under the Advanced EOP scenario from 2010–2050.

3.3.4. SO_2 emissions calculation for the steel industry

In the steel industry, over 90 percent of the SO_2 emissions are from sinter plants (Wang et al. 2016). To calculate the SO_2 emissions for the Chinese steel industry, we used the SO_2 emissions factors of 3.2 kg SO_2/ton product for sinter plants provided by Wang et al. (2016) based on the 2010 end-of-pipe SO_2 control technologies adoption rate. By multiplying this SO_2 emissions factor by the total sinter production in China in 2010, we calculated the total SO_2 emissions for sinter production in China in 2010.

Wang et al. (2014) gives the penetration rate of SO_2 control technologies in the sinter

plants in the Chinese steel industry in 2010. For the Base Case and Advanced scenarios, we assumed no changes in the share and penetration rate of control technologies up to 2050. Therefore, by multiplying the 2010 emissions factors by the production values from 2010–2050 in the Base Case and Advanced scenarios, we calculated the total SO_2 emissions for the sinter plants in China from 2010–2050 in these two scenarios.

For the Advanced EOP scenario, we assumed improvement in the control technologies share based on information from Wu et al. (2015) and projections given in Wang et al. (2014) up to 2030, and expert judgment for 2030–2050. Table 17 shows the assumed change in the adoption of SO_2 control technologies from 2010–2050 under the Advanced EOP scenario for sinter plants.

Table 17. Adoption rate of SO_2 control technologies in Chinese sinter plants assumed under the Advanced EOP scenario, 2010–2050

	2010 (%)	2015 (%)	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Absorbent addition	0	0	0	0	0	0	0	0	0
Wet scrubber	10	15	20	30	40	50	60	75	90
Activated carbon	0	0	0	0	0	0	0	0	0

Using the SO_2 emissions calculated above for the Advanced scenario, and average SO_2 emissions reduction efficiency of control technologies calculated based on their share of adoption in each year, we calculated the unabated SO_2 emissions in each year under the Advanced scenario. Then, using the adoption share and emissions reduction efficiency of SO_2 control technologies in the Advanced EOP scenario, we calculated the final total SO_2 emissions for the Chinese sinter plants under the Advanced EOP scenario from 2010–2050.

Since we assumed that sinter plants account for 90 percent of the SO_2 emissions from the steel industry, we divided the sinter plants' SO_2 emissions calculated above by 0.9 to calculate the total SO_2 emissions from the Chinese steel industry from 2010–2050.

3.4. PM abatement cost calculation for the cement industry

In addition to calculating the PM and SO_2 emissions for the cement and steel industry in 2010–2050, which is explained above, we also did an example calculation for the PM abatement cost for the cement industry in China. The PM abatement cost is calculated for PM control technologies, energy efficiency measures, and product change measures separately, as explained below. The PM abatement cost is calculated for a typical preheater-precalciner cement plant with a production capacity of 3,000 tons of clinker per day.

3.4.1. PM abatement cost calculation for PM control technologies

We considered two technologies that are the dominant PM control technologies in the cement industry in China: Electrostatic Precipitators and Fabric Filters. Table 18 shows the typical PM removal efficiency, capital cost, and operation and maintenance (O&M) cost, as well as the assumed lifetime, for these two control technologies.

Table 18. Typical PM removal efficiency, capital cost, and O&M cost for two PM control technologies in the cement industry

Technology	PM Emissions Reduction Efficiency (%)	Typical Investment Cost (million $)	Typical Annual O&M Cost ($/t clinker)	Assumed Lifetime
Electrostatic precipitators	96	1.1	0.15	20
Fabric filters	99	1.4	0.15	20

The abatement cost can be calculated using Equation 4 and Equation 5:

$$\text{PM Abatement Cost} = \frac{(\text{Annualized capital cost} + \text{Annual O\&M costs})}{\text{Annual PM emissions reduction}} \quad \text{(Eq. 4)}$$

$$\text{Annualized capital cost} = \text{Capital Cost} * (d / (1-(1+d)^{-n}) \quad \text{(Eq. 5)}$$

Where:
d = discount rate (*assumed 10%)*
n = lifetime of the technology

Using the information in Table 18 and the equations above, we can calculate the annualized cost for PM control technologies. To calculate the annual PM emissions reduction for each technology, we used the unabated PM emissions factor of 245 kg PM / ton of cement and applied that to the annual production of a cement plant with production capacity of 3,000 tons of clinker per day. We used the average clinker-to-cement ratio of 65 percent to convert clinker production to cement production. By multiplying the annual cement production by the unabated PM emissions factor and then multiplying by the PM reduction efficiency of each technology, we calculated the annual PM emissions reduction for each of the control technologies for the assumed cement plant. Then, using Eq. 4, we calculated the PM abatement cost for each control technology.

3.4.2. PM abatement cost calculation for energy efficiency measures

For the energy efficiency measures' PM abatement cost calculation, we used a list of 24 energy efficiency measures from our earlier study of the cement industry in China (Hasanbeigi et al. 2013). Of these 24 measures, 20 save electricity and 4 save fuel. Because fuel combustion in the cement kiln contributes only to a small fraction of total PM emissions, reducing or substituting fuel does not reduce PM emissions significantly. Therefore, we only calculated the PM abatement cost for the 20 electricity saving

measures. Since PM emissions from electricity production happen at a power plant's site, we used China's average grid PM emissions factor of 0.97 kg PM/megawatt-hours (MWh) in 2010 in our calculation. Also, as mentioned above, the calculation was done for a cement plant with production capacity of 3,000 tons of clinker per day. Table 19 shows the list of energy efficiency measures, along with their typical cost and electricity savings. It should be noted that all energy efficiency measures result to CO_2 emissions reduction and other benefits which are not included in this analysis.

Table 19. Electricity efficiency measures and their typical cost and electricity savings

No.	Electricity Efficiency Measure	Typical Electricity Saving (KWh/t clinker)	Typical Cost (RMB/t clinker)
1	New efficient coal separator for fuel preparation	0.3	0.1
2	Efficient roller mills for coal grinding	1.3	0.3
3	Installation of variable frequency drive and replacement of coal mill bag dust collector's fan with a high efficiency fan	0.2	0.2
4	Raw meal process control for vertical mill	1.4	2.7
5	High efficiency classifiers/separators for raw mill	5.1	23.5
6	High efficiency roller mill for raw materials grinding	10.2	58.9
7	Variable frequency drive (VFD) in raw mill vent fan	0.3	0.2
8	High efficiency fan for raw mill vent fan with inverter	0.4	0.2
9	Adjustable speed drive for kiln fan	6.1	1.6
10	Efficient kiln drives	0.6	1.1
11	Variable frequency drive in cooler fan of grate cooler	0.1	0.1
12	Replacement of preheater fan with high efficiency fan	0.7	0.5
13	Energy management and process control in grinding	4.0	3.2
14	Replacing a ball mill with vertical roller mill	25.9	53.5
15	High pressure roller press as pre-grinding to ball mill	24.4	53.5
16	Improved grinding media for ball mills	6.1	7.5
17	High-efficiency classifiers (for finish grinding)	6.1	21.4
18	Replacement of cement mill vent fan with high efficiency fan	0.1	0.1
19	High efficiency motors	4.6	2.4
20	Adjustable speed drives	9.2	9.6

Source: Hasanbeigi et al. 2013.

From the information in Table 19, we calculated the annual electricity saving, and subsequently annual PM emissions reduction, by each efficiency measure. Using Eq. 5, we calculated the annualized cost for each measure implemented in the given cement plant. Finally, we used Eq. 4 to calculate the PM abatement cost for each efficiency measure. For comparison with the PM abatement cost of control technologies calculated in the previous section, we calculated the weighted average PM abatement cost for all energy efficiency measures, using the individual PM abatement cost and PM abatement potential of each measure.

3.4.3. PM abatement cost calculation for production change measures

Product change measures allow for a higher substitution of clinker, which is the energy-intensive intermediary product in the cement production process with additives such as fly ash, pozzolans, blast furnace slag, or crushed limestone. For product change measures' PM abatement cost calculation, we used two measures from our earlier study for the cement industry in China (Hasanbeigi et al. 2013). We assumed that the blended cement measure and the limestone Portland cement measure substituted an additional 10 percent and 5 percent of clinker in a typical cement plant with 3,000 tons of clinker per day capacity, respectively. Also, based on Hasanbeigi et al. (2013), we assumed an average electricity intensity of 77.8 kWh/ton of clinker and a fuel intensity of 3.7 gigajoules (GJ)/ton of clinker for the given cement plant. Using this information, we calculated the annual electricity and fuel saving of each measure (Table 20). Then, using the emissions factors for electricity and clinker production provided in the previous section, we calculated the total annual PM reduction for each product change measure. Finally, we used the procedure explained in previous section, as well as Eq. 4 and Eq. 5, to calculate the PM abatement cost of product change measures. It should be noted that all energy efficiency measures result to CO_2 emissions reduction and other benefits which are not included in this analysis.

Table 20. Product change measures and their typical cost and energy savings

No.	Electricity Efficiency Measure	Typical Cost (RMB/t clinker)	Annual Electricity Saving (MWh/year)	Annual Fuel Saving (GJ/year)
1	Blended cement (Additives: fly ash, pozzolans, and blast furnace slag)	4.9	7,469	352,713
2	Limestone Portland cement	0.8	3,735	176,356

4. Results and Discussions

The following sections present the results of PM and SO_2 emissions projection for the Chinese cement and steel industry between 2010 and 2050. The abatement costs for PM reduction in the Chinese cement industry using end-of-pipe control technologies, energy efficiency and product change measures are also presented.

4.1. PM emissions projection for the cement industry in China

Figure 5 show the total PM emissions from the Chinese cement industry from 2010–2050 under the Base Case, Advanced, and Advanced EOP scenarios. As can be seen, there is not a substantial difference between cement industry PM emissions under the Base Case and Advanced scenarios. This is because, as explained in Section 3.3.1, we assumed a similar share and penetration rate of control technologies from 2010 to 2050 for these two scenarios. Also, the cement production in the Advanced scenario is not significantly lower than that in the Base Case scenario, which would be necessary to lower the emissions for this scenario substantially. However, the Advanced EOP scenario has

significantly lower PM emissions, reaching 1.7 million tons of PM in 2050, which is less than half that in the other two scenarios. This is because of an accelerated and higher penetration of an advanced control technology—fabric filters—which have higher PM removal efficiency compared to that of electrostatic precipitators. In addition, the Chinese cement industry PM emissions under all three scenarios peak by 2020. This is mainly because cement production in China is projected to peak between 2015 and 2020.

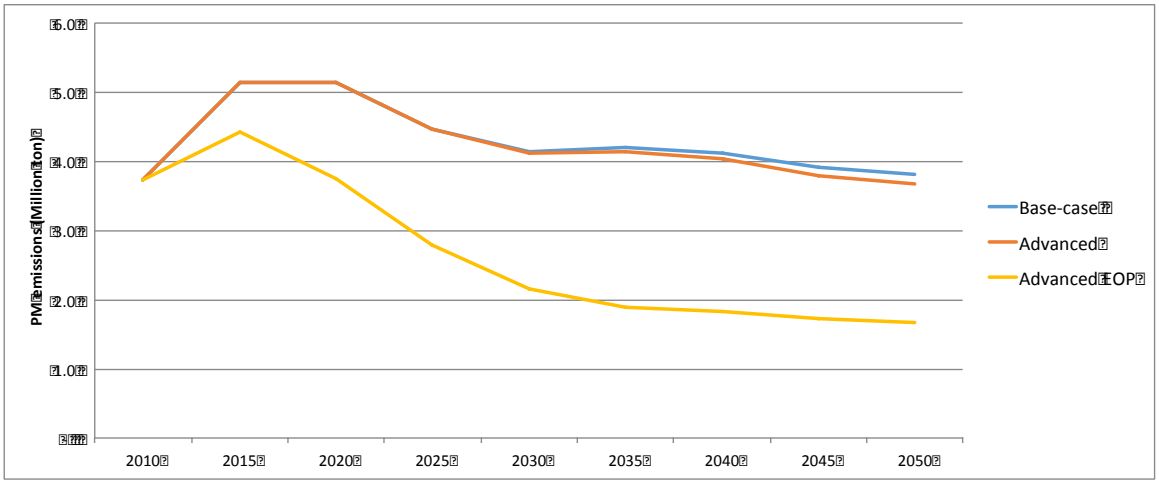


Figure 5. Total PM emissions of the Chinese cement industry under different scenarios from 2010–2050

4.2. SO_2 emissions projection for the cement industry in China

Figure 6 shows that the Advanced EOP scenario has the lowest SO_2 emissions for the cement industry in China, with emissions reaching 212,000 tons of SO_2 in 2050, which is equal to 40 percent of the SO_2 emissions in the Advanced scenario and 30 percent of the emissions in the Base Case scenario. The difference between the SO_2 emissions of the Base Case and Advanced scenarios is mainly due to significantly lower coal consumption in the Advanced scenario compared to the Base Case scenario. The Advanced EOP scenario has even lower SO_2 emissions because of the penetration of SO_2 control technologies (i.e., wet scrubber and activated carbon) between 2010 and 2050. Similar to PM emissions, the SO_2 emissions of the Chinese cement industry peaks in 2015, mainly because cement production in China is projected to peak between 2015 and 2020.

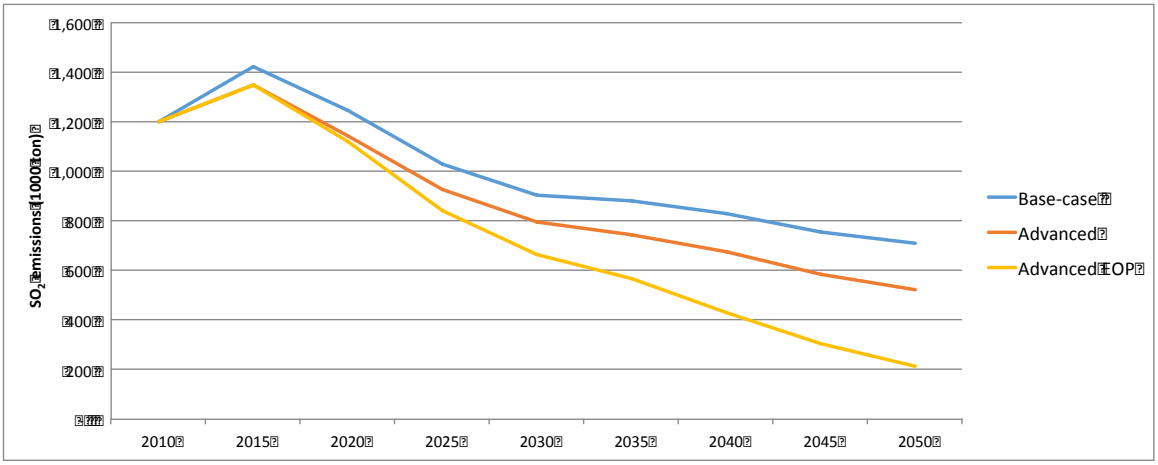


Figure 6. Total SO_2 emissions of the Chinese cement industry under different scenarios from 2010–2050

4.3. PM emissions projection for the steel industry in China

Similar to the cement industry, the PM emissions of the Chinese steel industry do not vary substantially between the Base Case and the Advanced scenario (Figure 7). This is also because we assumed a similar share and penetration rate of control technologies from 2010 up to 2050 for these two scenarios. The Advanced EOP scenario, however, has significantly lower PM emissions for the Chinese steel industry, reaching approximately 1.2 million tons in 2050. This is about 65 percent of the PM emissions under the other two scenarios in 2050. The main reason for this difference is a higher penetration of fabric filters under the Advanced EOP scenario, as explained in Section 3.3.3. Under the Base Case and Advanced scenarios, the PM emissions of the Chinese steel industry peaks in 2020, which is the year that steel production is projected to peak in China. However, in the Advanced EOP scenario, PM emissions peak in 2015. The accelerated penetration of the fabric filter, which has a higher PM removal efficiency compared to other PM control technologies, contributes to the earlier peak in PM emissions of the steel industry in the Advanced EOP scenario.

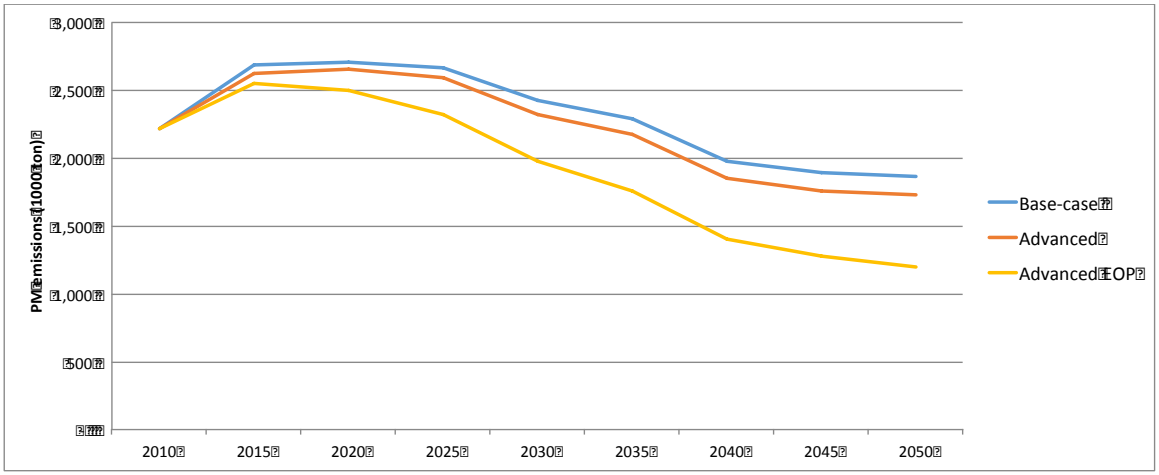


Figure 7. Total PM emissions of the Chinese steel industry under different scenarios from 2010–2050

4.4. SO_2 emissions projection for the steel industry in China

The SO_2 emissions of the Advanced scenario are slightly lower than those of the Base Case scenario, mainly because of the lower steel production in the Advanced scenario (Figure 8). The SO_2 emissions of the Advanced EOP scenario is significantly lower than that of the two other scenarios, with emissions declining to 323,000 tons in 2050, which is equal to 21 percent and 17 percent of the emissions of the Advanced and Base Case scenarios in 2050, respectively. This is due to the assumption of a higher penetration of wet scrubbers in sinter plants in China between 2010 and 2050. Under all scenarios, the SO_2 emissions from the Chinese steel industry peak in 2015.

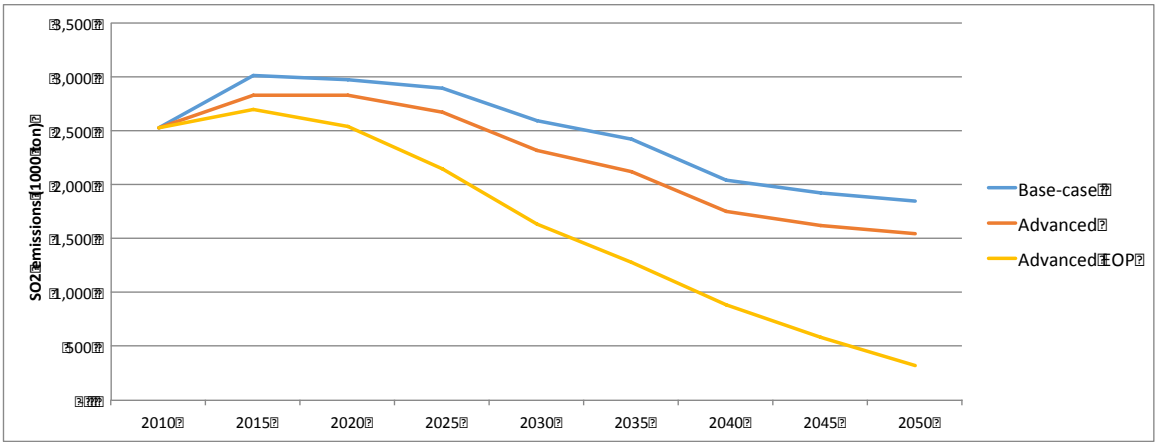


Figure 8. Total SO_2 emissions of the Chinese steel industry under different scenarios from 2010–2050

4.5. PM abatement cost for the cement industry in China

In addition to having PM emissions projections, it is important to have an estimate of the PM abatement cost for different PM abatement options, i.e., end-of-pipe control technologies, energy efficiency measures, and production change measures for the cement industry. We conducted the economic analysis for the PM reduction in the cement industry as an example to illustrate how such analysis can be conducted and to show the results for the cement industry. The results of this economic analysis will help to better understand the cost for reducing a unit of PM pollution using different abatement options. This will help policy makers, industry, and other interested parties to make a more informed decision, policy design, and analysis.

Using the methodology explained in Section 3.4, we calculated the PM abatement cost for the following PM abatement options implemented in a typical preheater-precalciner cement plant with a production capacity of 3,000 tons of clinker per day:

- Two end-of-pipe PM control technologies: electrostatic precipitators and fabric filters (Table 21)
- Twenty energy efficiency measures (Table 22)
- Two product change measures (Table 23)

Results show that end-of-pipe PM control technologies have the lowest abatement cost

per ton of PM reduced, followed by product change measures and energy efficiency measures, respectively. However, compared to many energy efficiency measures and product change measures, end-of-pipe PM control technologies often have higher initial capital cost. Also, note that these PM abatement options are rather complementary and may not necessarily substitute for each other. In particular, end-of-pipe PM control technologies have over 96 percent PM emissions reduction efficiency, which cannot be met by energy efficiency measures. Therefore, it is best to have end-of-pipe control technologies in place and then implement as many energy efficiency and product change measures as possible on top of the control technologies in order to have maximum PM emissions reduction.

Table 21. PM abatement cost for PM control technologies in the cement industry in China

Technology	PM Abatement Cost (RMB/ton PM-Abated)*
Electrostatic precipitators	12
Fabric filters	13

* This was calculated for a cement plant with a production capacity of 3,000 tons of clinker per day. The 2010 exchange rate of 6.8 was used to convert US$ to RMB.

Table 22. PM abatement cost for energy efficiency technologies in the cement industry in China

No.	Electricity Efficiency Measure	PM Abatement Cost (RMB/ton PM-Abated)*
1	New efficient coal separator for fuel preparation	39
2	Efficient roller mills for coal grinding	29
3	Installation of Variable Frequency Drive & replacement of coal mill bag dust collector's fan with high efficiency fan	156
4	Raw meal process control for Vertical mill	257
5	High Efficiency classifiers/separators for raw mill	626
6	High Efficiency roller mill for raw materials grinding	783
7	Variable Frequency Drive (VFD) in raw mill vent fan	70
8	High efficiency fan for raw mill vent fan with inverter	85
9	Adjustable speed drive for kiln fan	35
10	Efficient kiln drives	281
11	Variable Frequency Drive in cooler fan of grate cooler	102
12	Replacement of Preheater fan with high efficiency fan	90
13	Energy management & process control in grinding	109
14	Replacing a ball mill with vertical roller mill	279
15	High pressure roller press as pre-grinding to ball mill	296
16	Improved grinding media for ball mills	166
17	High-Efficiency classifiers (for finish grinding)	474
18	Replacement of Cement Mill vent fan with high efficiency fan	64
19	High efficiency motors	70
20	Adjustable Speed Drives	142
	Weighted Average PM Abatement Cost **	**304**

* This calculation was for a cement plant with a production capacity of 3,000 tons of clinker per day.

** The weighted average was calculated using an individual measure PM abatement cost and the annual PM abatement potential of each efficiency measure.

Table 23. PM abatement cost for product change measures in the cement industry in China

No.	Product Change Measure ***	PM Abatement Cost (RMB/ton PM-Abated)*
1	Blended cement (Additives: fly ash, pozzolans, and blast furnace slag)	62
2	Limestone Portland cement	21
	Weighted Average PM Abatement Cost **	48

* The calculation was for a cement plant with a production capacity of 3,000 tons of clinker per day.
** The weighted average was calculated using the individual measure PM abatement cost and the annual PM abatement potential of each efficiency measure.
** We assumed that the blended cement measure and the limestone Portland cement measure substitute an additional 10 percent and 5 percent of the clinker in a typical cement plant with 3,000 tons of clinker per day capacity, respectively.

5. Conclusions

This study quantified the total PM and SO_2 emissions of Chinese cement and steel industry under different scenarios from 2010–2050. Further, we conducted a detailed technology-level economic analysis, estimating the PM abatement costs for different abatement options in the cement industry in China.

The results show that the PM emissions of the Chinese cement and steel industry do not vary significantly between the Base Case and Advanced scenarios. This is mainly because PM emissions in the cement industry caused mainly by production process and not the fuel use. Since our forecast for the cement production in the Base Case and Advanced scenarios are not too different from each other, this results in only slight difference in PM emissions forecast for these two scenarios. Also, we assumed a similar share and penetration rate of control technologies from 2010 up to 2050 for these two scenarios for the cement and steel industry. However, the Advanced EOP scenarios have significantly lower PM emissions for the Chinese cement and steel industry due to the higher penetration of fabric filters under this scenario. The Advanced EOP scenario also has the lowest SO_2 emissions for the cement and steel industries in China. In addition to less coal consumption in the cement industry and less steel production in the steel industry under the Advanced EOP scenario, a higher penetration of wet scrubbers is a major contributor to lower SO_2 emissions in this scenario.

The economic analysis showed that for the Chinese cement industry, end-of-pipe PM control technologies have the lowest abatement cost per ton of PM reduced, followed by product change measures and energy efficiency measures, respectively.

In summary, in order to meet Chinese national and regional air quality standards, best practice end-of-pipe emissions control technologies must be installed in both cement and steel industry and it must be supplemented by implementation of energy efficiency

technologies and reduction of cement and steel production through structural change in industry.

Despite the uncertainties associated with this analysis and assumptions made, we believe it provides valuable information for policy makers on the different future PM and SO_2 emissions scenarios and mitigation strategies for the cement and steel industry in China.

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Appendix A

A.1. Description of Cement Production

Portland cement was invented in Britain during the late nineteenth century and named for its resemblance to stone from the Isle of Portland off the British coast. It is the most commonly used type of cement worldwide (PCA 2012) and is the fundamental constituent of concrete. The original Portland cement was made by heating a combination of finely ground limestone and clay that hardened when combined with water. Cements that harden when combined with water are known as hydraulic cements (PCA 2012).

The general process by which cement is manufactured today entails quarrying and crushing or grinding of the raw materials—commonly, limestone, chalk, and clay—and then combining them and passing them through a kiln in the form of either a dry powder or a wet slurry. Kiln temperatures is around 1,450°C. The heat fuses the raw materials into small pellets known as *clinker.* The cooled clinker is combined with gypsum and ground into the fine powder known as Portland cement. The American Society for Testing and Materials (ASTM) defines several types of Portland cement with different properties, as well as several blended hydraulic cements that are made by combining materials such as Portland cement, fly ash, natural pozzolana (a siliceous volcanic ash), and blast furnace slag (PCA 2012). The subsections below describe the process by which cement is produced in more detail, with a focus on the energy and carbon dioxide (CO_2) emissions impacts of cement production processes.

A.1.1. Mining and Quarrying

As noted above, the most common raw materials used in cement production are limestone, chalk, and clay, with limestone or chalk forming the majority of the ingredients in cement. These materials are usually extracted from a quarry adjacent or very close to the cement plant. Limestone provides calcium oxide and some of the other oxides, and clay, shale, and other materials provide most of the silicon, aluminum, and iron oxides required for cement manufacture. Approximately 5 percent of CO_2 emissions from cement production are associated with quarry mining and transportation (WWF 2008).

A.1.2. Raw Material Grinding and Preparation

Grinding raw materials for cement is an electricity-intensive step, generally requiring about 25 to 35 kilowatt-hours (kWh)/ton (t) of raw material. The grinding differs according to the type of process used in the clinker production. In dry processing, the raw materials are ground into a flowable powder in horizontal ball mills, vertical roller mills, or roller presses. Materials might be dried using waste heat from the kiln exhaust or clinker cooler hood, or auxiliary heat from a stand-alone air heater. The moisture content in the dry feed is typically approximately 0.5 percent but can range from 0 to 0.7 percent. When raw materials are very moist, as is the case in some countries and

regions, wet processing may be preferable. In the wet process, raw materials are ground in a ball or tube mill with the addition of water to produce a slurry whose water content ranges from 24 to 48 percent but is typically 36 percent (Worrell and Galitsky 2004).

A.1.3. Clinker Production

Clinker production is the most energy-intensive stage in cement production, accounting for more than 90 percent of total cement industry energy use and virtually all of the fuel use. Kiln systems evaporate the inherent water in the raw meal, calcine the carbonate constituents (*calcination*),[6] and form cement minerals (*clinkerization*).

The main type of high-heat or pyroprocessing kiln used today is the dry rotary kiln. A dry rotary kiln uses feed material with a low moisture content (0.5 percent). The first dry kiln process was developed in the United States and did not involve preheating. Later developments added multi-stage suspension preheaters (cyclones) or shaft preheaters. More recently, precalciner technology was developed, in which a second combustion chamber is added between the kiln and a conventional pre-heater that allows for further reduction of kiln fuel requirements. The typical fuel consumption of a dry kiln with four-, five-, or six-stage preheating can vary between 2.9 and 3.5 gigajoules (GJ)/t of clinker, and almost all the process-related CO_2 emissions from cement production are associated with calcination during clinker production.

Once the clinker is formed in the rotary kiln, it is cooled rapidly to minimize the formation of glass and ensure the maximum yield of alite (tricalcium silicate), an important component for the hardening properties of cement. The main cooling technologies are the grate cooler or the tube or planetary cooler. In the grate cooler, which is most common today, the clinker is transported over a reciprocating grate through which air flows perpendicular to the clinker flow (Worrell and Galitsky 2004).

A.1.4. Finish Grinding

To produce powdered cement, the nodules of clinker are finely ground in ball mills, ball mills combined with roller presses, roller mills, or roller presses. At this stage, 3 to 5 percent gypsum is added to control the setting properties of the cement. The amount of electricity used for raw meal and finish grinding depends strongly on the hardness of the materials (e.g., limestone, clinker, pozzolana) and the desired fineness of the cement, as well as the amount of additive. Blast furnace slag is harder to grind, and thus requires more grinding power. Traditionally, ball mills are used in finish grinding, but many plants use vertical roller mills too. Modern state-of-the-art approaches utilize a high-pressure roller mill or horizontal roller mill (e.g., Horomill®). Finished cement is stored in silos, tested, and bagged or shipped in bulk on bulk cement trucks, railcars, barges, or ships (Worrell and Galitsky 2004).

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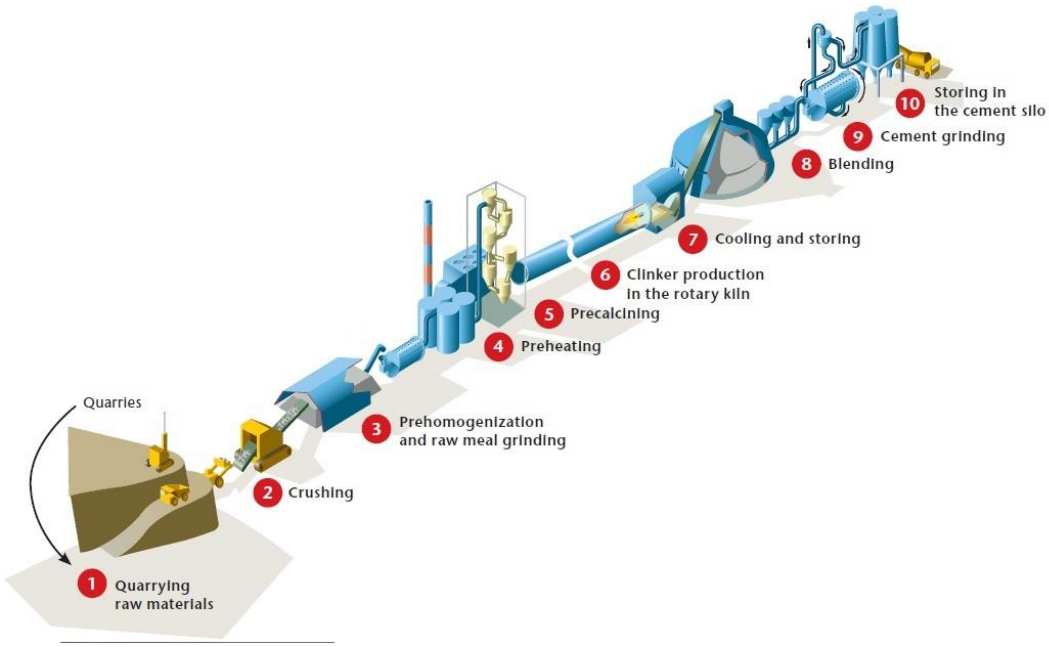
[6] *Calcination* is the process of heating a substance to a high temperature that is below the substance's melting or fusing point, to change the substance's physical or chemical constitution.

Figure A.1 shows the steps of the cement production process using the new suspension preheater and precalciner (NSP) kiln.[7]



Source: WBCSD/IEA 2009.

Figure A.1. Steps in the cement production process using the new suspension preheater and precalciner kiln

[7] This description of the cement production process is partially excerpted from Worrell and Galitsky (2004).

A.2. Description of Iron and Steel Production

Iron ore is chemically reduced to produce steel by one of three process routes: (1) blast furnace (BF)/basic oxygen furnace (BOF), (2) direct reduction/electric arc furnace (EAF), or (3) smelting reduction/BOF (European Commission 2010). Steel is also produced by direct melting of scrap in an EAF. Each of these processes is briefly explained below.

Figure A.2 is a simplified flow diagram of the steel production processes.

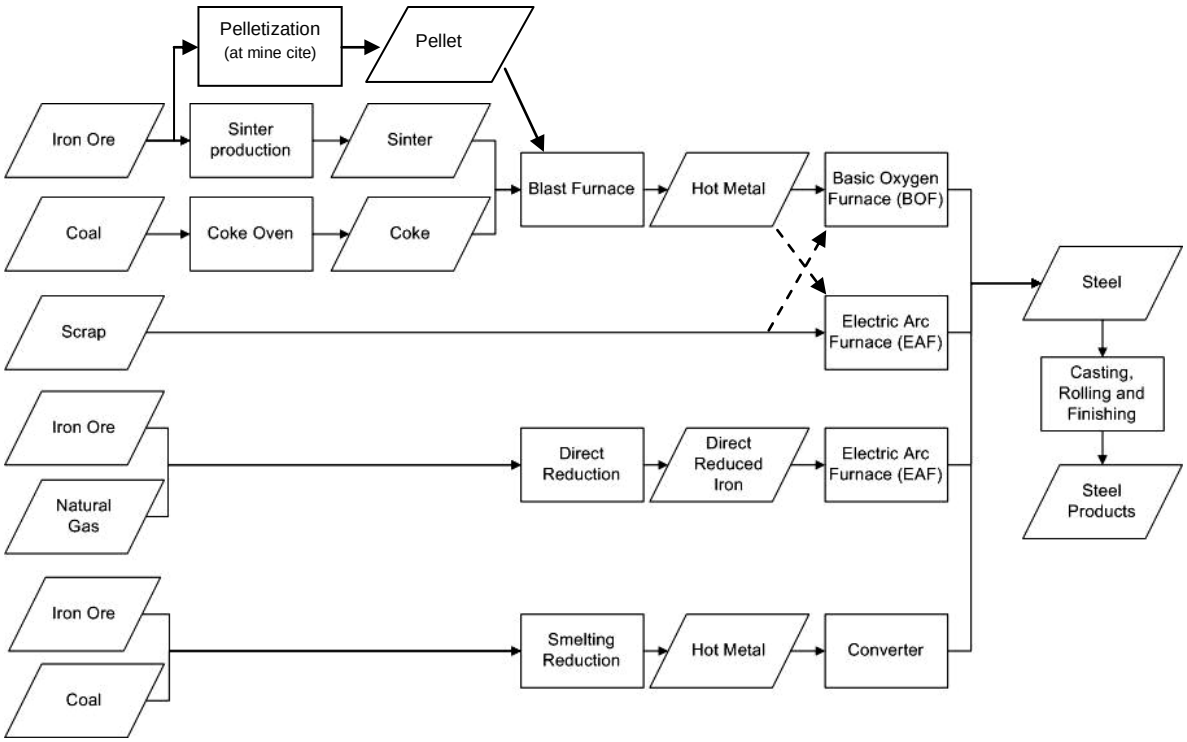


Figure A.2. Flow diagram of steel production

Blast furnace/basic oxygen furnace (BF-BOF) and EAF production are the most common steel production processes worldwide. In 2010, BF-BOF production accounted for approximately 65 percent of the steel manufactured worldwide, and EAF production accounted for approximately 30 percent (worldsteel 2011). In China, BF-BOF production process accounted for 89.6 percent of total steel production in that country and 92.8 percent of the steel produced by key medium- and large-sized steel enterprises in China in 2010. Almost all the remaining steel is produced by the EAF in China.[8]

A.2.1. Raw materials

Sintering

In *sintering,* iron ore fines, other iron-bearing wastes, and coke dust are blended and combusted; the heat induces incipient fusion to convert the fines into coarse lumps (sinter) that can be used as raw material (charge) in a BF. Sintering enables

[8] The description of process is partially excerpted from (APP 2010, AISI 2010, US EPA 2010). More detailed descriptions can be found in these sources.

manufacturers to use iron ore fines and other iron-bearing wastes but requires a large capital investment and air pollution controls (APP 2010).

Pelletizing

In *pelletizing,* iron ore is crushed and ground to remove impurities. The resulting beneficiated (iron-rich) ore is mixed with a binding agent and then heated to create durable, marble-sized pellets. These pellets can be used in both BF and direct reduction steel manufacturing (APP 2010). Pellet plants are mostly located at mining sites.

Coke Making

Coke is a carbon product formed by thermal distillation of metallurgical coal at high temperatures in the absence of air. Coke is produced in batteries of coke ovens. It is used to provide a reducing atmosphere in a BF and is also a source of fuel. One of the key characteristics of coke is its porosity, which enables the gas exchange throughout the BF from the bottom to the top. Approximately one-third of the cleaned coke oven gas (COG) is used to fuel the coke ovens, and the remainder is used in other steel plant combustion units. Some newer coke plants use non-recovery coke ovens that burn rather than recover the by-products. The new non-recovery coke plants capture combustion waste heat to generate steam and electricity. The primary CO_2 emissions point at coke plants is the combustion stack from the ovens (U.S. EPA 2010).

A.2.2. Ironmaking

The subsections below describe three ironmaking processes: (1) the BF/BOF, (2) direct reduction, and (3) smelting reduction (SR) processes.

Blast Furnace

A blast furnace is a huge shaft furnace that is top-fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas. The heat melts the charge, and the CO removes the oxygen from the iron ore, producing hot metal.[9] Hot metal is a solution of molten iron at approximately 1,480°C, which contains 4 percent carbon and some silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically "tapped" from the furnace into transfer cars and transported to the BOF where it is refined into steel. The BF is the most energy-intensive step in the BF-BOF steelmaking process, generating large quantities of CO_2 (AISI 2010).

[9] When hot metal is allowed to solidify in a pig iron casting machine, the resultant solid iron is called *pig iron*.

A.2.3. Steelmaking

The subsections below describe the steelmaking processes.

Basic Oxygen Furnace (BOF)

The BOF converts liquid hot metal from the BF into steel. The main operation is the addition of oxygen to remove carbon from the hot metal. In recent years, extensive ladle metallurgy processes have been developed to improve steel quality. A BOF uses virtually no energy and does not produce net energy (IEA 2007).

Electric Arc Furnace (EAF)

Electric arc furnaces are used mainly to produce steel by recycling ferrous scrap. Direct reduced iron (DRI) and pig iron also can be fed to the EAF as a scrap substitute. Electric arc furnaces are equipped with carbon electrodes that can be raised or lowered through the furnace roof to provide the necessary energy by an electric arc. Energy consumption in EAF-steelmaking is much lower, as the energy-intense reduction of iron ore has already been carried out in the BF (or in the DRI or SR plant). Electric arc furnace steelmaking can use a wide range of scrap types, DRI, pig iron, and molten iron (up to 30 percent) as the feed charge. The liquid steel from an EAF is generally sent to a ladle metallurgy station (LMS) to improve the steel quality. Recycling of scrap into steel saves virgin raw materials, as well as the energy required to convert them (APP 2010).

A.2.4. Casting, rolling, and finishing

The molten steel produced by both BOFs and EAFs follows similar routes after leaving the furnace: it is transferred from the LMS to the continuous caster, which forms the steel into semi-finished shapes (e.g., slabs, blooms, billets, rounds, and other special sections). Steel from the continuous caster is mainly processed in rolling mills to produce the final shapes that are sold by the steel mill. These shapes include coiled strips, rails, sheets, many structural shapes, rods, and bars. Because rolling mills consume electricity, they contribute to indirect greenhouse gas emissions. Fossil fuels (e.g., natural gas) are consumed in furnaces to reheat the steel before rolling. The products from the hot rolling mill may be further processed in various ways, such as annealing, hot forming, cold rolling, heat treating (tempering), pickling, galvanizing, coating, or painting. The furnaces are custom designed for the type of steel, the dimensions of the semi-finished steel pieces, and the desired temperature (U.S. EPA 2010).

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