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National Level Co-Control Study of the Targets for Energy Intensity and Sulfur Dioxide in China

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Disclaimer

Abstract

Since 2006, China has set goals of reducing energy intensity, emissions, and pollutants in multiple guidelines and in the Five Year Plans. Various strategies and measures have then been taken to improve the energy efficiency in all sectors and to reduce pollutants. Since controlling energy, CO_2 emissions, and pollutants falls under the jurisdiction of different government agencies in China, many strategies are being implemented to fulfill only one of these objectives. Co-controls or integrated measures could simultaneously reduce greenhouse gas (GHG) emissions and criteria air pollutant emissions. The targets could be met in a more cost effective manner if the integrated measures can be identified and prioritized. This report provides analysis and insights regarding how these targets could be met via co-control measures focusing on both CO_2 and SO_2 emissions in the cement, iron &steel, and power sectors to 2030 in China. An integrated national energy and emission model was developed in order to establish a baseline scenario that was used to assess the impact of actions already taken by the Chinese government as well as planned and expected actions. In addition, CO_2 mitigation scenarios and SO_2 control scenarios were also established to evaluate the impact of each of the measures and the combined effects.

The research finds:

In the power sector, although the end of pipe SO_2 control technology such as flue gas desulfurization (FGD) has the largest reduction potential for SO_2 emissions, other CO_2 control options have important co-benefits in reducing SO_2 emissions of 52.6 Mt of SO_2 accumulatively. Coal efficiency improvements along with hydropower, renewable and nuclear capacity expansion will result in more than half of the SO_2 emission reductions as the SO2 control technology through 2016. In comparison, the reduction from carbon capture and sequestration (CCS) is much less and has negative SO_2 reductions potential. The expanded biomass generation scenario does not have significant potential for reducing SO_2 emissions, because of its limited availability.

For the cement sector, the optimal co-control strategy includes accelerated adoption of energy efficiency measures, decreased use of clinker in cement production, increased use of alternative fuels, and fuel-switching to biomass. If desired, additional SO_2 mitigation could be realized by more fully adopting SO_2 abatement mitigation technology measures. The optimal co-control scenario results in annual SO_2 emissions reductions in 2030 of 0.16 Mt SO_2 and annual CO_2 emissions reductions of 76 Mt CO_2.

For the iron and steel sector, the optimal co-control strategy includes accelerated adoption of energy efficiency measures, increased share of electric arc furnace steel production, and reduced use of coal and increased use of natural gas in steel production. The strategy also assumes full implementation of sinter waste gas recycling and wet desulfurization. This strategy results in annual SO_2 emissions reductions in 2030 of 1.3 Mt SO_2 and annual CO_2 emissions reductions of 173 Mt CO_2.

Executive Summary

As a part of the 11th Five Year Plan, China announced a goal of reducing both energy intensity, defined as energy use per unit of gross domestic product (GDP) by 20% by 2010 and absolute sulfur dioxide (SO_2) emissions by 10%. Similar targets will likely be included in the 12th Five Year Plan. In November 2009, China also committed to reduce its carbon intensity (CO_2 per unit of GDP) by 40% to 45% percent below 2005 levels by 2020.

In light of these goals, this report provides analysis and insights regarding how these targets could be met via co-controls or integrated measures that are defined as simultaneously reducing greenhouse gas (GHG) emissions and criteria air pollutant emissions. This research utilizes existing tools and analytical frameworks already established for China and conducts an analysis of the expected co-benefits of adopting a range of different strategies for meeting the goals as well as evaluating the potentials for co-control strategies to 2030.

This study focuses on both CO_2 and SO_2 emissions. An integrated national energy and emission model was developed in order to establish a baseline scenario that was used to assess the impact of actions already taken by the Chinese government as well as planned and expected actions, and to evaluate the potential for China to control energy demand growth and mitigate emissions. Three key sectors in terms of importance and potential - the power, cement, and iron and steel sectors – were selected for this analysis. Various scenarios were developed to assess the potential energy efficiency, CO_2 control and SO_2 control technologies in each of the sectors. Due to a lack of data, cost-effectiveness analysis was not conducted.

The primary analytical tool used in this study is LBNL's China End-Use Energy Model which is an accounting framework of China's energy and economic structure built using the Long-Range Energy Alternatives Planning (LEAP) modeling software. This approach allowed a detailed consideration of technological development—industrial production, equipment efficiency, power sector efficiency, etc. —as a way to evaluate China's energy and emission reduction development path below the level of its macro-relationship to China's economic development path.

A baseline Continued Improvement (CI) scenario and an accelerated energy efficiency (AEE) scenario were developed for the power, cement, and iron and steel sectors to assess the impact of actions already taken by the Chinese government as well as planned and expected actions, and to evaluate the potential for China to control energy demand growth and mitigate emissions. In addition, CO_2 mitigation scenarios and SO_2 control scenarios were also established to evaluate the impact of each of the measures and the combined effects. Building upon the results of the individual scenarios, co-control scenarios were also developed to assess the optimal strategies to control both CO_2 and SO_2 emissions simultaneously. A description and details of these scenarios are elaborated in the sectoral analyses of each of the three sectors.

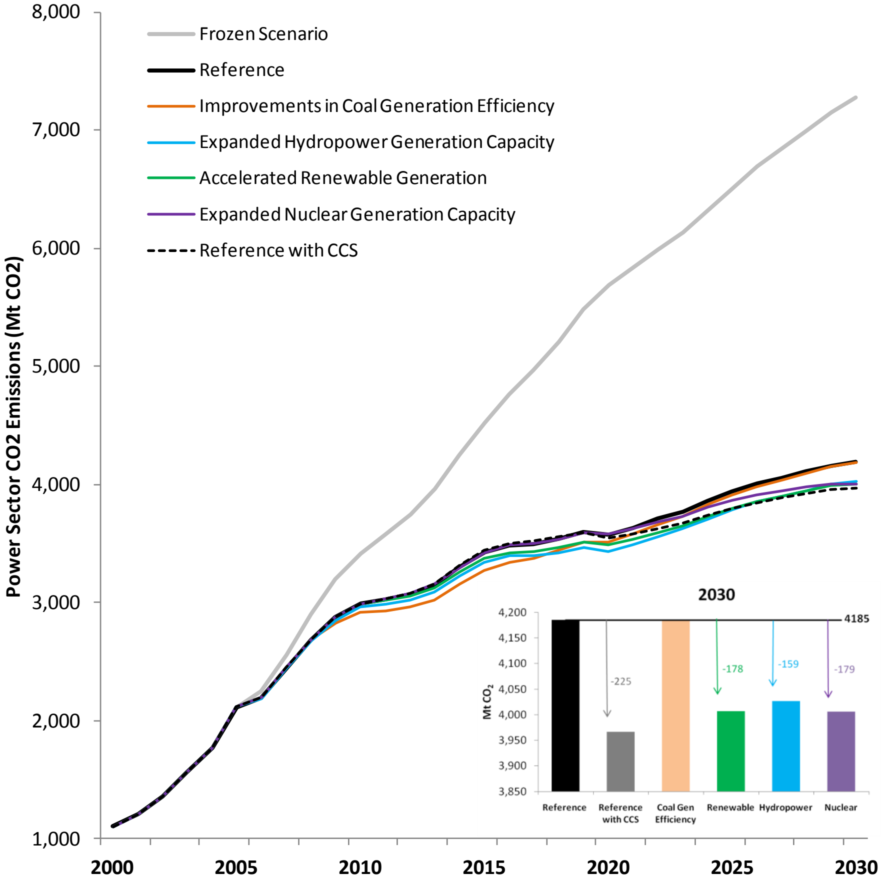
In addition, a carbon capture and sequestration (CCS) scenario was also constructed to evaluate the potential impact of further decarbonization of the power sector, and the implication on CO_2 and SO_2 emissions from the CCS application.

The key findings of this report are:

Power Sector

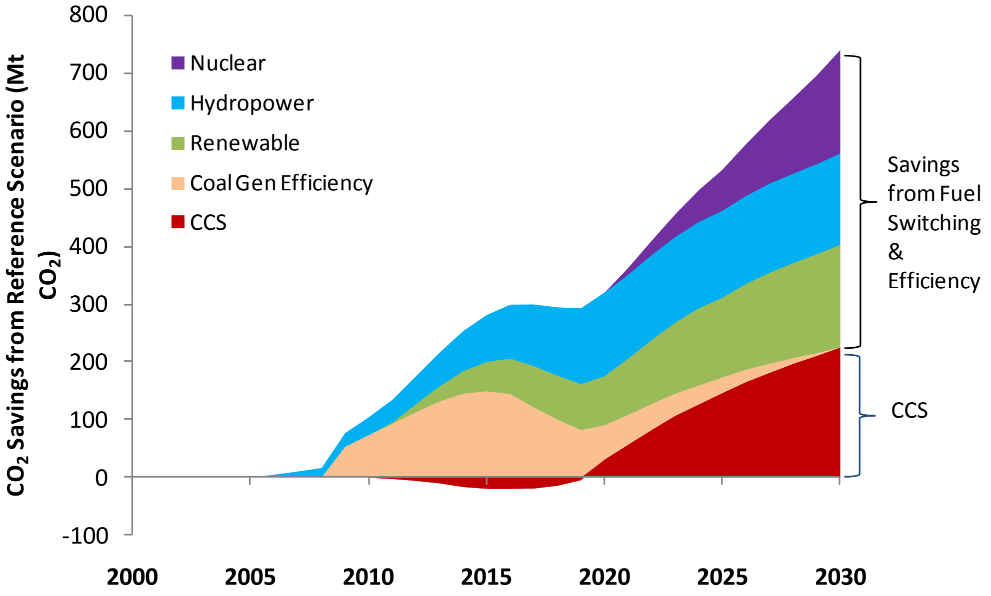
Hydropower in particular has the greatest CO_2 emission reductions potential at 2,499 $MtCO_2$ as a single co-control measure, followed by renewables at 1,927 $MtCO_2$, making the decarbonization of the power sector the most effective CO_2 mitigation measure. The improvement of coal power generation efficiency also encompasses significant reduction potential. The CCS scenario results in the greatest annual CO_2 emission reduction by 2030 compared to other individual CO_2 mitigation scenarios, with CO_2 emissions 225 Mt less in 2030 than in the reference scenario. However, the cumulative CO_2 emissions reduction from CCS between 2005 and 2030 is much less than those realized through efficiency improvement and decarbonization of the power sector.

Figure ES-1 CO_2 Emissions of Power Sector CO_2 Control Scenarios, 2000 - 2030



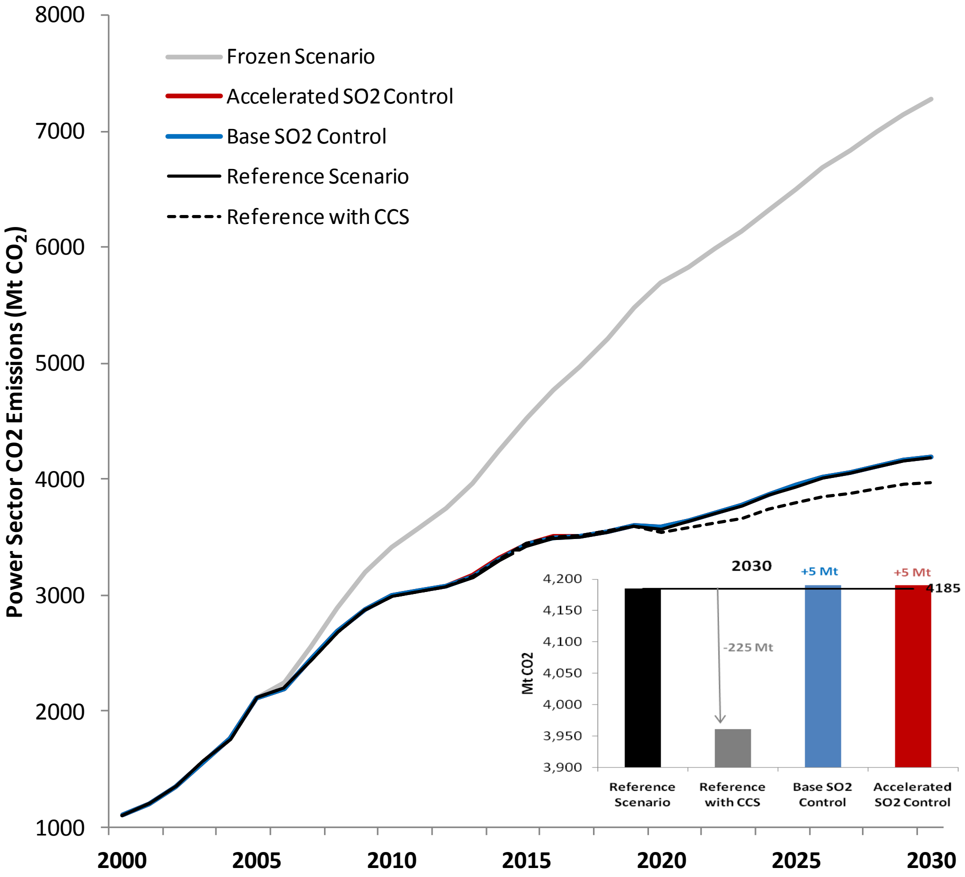
Note: Y-axis not scaled to zero.

Figure ES-2 CO_2 Emission Reduction by CO_2 Control Scenario, 2005 - 2030



In terms of SO_2 emission reduction, the base and accelerated SO_2 control scenarios show a very small net increase in CO_2 emissions relative to the reference case, which ranges from a low of 5 $MtCO_2$ in 2030 to a high of 19 $MtCO_2$ emissions for the accelerated SO_2 control case and 16 $MtCO_2$ emissions for the base SO_2 control case in 2015. Both control scenarios flatten out after 2020 with very small incremental reductions through 2030 as the SO_2 control technology reaches full penetration and removal rate.

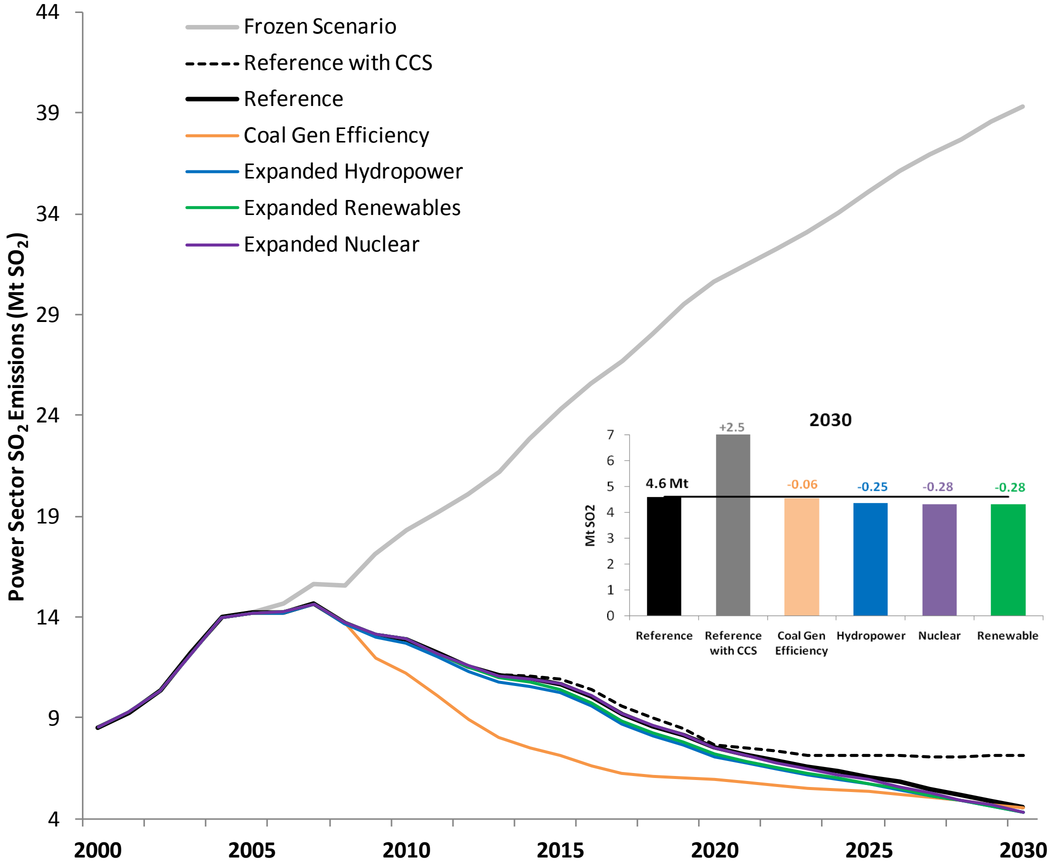
Figure ES-3 Total CO_2 Emissions for Power Sector SO_2 Control Scenarios



Note: Y-axis not scaled to zero.

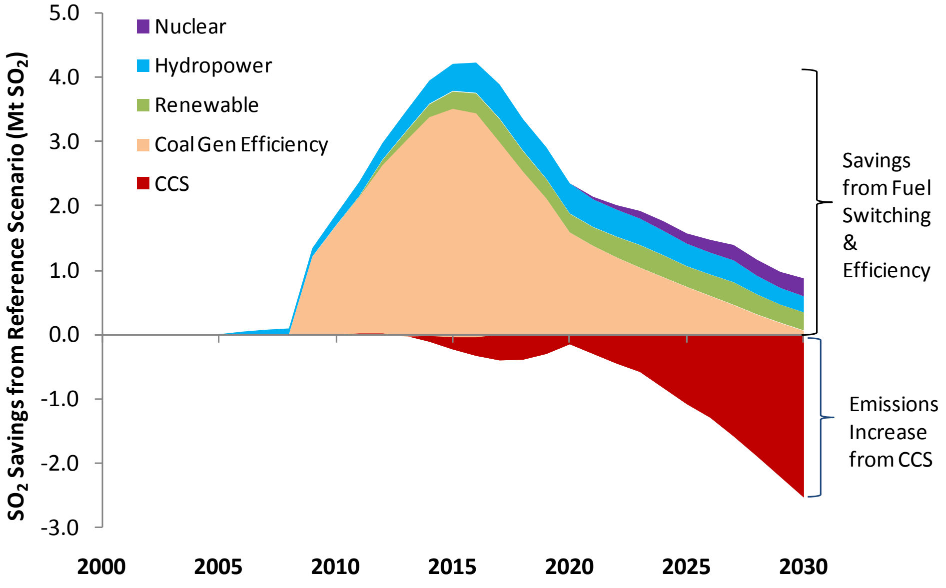
Although the base and accelerated SO_2 control scenarios have the largest reduction potential on an annual and cumulative basis, the other CO_2 control options also have important co-benefits in reducing SO_2 emissions. Improving coal generation efficiency for CO_2 mitigation has important co-benefits in significantly reducing SO_2 emissions by as much as 3.6 $MtSO_2$ in 2015by eliminating inefficient coal use, but declines after 2015 as all the inefficient plants will have been phased out. Expanding hydropower and renewable capacity also have important co-benefits in reducing cumulative SO_2 emissions. As the contribution from coal generation efficiency declines, decarbonization will play a much greater role. Hydropower and renewable capacity expansion have the second and third largest cumulative SO_2 reductions potential with 8 $MtSO_2$ and 5.5Mt SO_2, respectively. Coal efficiency improvements along with hydropower, renewable and nuclear capacity expansion will achieve more than half of the SO_2 emission reductions as the base control scenario through 2016. At its peak reductions in 2015, coal efficiency with hydropower, renewable and nuclear capacity expansion will achieve reductions of 4.27 $MtSO_2$ per year while accelerated SO_2 control can achieve 10.3 $MtSO_2$ in reductions. Despite declines after 2015, power sector efficiency improvements and decarbonization can still reduce SO_2 emissions by nearly 0.9 Mt in 2030, or 20% of the reduction potential of accelerated base control.

Figure ES-4 Total SO_2 Emissions for Power Sector CO_2 Control Scenarios



Note: Y-axis not scaled to zero.

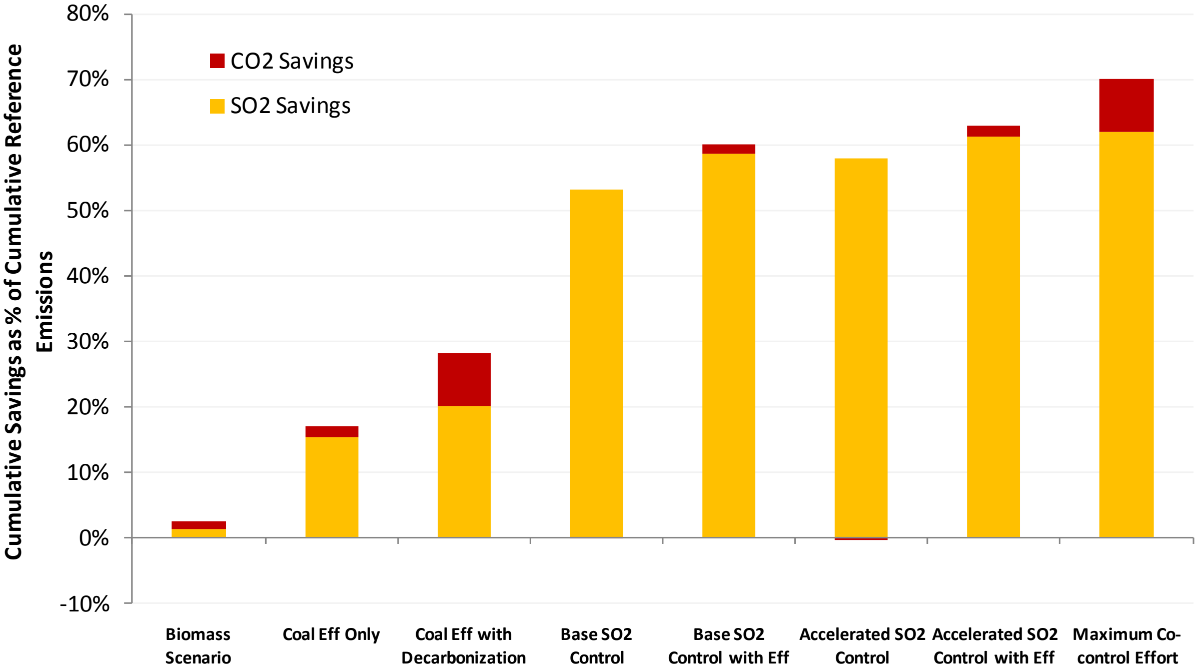
Figure ES-5 SO_2 Emission Reductions by CO_2 Scenario, 2005 - 2030



CCS is the only CO_2 control scenario that has negative SO_2 reductions potential. Adopting efficiency and decarbonization can achieve the maximum CO_2 reductions. Combining it with accelerated SO_2 control has the added benefit of reducing much greater SO_2 emissions without significantly increasing CO_2 emissions. Without decarbonization, however, the power sector will not achieve significant CO_2 reductions, particularly in the later years.

As co-control scenarios, the base and accelerated SO_2 control with coal generation efficiency improvement will have the largest SO_2 emission reductions potential. Decarbonization, however, has very negligible additional SO_2 reductions when SO_2 control is already in place because most of the reductions potential has been captured by SO_2 control technology. The expanded biomass generation scenario does not have significant potential for reducing SO_2 emissions, with annual reductions in the range of 0.1 to 0.2 $MtSO_2$ because of its much lower sulfur content than that of carbon content of up to 90% by weight, and its limited availability.

Figure ES-6 2005-2030 CO_2 and SO_2 Relative Emissions Reduction Potential of Co-control Scenarios

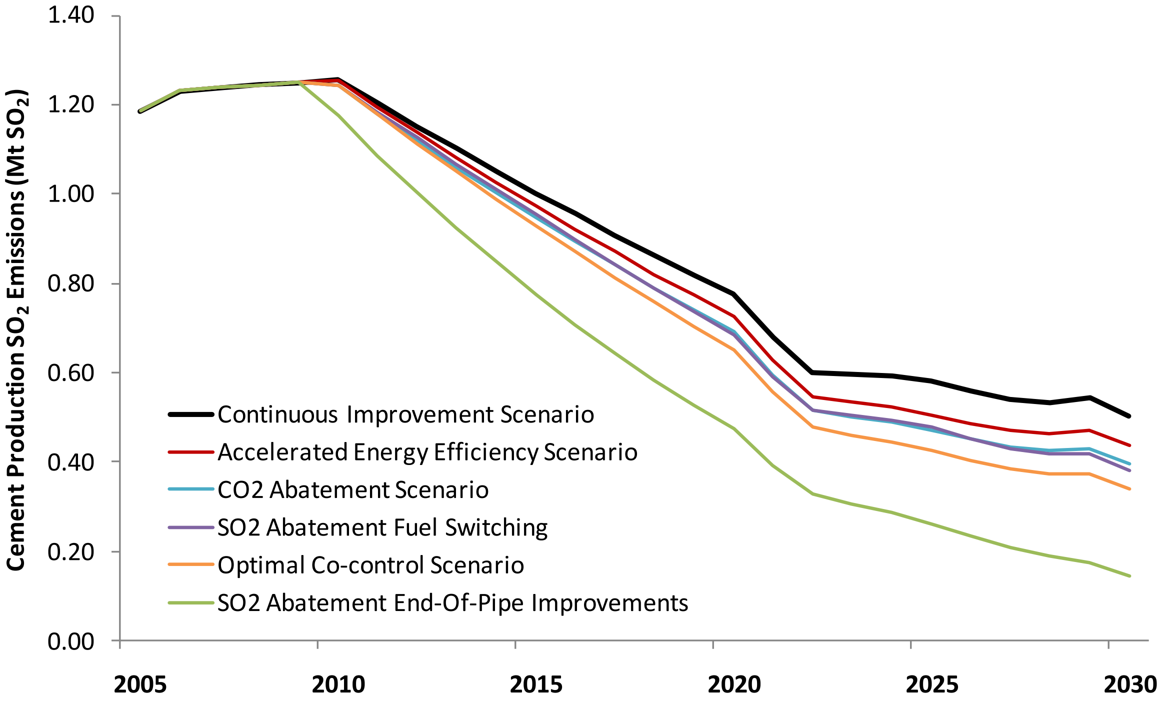


Cement Sector

There are numerous options for reducing SO_2 and CO_2 emissions in the cement sector in China. Both SO_2 and CO_2 emissions reductions can be realized through the accelerated adoption of energy efficiency options. Numerous energy efficiency technologies and measures were identified that have not been fully implemented in China's cement industry.

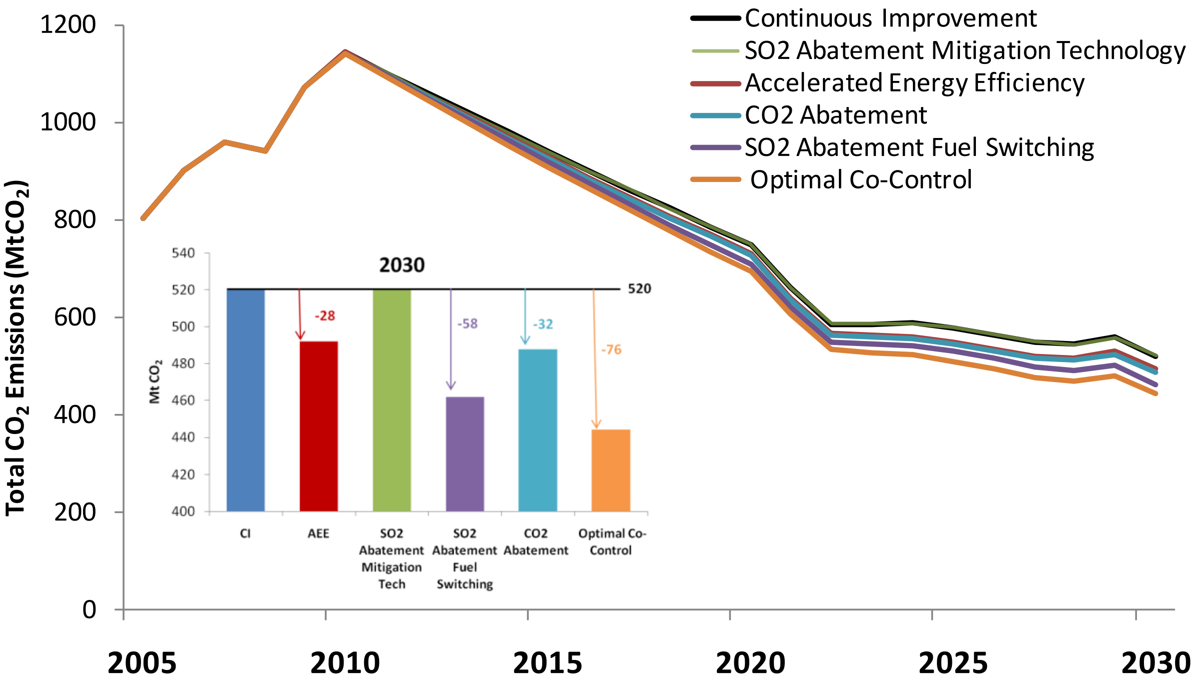
SO_2 emissions can also be reduced through the implementation of SO_2 abatement end-of-pipe technology options (such as absorbent addition, wet scrubbers, and activated carbon) and through increasing the share of biomass used in the cement kiln. Given the assumptions outlined in this report, the SO_2 mitigation scenarios resulted in annual savings in 2030 of 0.07 Mt SO_2 from accelerated adoption of energy efficiency, 0.12 Mt SO_2 from fuel switching, and 0.36 Mt SO_2 from implementation of SO_2 abatement end-of-pipe technology options.

Figure ES-7 Total SO_2 Emissions for Cement Production by Scenario, 2005-2030



In addition to the implementation of energy efficiency measures that have not yet been adopted, CO_2 emissions reduction options also include reduced use of clinker through increased blending of additives in cement production, and reduction of coal use in the cement kiln through the substitution of coal with alternative fuels. Given the assumptions outlined in this report, an Accelerated Energy Efficiency scenario, that includes the energy efficiency and clinker substitution measures, resulted in annual savings in 2030 of 28 Mt CO_2. A CO_2 Abatement scenario that also reduces the use of coal from 85% to 60% by 2030 resulted in annual savings in 2030 of 32Mt CO_2. It should be noted that carbon capture and storage (CCS) for control of CO_2 in the cement sector was not considered in this report due to uncertainty regarding its commercialization, cost, and the fact that its use could increase plant electricity use significantly, resulting in an energy penalty that could significantly reduce the overall amount of sequestered CO_2.

Figure ES-8 Total CO_2 Emissions (Energy- and Process-Related) for Cement Production in China, 2005-2030



A combined approach that relies on full or nearly full adoption of each of these measures by 2030 results in the greatest combined SO_2 and CO_2 emissions reductions for the cement industry. This Optimal Co-Control scenario includes accelerated adoption of energy efficiency measures, decreased use of clinker in cement production, increased use of alternative fuels and fuel-switching to biomass. Due to the high cost of SO_2 abatement mitigation technology measures, these technologies are not fully implemented in this scenario in order to determine the maximum SO_2 and CO_2 emissions reductions that can be realized using measures that "co-control" – or influence both types of emissions – at a minimum cost. If desired, additional SO_2 mitigation could be realized by more fully adopting these measures. The optimal co-control scenario results in annual SO_2 emissions reductions in 2030 of 0.16 Mt SO_2 and annual CO_2 emissions reductions of 76 Mt CO_2.

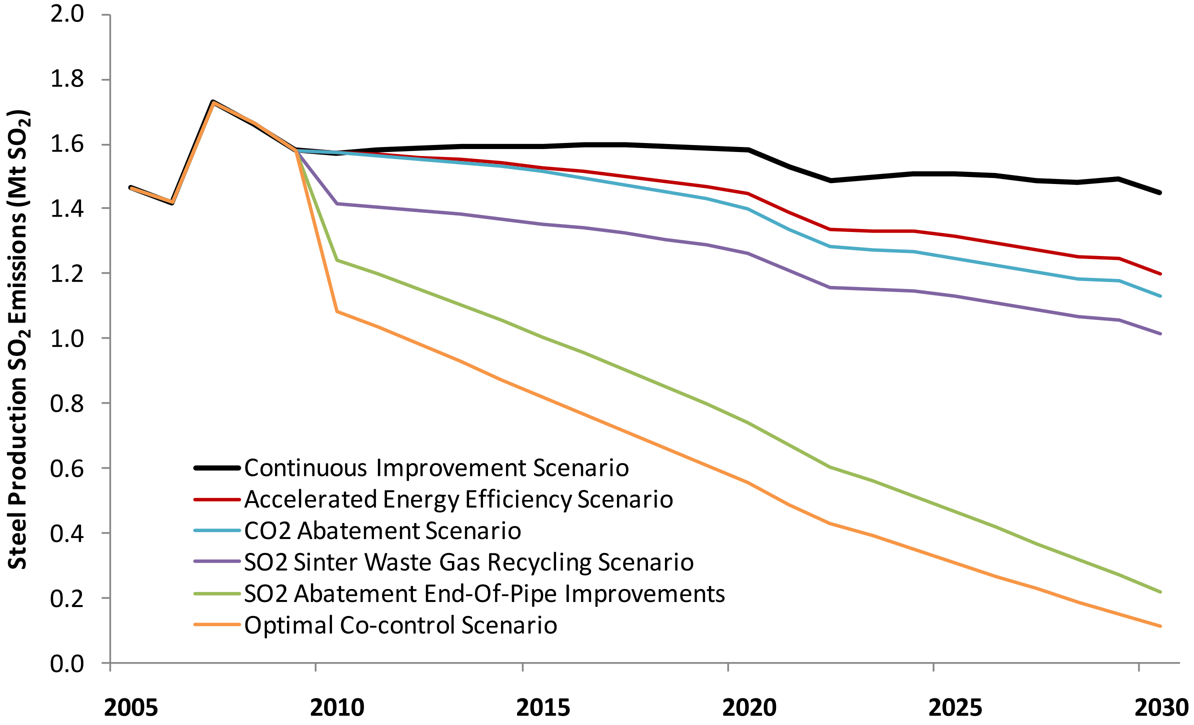
Iron and Steel Sector

It was also possible to identify numerous options for reducing SO_2 and CO_2 emissions in the iron and steel sector in China. As with the cement industry, many energy efficiency technologies and measures were identified that have not been fully implemented in China's steel industry.

SO_2 emissions from steel production can also be mitigated by minimizing the sulfur content in the raw materials (especially the sinter feed) and coal, sinter waste gas recycling, sinter flue gas desulfurization, and use of other selected mitigation technologies such as fabric filters, dry-gas off-gas cleaning, fine wet scrubbers, and regenerative activated carbon (RAC). Two SO_2

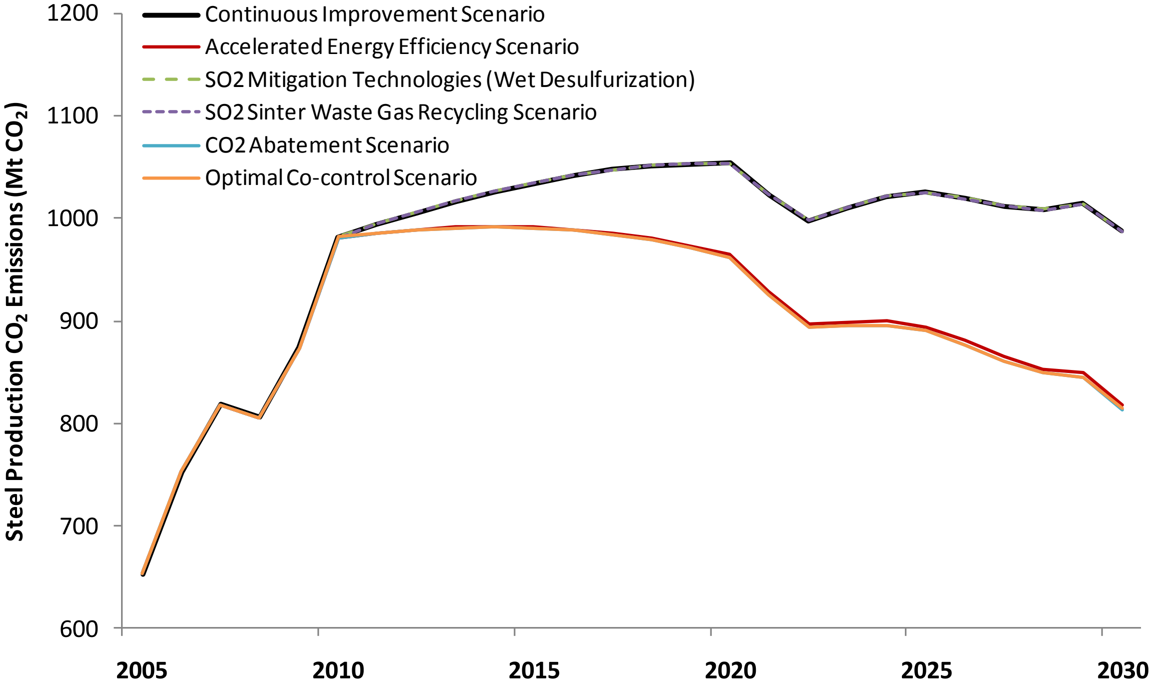
mitigation scenarios were developed. The first scenario, which focuses on full implementation of wet desulfurization which is one of the mitigation technologies available for steel production, resulted in annual 2030 SO_2 emissions reductions of 1.2 Mt SO_2. The second scenario assumes full implementation of sinter waste gas recycling and resulted in annual SO_2 emissions reductions in 2030 of 0.44 Mt SO_2.

Figure ES-9 Total SO_2 Emissions for Steel Production in China, 2005-2030



CO_2 emissions reductions can be realized through adoption of energy efficiency measures, increasing the share of steel made using the electric arc furnaces (EAFs), and reducing the share of coal used for all types of steel production. An Accelerated Energy Efficiency scenario was developed that increases the adoption of energy efficiency measures so that China's steel industry reaches the 2005 international best practice energy intensity level by 2030 and assumes that steel produced by EAFs in China grows from slightly over 16% in 2000 to slightly over 26% in 2030. Annual CO_2 emissions reductions from this scenario in 2030 are 169 Mt CO_2. Another CO_2 Abatement scenario adopts the same measures as the AEE scenario, but also includes reduced use of coal and increased use of natural gas. This scenario results in annual 2030 CO_2 emissions reductions of 173 Mt CO_2.

Figure ES-10 Total CO2 Emissions for Steel Production in China, 2005-2030



A combined approach that represents a combination of most of the accelerated variables presented in the above individual scenarios results in the greatest combined SO_2 and CO_2 emissions reductions for the steel industry. This Optimal Co-Control scenario includes accelerated adoption of energy efficiency measures, increased share of EAF steel production, and reduced use of coal and increased use of natural gas in steel production. This scenario also assumes total SO_2 emissions reductions of 90% in 2030 comprised of SO_2 emissions reductions from energy efficiency and CO_2 emissions mitigation technologies and measures, full implementation of sinter waste gas recycling and the remaining reductions through the implementation of wet desulfurization. The Optimal Co-control scenario results in annual SO_2 emissions reductions in 2030 of 1.3 Mt SO_2 and annual CO_2 emissions reductions of 173 Mt CO_2.

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1. Introduction

As a part of the 11th Five Year Plan, China announced a goal of reducing both energy intensity, defined as energy use per unit of gross domestic product (GDP) by 20% by 2010 and absolute sulfur dioxide (SO_2) emissions by 10%. Similar targets will likely be included in the 12th Five Year Plan. In November 2009, China also committed to reduce its carbon intensity (CO_2 per unit of GDP) by 40% to 45% percent below 2005 levels by 2020.

In light of these goals, this report provides analysis and insights regarding how these targets could be met via co-controls or integrated measures that simultaneously reduce greenhouse gas (GHG) emissions and criteria air pollutant emissions. Options to meet these targets are evaluated through a co-control framework to provide detailed information on approaches for reduction of emissions. The framework examines existing policies, measures and technologies including measures consistent with China's 2007 National Climate Action Plan.

This research utilizes existing tools and analytical frameworks already established for China and conduct an analysis of the expected co-benefits of adopting a range of different strategies for meeting the 20% energy intensity reduction, 10% reduction in SO_2 emissions, and the 40-45% carbon intensity reduction goals by 2020. This research focuses on strategies to meet these goals as well as evaluating the potential for co-control strategies to 2030.

The specific objectives include:

- Provide meaningful input to the implementation regulations and activities for China's various targets for energy intensity, carbon intensity and SO_2 emission control.
- Provide meaningful input on integrated planning, integrated measures, and co-controls to support future Five Year planning efforts.
- Conduct a detailed analysis of various co-control measures.
- Identify integrated energy (energy efficiency, fuel substitution, clean energy) and provide environmental policy implications to support the goals through the use of co-control measures.
- Provide analytical results that support and inform the appropriate implementing/regulatory agencies to work jointly to implement CO_2/SO_2 co-control measures.

The primarily analytical tool used in this study was an accounting framework of China's energy and economic structure, built using the Long-Range Energy Alternatives Planning (LEAP) modeling software. Over the past seven years, LBNL has established and significantly enhanced the China End-Use Energy Model based on the LEAP modeling software which focuses on the diffusion of end-use technologies and other physical drivers of energy demand. This model presents an important new approach for helping understand China's complex and dynamic drivers of energy consumption and the implications of energy efficiency and emission mitigation policies through scenario analysis. The model has been used as the framework for this study.

2. Methodology

Typically, an assessment of energy demand, supply, and emissions can be undertaken using either a so-called “bottom-up” or “top-down” approach. The *bottom-up approach* focuses on individual technologies for delivering energy services, such as household appliances and industrial process technologies. The *top-down* method assumes a general balance or macroeconomic perspective, wherein costs are defined in terms of changes in economic output, income, or GDP. Each approach captures details on technologies, consumer behavior, or impacts that the other does not. Ideally, a comprehensive assessment would combine elements of each approach to ensure that all relevant impacts are accounted for and that technology trends and policy options for reducing energy consumption or mitigating climate change are adequately understood.

The methodology used in this report is based on a bottom-up approach which allows for detailed consideration of technological development—industrial production, equipment efficiency, power sector efficiency, etc. —as a way to evaluate China’s energy and emission reduction development path below the level of its macro-relationship to China’s economic development path.

The primary analytical tool used in this study is LBNL’s China Energy-Use Energy Model which is an accounting framework of China’s energy and economic structure built using the Long-Range Energy Alternatives Planning (LEAP) modeling software. The model consists of both the energy consumption sector and the energy production sector (transformation sector) including:

- residential buildings,
- commercial buildings,
- industry,
- transportation,
- agriculture, and
- transformation.

Key drivers of energy use include activity drivers (total population growth, urbanization, building and vehicle stock, commodity production), economic drivers (total GDP, income), energy intensity trends (energy intensity of energy-using equipment and appliances). These factors are in turn driven by changes in consumer preferences, energy and technology costs, settlement and infrastructure patterns, technical change, and overall economic conditions.

The study focuses on the co-control of CO_2 and SO_2 emissions from a base year of 2005 to 2030. CO_2 emissions result primarily from energy consumption of fossil fuels, as well as from non-energy industrial processes (like cement production), and forest loss. This report focuses on CO_2 emissions from energy use, but also includes process emissions from cement manufacturing. The report also focuses on the electricity, steel, and cement sectors due to their importance vis-à-vis the economy, energy use, and emissions.

Sectoral energy consumption data are available in published statistics. China's energy statistics were used to develop a time series of primary energy use (included the losses that occur in the transformation sector). After building the model from the bottom-up, the data were calibrated by comparing the energy consumption results with the statistical data for the base year (top-down). Detailed description on methodologies and further end use breakdowns could be found in an earlier study (Zhou et al. 2007).

For SO_2 emissions, current emissions and SO_2 control technologies by key sectors evaluated in the report were obtained through literature review and calibrated against the statistics. Information on current SO_2 technologies commonly used in these sectors, with detailed description, removal rate and energy use were complied based on existing research and are presented in the Appendix. Due to a lack of data, cost-effectiveness is not covered comprehensively in this report, but rather information on costs is included and used to make informed decisions related to technology choices where possible.

A baseline Continued Improvement (CI) scenario and an accelerated energy efficiency (AEE) scenario were developed for the power, cement, and iron and steel sectors to assess the impact of actions already taken by the Chinese government as well as planned and expected actions, and to evaluate the potential for China to control energy demand growth and mitigate emissions. In addition, CO_2 mitigation scenarios and SO_2 control scenarios were also established to evaluate the impact of each of the measures and the combined effects. Building upon the results of the individual scenarios, co-control scenarios were also developed to assess the optimal strategies to control both CO_2 and SO_2 emissions simultaneously. A description and details of these scenarios are elaborated in the sectoral analyses of each of the three sectors.

In addition, a carbon capture and sequestration (CCS) scenario was also constructed to evaluate the potential impact of further decarbonization of the power sector, and the implication on CO_2 and SO_2 emissions from the CCS application.

3. Key Drivers of the Energy Consumption and Emissions

3.1 Macroeconomic Drivers

One of the key drivers for the bottom-up modeling and scenario analysis is the urbanization rate and growth of the urban population. As a developing country, China will continue to undergo changes in its physical built environment as a result of rapid urbanization. For example, China added 290 million new urban residents between 1990 and 2007, and 380 million new urban residents are expected from 2007 to 2030. All the new urban residents need to be provided with housing, energy, water, transportation, and other energy services. Urbanization and the related demand for infrastructure and residential energy services will therefore be important driving forces for future energy consumption in China. The urbanization rate used in this report is projected to increase to 70% in 2030 from 45% in 2007 (see Figure 1).

Figure 1 Historical and Projected Population and Urbanization Trends

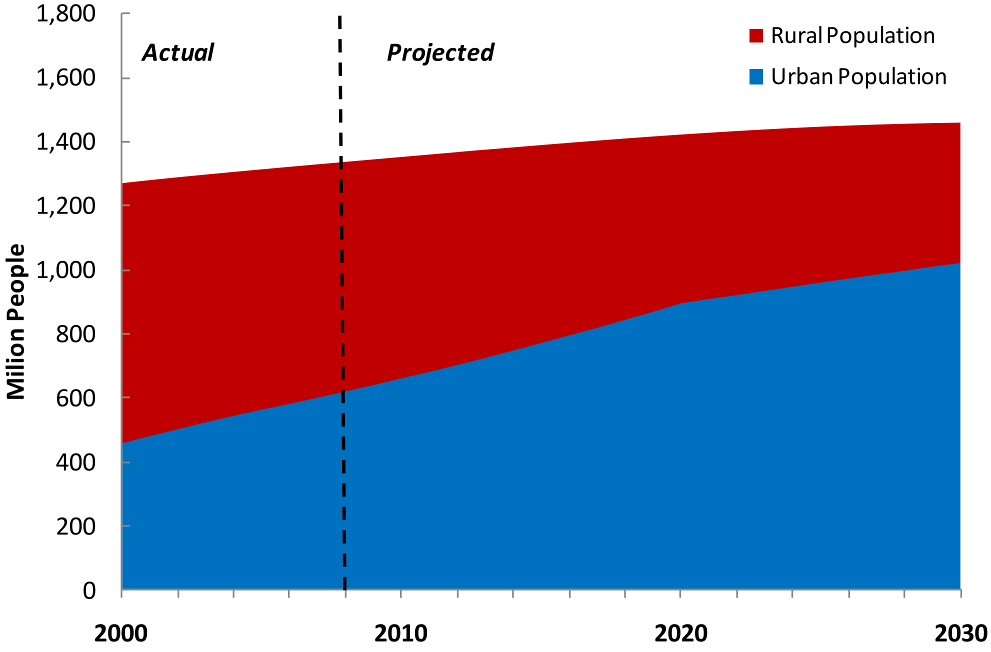


Table 1 provides information on the macroeconomic parameters such as population, urbanization, and economic growth rates are assumed to be the same for each scenario developed for this study. China's population is assumed to grow from 1.31 billion in 2005 to 1.46 billion in 2030 (UN 2009).

Urbanization is expected to be a major force shaping China's development and energy pathways. The addition of new mega-cities and second-tier cities will drive commercial and residential demand for energy services and infrastructure development, as well as spur inter- and intra-city passenger transport activity. For this study, it is assumed that the urbanization rate of 43% in 2005 increases to 70% in 2030 (ERI 2009).

International experience and China's recent experience with economic development highlight the important linkages between industrialization and rising energy demand, particularly in the industrial and transport sectors that fuel GDP growth. China's economy grew at a rate of 9.4% per year between 2000 and 2010. Fast GDP growth is expected to continue for the next decade, but will gradually slow by 2020 as the Chinese economy matures and shifts away from industrialization. Thus, this report assumes that GDP growth will be 7.7% for the period between 2010 and 2020 and 5.9% for the period between 2020 and 2030.

Table 1 Key Macroeconomic Parameters for All Scenarios

	2005	2030
Population	1.31 Billion	1.46 Billion
Urbanization Rate	43%	70%
GDP Growth		
2000-2010	9.4%	
2010-2020	7.7%	
2020-2030	5.9%	

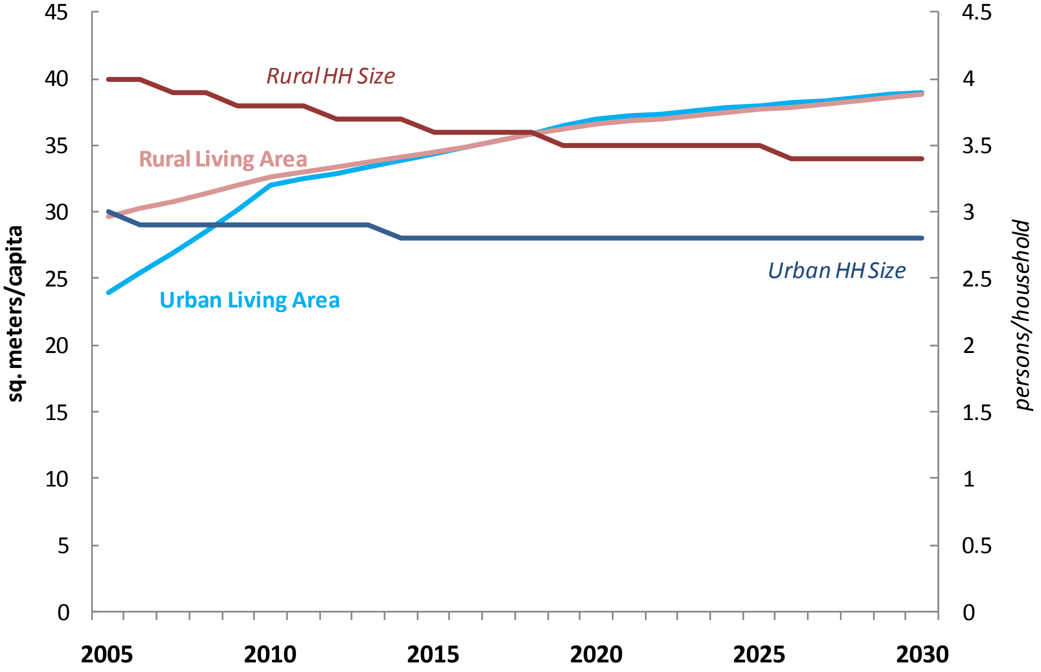
3.2 Key Drivers in the Residential Buildings Sector

There are two key drivers of growth in the residential buildings sector: urbanization and growth in household incomes. Population growth is not a main driver of energy consumption in China per se as population growth has slowed, and total population is expected to peak between 2020 and 2030. However, China has been experiencing extremely rapid urbanization in recent years, and this trend is expected to continue with urban households generally consuming more energy than rural households, especially forms of energy that are not based on biomass. Therefore, urbanization is a very significant driver of overall residential sector energy demand growth. In addition, incomes are rising for both urban and rural households. The main impacts of household income growth are an increase in the size of housing units, which in turn increases the heating and cooling load and lighting. Increased incomes also correspond to increased ownership and use of energy-consuming appliances.

Globally, household size tends to decline with increasing income and urbanization. In the case of China, the "One Child Policy" enforced such a decline particularly rigorously with average household size in China dropping from 5.2 persons per household in 1981 to 3.16 persons per household in 2008 (Figure 2). This trend is expected to continue, with urban household size decreasing from 3.13 persons/household in 2000 to 2.80 persons/household in 2020, the size of Japanese households today, then declining at a slower rate to 2.75 persons/household in 2030. It is also assumed that rural household size will decline at a slightly faster rate from 4.2 persons/household in 2000 to 3.4 persons/household in 2030.

In developed countries, the average household floor space per person has been gradually increasing since at least the early 1970s. Similarly, in China, floor space per person increased from 13.7 m^2 in 1990 to 24 m^2 in 2008 in urban residences and from 17.8 m^2 to 32.4 m^2 in rural residences. In 2030, urban residences are assumed to continue to grow in floorspace to 39 m^2 per capita while rural residences will have 38.8 m^2 per capita. The decline in household size leads to an increase in the total number of households which, together with the increase in living area, will multiply the contribution of energy demand from households.

Figure 2 Historical and Projected Residential Living Area and Household Size

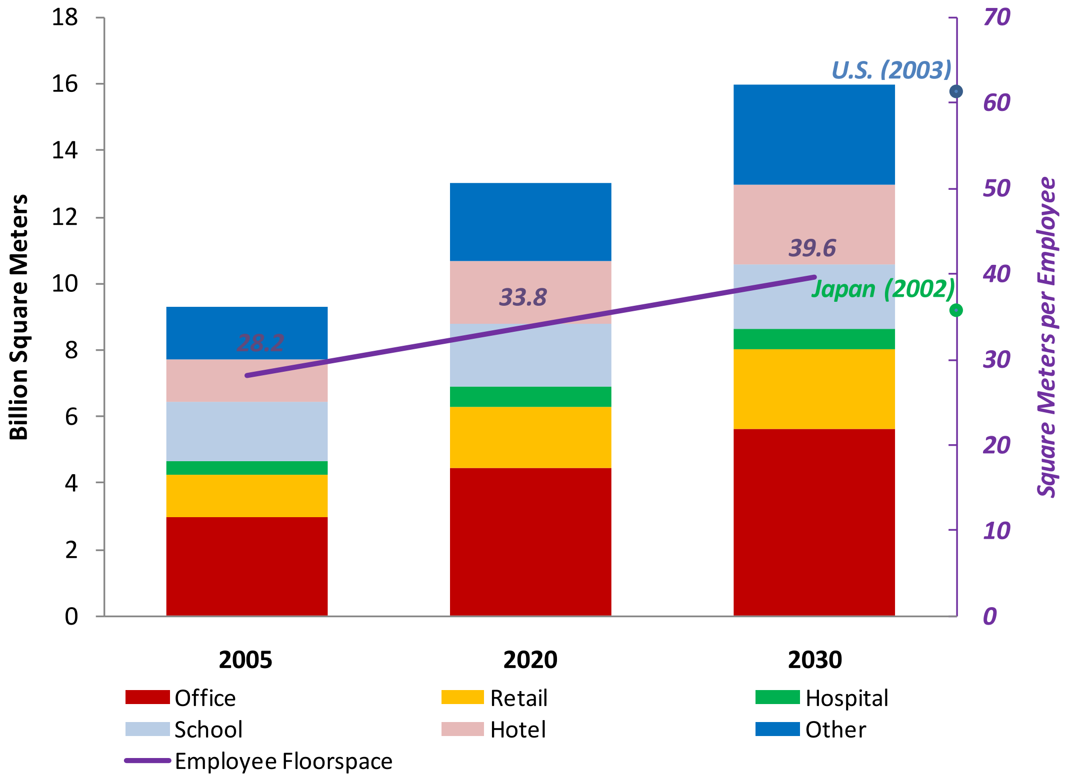


3.3 Key Drivers in the Commercial Buildings Sector

Commercial building energy demand is the product of two factors: building area (floor space) and end use intensity (MJ per m^2). Forecasting commercial building floor space demands an understanding of the drivers underlying recent growth of the sector, and where these trends are likely to be heading. In simple terms, commercial floor space is determined by the total number of service sector employees and the amount of built space per employee. Commercial building construction in China is driven by the expansion of the services sector. According to national statistics, the share of Chinese workers employed in the tertiary/service sector increased from 27% in 2000 to 32% in 2006, a relative increase of 19% in just 6 years. When these values are corrected to include the number of unregistered workers likely to be working in urban service-sector businesses, the current share is already estimated to be 43%. In general, as economies develop, employment shifts away from agriculture and industry toward the service sector. This trend is expected to continue in China, leading to further increases in commercial building floor space. The potential for growth is not unlimited, however, as the Chinese population is expected to peak by about 2030. Furthermore, China's aging population also suggests that the number of employees will peak closer to 2015.

By comparing Chinese GDP per capita to that of other countries, it is estimated that the percentage of workers in the tertiary sector will reach 60% by 2050. Under these assumptions, the total number of tertiary sector employees will increase by only about 33% by 2030 compared to 2005. Floor space per employee has some room to grow: an increase of about 25% by 2030 is forecast.

Figure 3 Commercial Floor Space Change



3.4 Key Drivers in the Industrial Sector

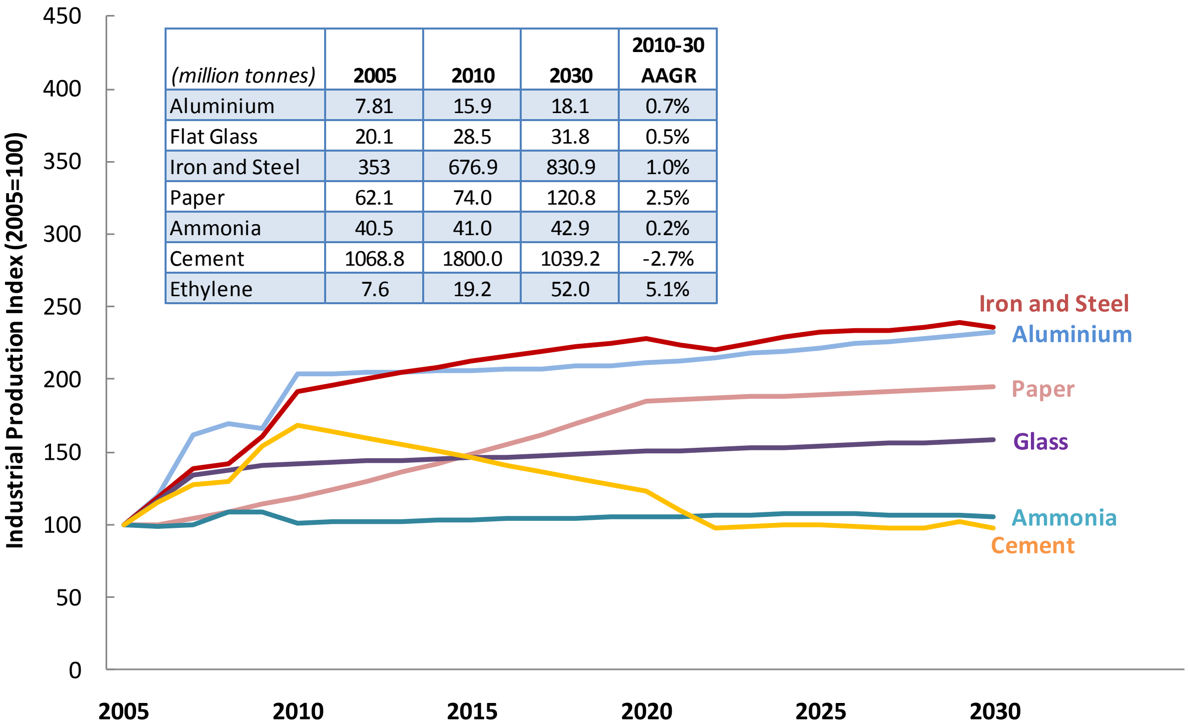
The China Energy-Use Energy Model includes seven energy-intensive industrial sub-sectors: cement, iron and steel, aluminum, ammonia, ethylene, paper and glass in addition to an "other industry" category. The analysis presented in this report focuses on the steel and cement industries.

For steel and cement, the model uses major physical driver relationships for the built environment requirements of China's growing urban population, with floor space construction area used as a proxy. For each sub-sector, projections of process efficiency requirements and technology shift for materials production were developed.

Overall, the steep rise in industrial output that China has experienced from 2002 to 2009 is not expected to continue. For all scenarios, the output of energy-intensive products such as cement and chemicals are assumed to mostly likely level off in earlier years, while others such as steel, aluminum and glass production will increase with an average growth rate of around 3% until 2020 and start leveling off or declining thereafter. Ethylene stands out as an exception based on the assumption that China will reach Japan's 2007 primary plastics demand per person by 2025. In addition, the surge in growth of ethylene demand assumes that China will be largely self-sufficient in ethylene production—unlike today—and that imports will be no higher than in 2008.

In the case of cement production, future projection is derived based on the amount of cement required to construct China's urban and rural buildings, Class I and II highways and expressways and urban paved areas and new railway track. This methodology takes into account growing commercial and residential building construction demand as well as targeted expansion of urban paved areas, highways and rail track. Based on the assumptions and methodology described above, all scenarios expect cement production to rise from 1.36 billion tonnes in 2007 to 1.8 billion tonnes in 2010 and then begin slowing and declining from 2010 onwards.

Figure 4 Selected Industrial Production Projection and Drivers



(million tonnes)	**2005**	**2010**	**2030**	**2010-30 AAGR**
Aluminium	7.81	15.9	18.1	0.7%
Flat Glass	20.1	28.5	31.8	0.5%
Iron and Steel	353	676.9	830.9	1.0%
Paper	62.1	74.0	120.8	2.5%
Ammonia	40.5	41.0	42.9	0.2%
Cement	1068.8	1800.0	1039.2	-2.7%
Ethylene	7.6	19.2	52.0	5.1%

3.5 Key Drivers in the Transportation Sector

Transportation demand is driven by demand for both passenger and freight transport. Freight transport is calculated as a function of economic activity measured by value added GDP while passenger transport is based on average vehicle-kilometers traveled by mode (e.g., bus, train, car) of moving people. In the model, freight transport demand is driven by faster economic growth in the earlier years as GDP is expected to continue its recent rapid growth with international trade continuing to play an important role in coming years. In later years, however, road freight growth is slowed to a linear function as the relative importance of foreign trade in GDP is expected to decline. The important roles of both domestic and international freight transport demand is reflected in two major modes of freight transport: water and rail transport. Water transport includes growing international ocean transport as well as domestic coastal and inland transport while demand for road freight transport reflects primarily high demand for domestic freight transport with doubling rail freight intensity.

For passenger transport, growing vehicle-kilometers traveled in different modes is driven by population growth and growing demand for personal transport with rising income levels. Air transport activity growth, for instance, is driven by growing demand for both domestic and international travel in terms of rising per capita passenger-km. Similarly, passenger rail transport activity is also expected to rise with growth of high-speed rail and increased use of rail for short distance domestic travel. The largest mode of passenger transport is in road transport, which is driven primarily by the burgeoning ownership of private cars that follows rising per capita income (Figure 5). Personal car ownership is forecasted on a per-household basis by relating current car ownership rates around the world to household income, with a slight adjustment for the fact that current Chinese personal car ownership is low even compared to countries of similar income. By 2030, personal car ownership reaches 0.34 per household, which while extremely high compared to current values, is still considerably below current levels in the United States and Europe. As personal income and private car ownership rises, motorcycle and taxi passenger transport plateaus after 2020.

Figure 5 Passenger Road Transport Stock

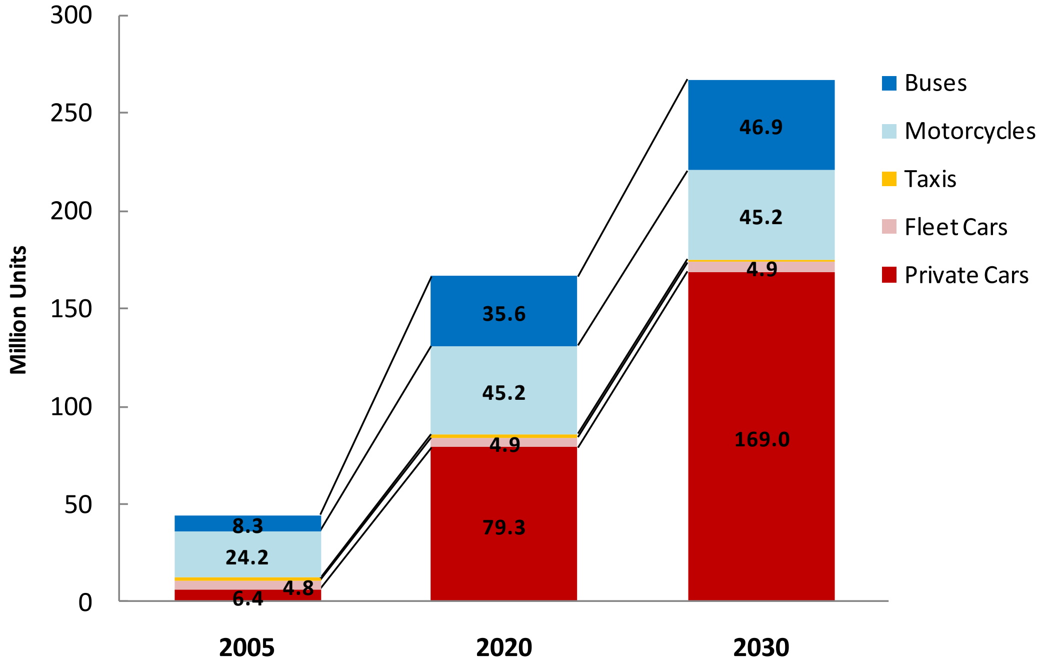
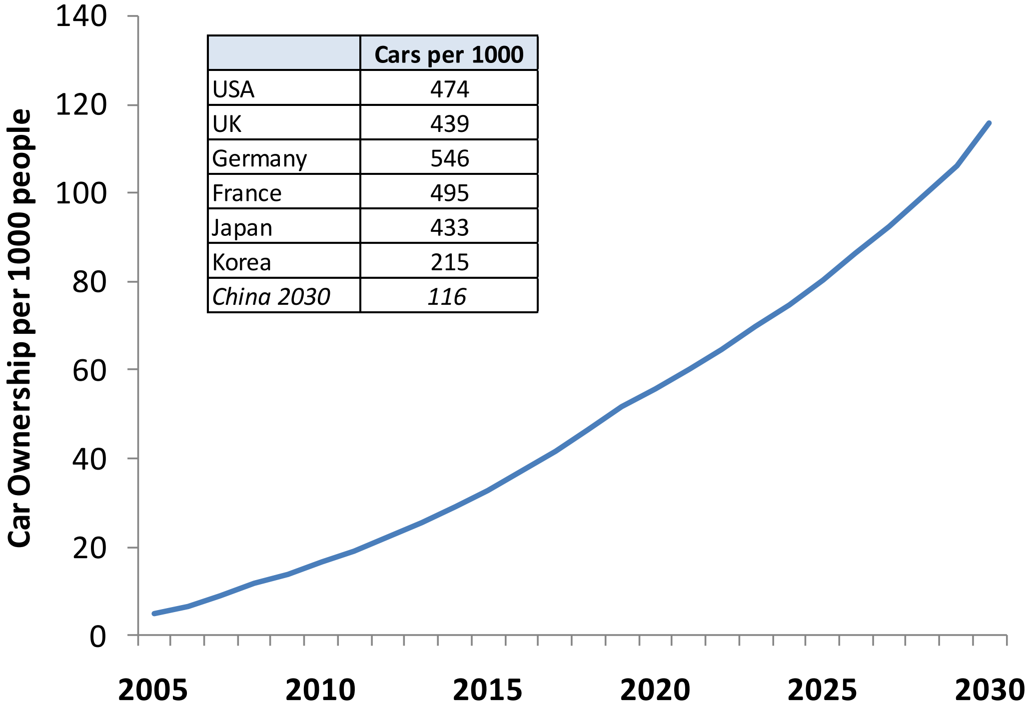


Figure 6 Projected Car Ownership Trends



	Cars per 1000
USA	474
UK	439
Germany	546
France	495
Japan	433
Korea	215
China 2030	*116*

Source: International data from World Bank Development Indicators, 2003.

4. Aggregate Model Results

LBNL's China Energy-Use Energy Model uses a bottom-up, physical-based approach to quantifying electricity supply, generation efficiency, dispatch, transmission and distribution, and final demand. Reported electricity data from the China National Bureau of Statistics and the State Electricity Regulatory Commission were used to calibrate 2005 base year values. Scenario analysis was extended through 2030 and energy data were used to separately calculate related carbon dioxide emissions. The model uses generation dispatch algorithms, efficiency levels, and capacity factors to calculate the amount of capacity required to serve a given level of final demand.

4.1 Total Primary Energy Use

Under the frozen scenario where energy intensity is frozen at the 2005 base year level of 1.19 kgce per US $ through 2030, total primary energy use would rise at annual average rate of 8.1% until 2020 before slowing down to an annual average rate of 5.7% through 2030 (Figure 7). In contrast, under the reference scenario which incorporates China's current and planned energy efficiency policies, the energy use only rises at 4.5% per year until 2020 and then slows down to 1.5% per year through 2030. This implies a total of over 67 billion tonnes of coal equivalent could be saved between 2005 and 2030 from what China is doing and planning to do, which already requires significant effort.

Figure 7 Total Primary Energy Use for Frozen vs. Reference Scenario

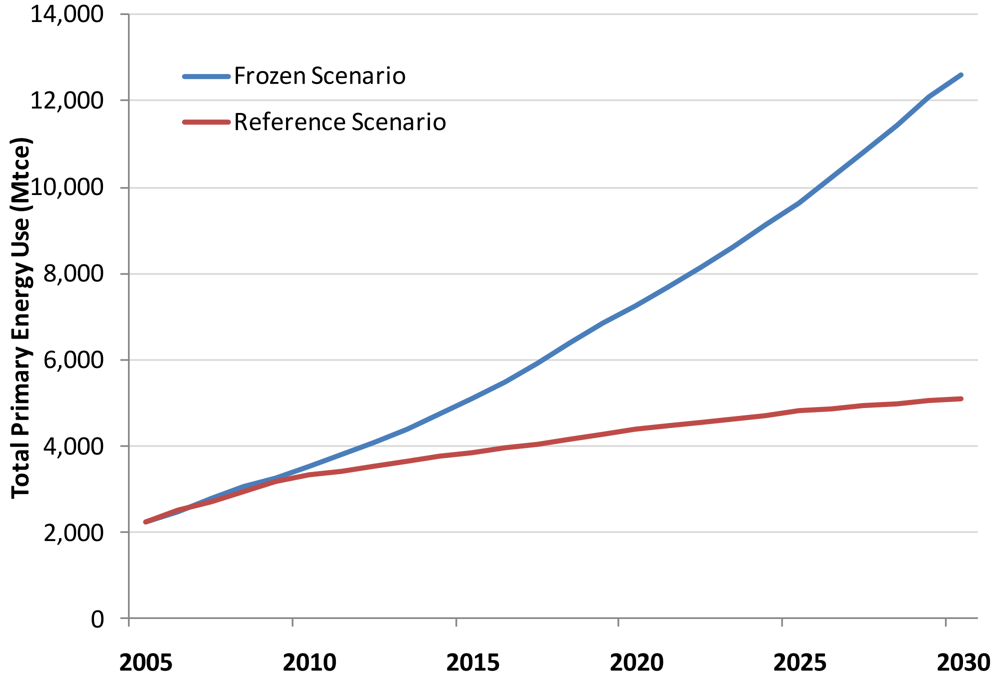
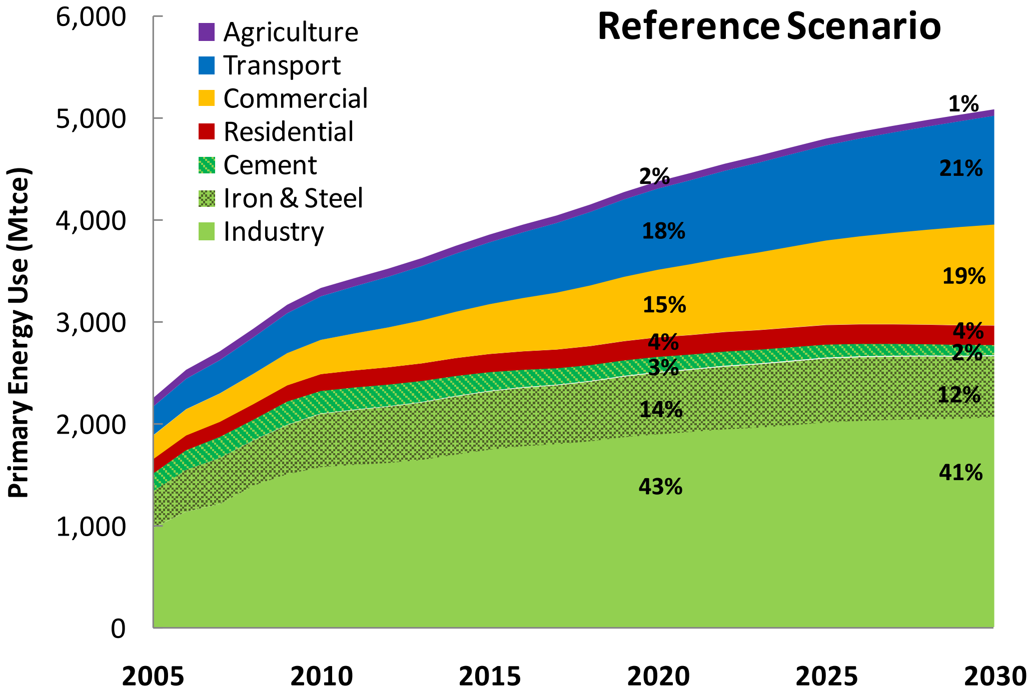


Figure 8 shows that under the reference scenario, the industrial sector (indicated in green and green hashed areas) has the largest but slowly declining share of primary energy consumption, with 60% in 2020 and 55% in 2030. Of this, the iron and steel and cement subsectors together are responsible for a quarter of all industrial energy use, with 12% and 2% shares of total primary energy demand in 2030, respectively. The commercial buildings and transport sectors both have rising shares of primary energy demand with growing demand for the built environment, energy services, and transport to accommodate the needs of the expanding urban population.

Figure 8 Total Primary Energy Use by Sector for Reference Scenario



4.2 CO_2 Emissions

CO_2 emissions under the frozen scenario in which there is no fuel switching or efficiency improvements in generation from 2005 onwards (i.e., frozen carbon intensity in terms of kg CO_2 per kgce) rises at much faster growth than the reference scenario, which has some fuel switching and efficiency improvements in coal-fired generation (Figure 9). As a result, China’s total CO_2 emissions under a frozen scenario could be more than three times higher than if it were to continue its current portfolio of policies and pace of technological deployment. By 2030, CO_2 emissions could reach over 30 gigatonnes CO_2 ($GtCO_2$) under the frozen scenario compared to nearly 11 $GtCO_2$ under the reference scenario. In cumulative terms, this translates into a total reduction potential of 181 $GtCO_2$ emissions between 2005 and 2030 under the reference case.

When look at the total CO2 from its Source, Under the reference scenario, industry is responsible for more than half of the total CO_2 emissions, followed by commercial and transport sectors (Figure 10). The iron and steel subsector, in particular, is responsible for 15% of national CO_2 emissions in 2030 compared to total industrial share of 56%. As with primary energy use, while the industrial share declines over time, the transport and commercial shares of total CO_2 emissions rise quickly after 2010.

However, when look at the emissions from where it occurs, then power sector accounts for close to 40% of the total CO2 emission in 2010, and these share will decline over time owning to the decarbonization of the power sector (Figure 11).

Figure 9 Total CO_2 Emissions for Frozen vs. Reference Scenario

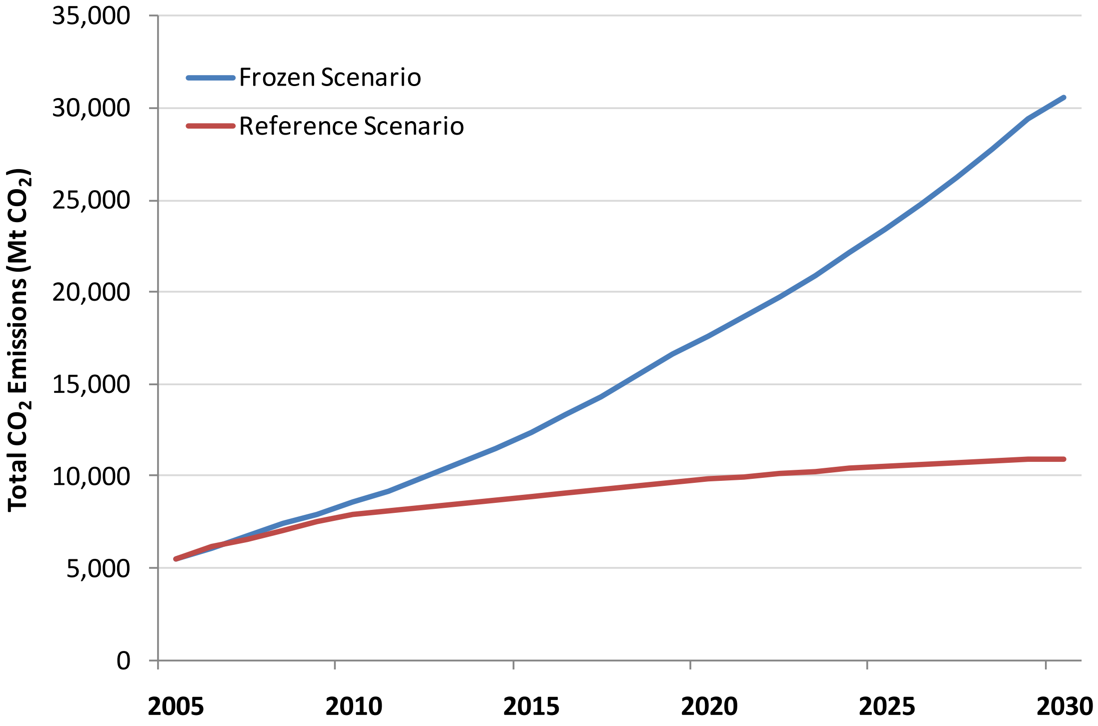


Figure 10 Total CO_2 Emissions Allocated to Demand Sector for Reference Scenario

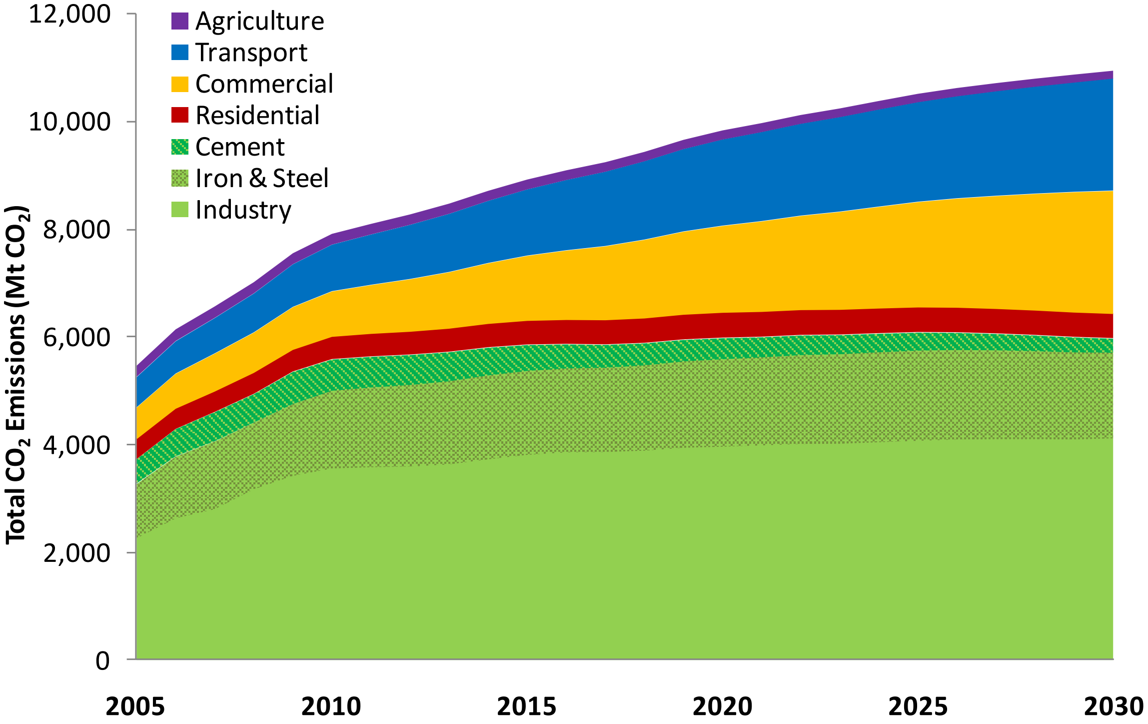
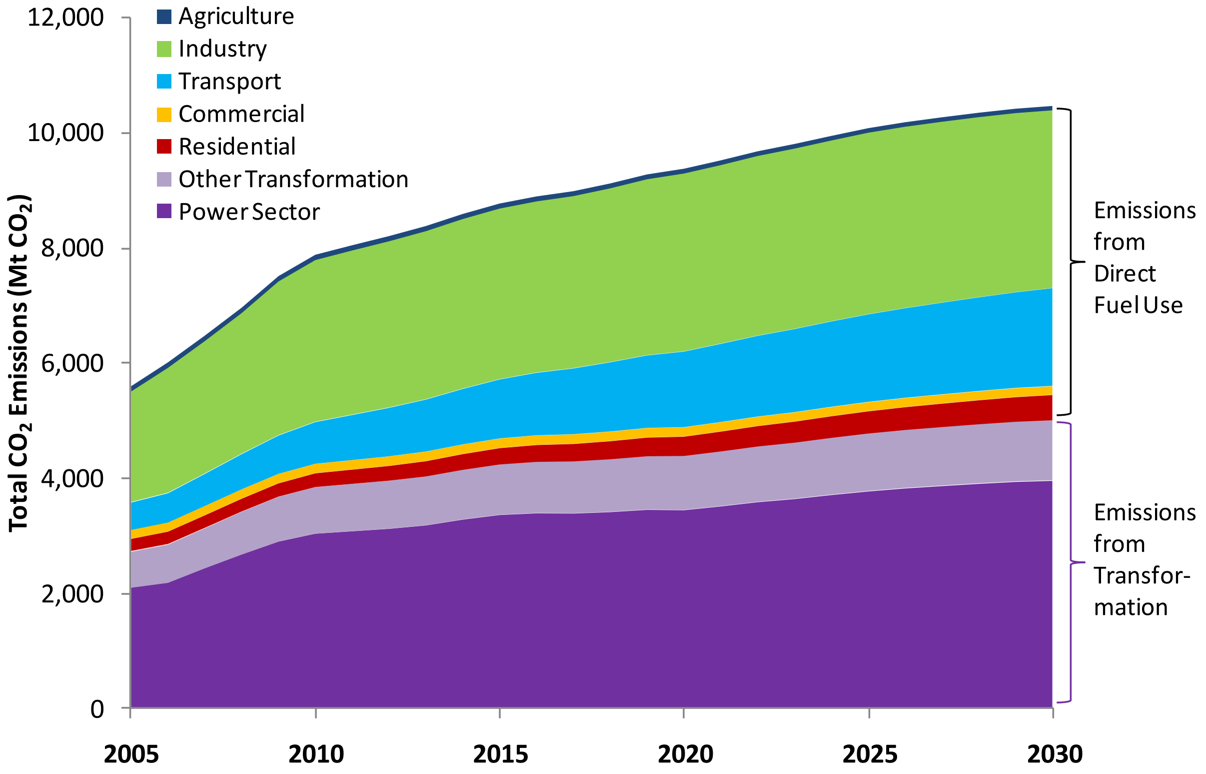


Figure 11 CO_2 Emissions by End-use and Transformation Sectors



4.3 SO_2 Emissions

Unlike CO_2 emissions, SO_2 emissions will decline over the next two decades at annual average rates of -1% to -2% with declining direct use of coal and shift towards electricity for providing energy services. This is particularly evident in the residential sector, which has declining SO_2 emissions as a result of declining direct use of coal and coke but rising electricity demand (Figure 14). The majority of SO_2 emissions in the commercial and residential sectors are from electricity use, with 100% and 59% in 2030, respectively. Despite decreasing absolute SO_2 emissions, the industrial sector still has the largest share of SO_2 emissions, with total industrial consumption of 13 Mt SO_2 in 2030 under the reference scenario. Of this, the iron and steel subsector has the largest share at 30% of total industrial emissions or 2.82 Mt SO_2 emissions in 2030. However, when look at the emissions from where it occurs, then power sector accounts for over 46% in 2010, and will only be 21% in 2030 (Figure 13).

Figure 12 Frozen vs Reference Scenario SO_2 Emissions

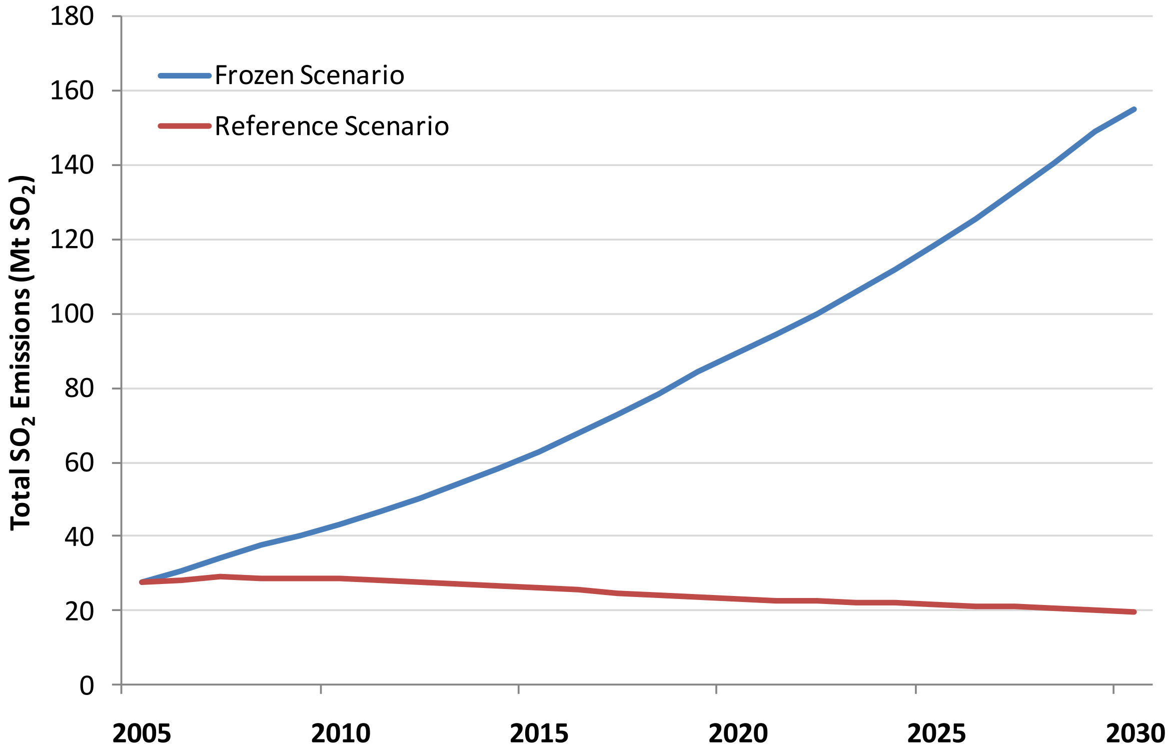


Figure 13 Total SO_2 Emissions by End-use and Transformation for Reference Scenario

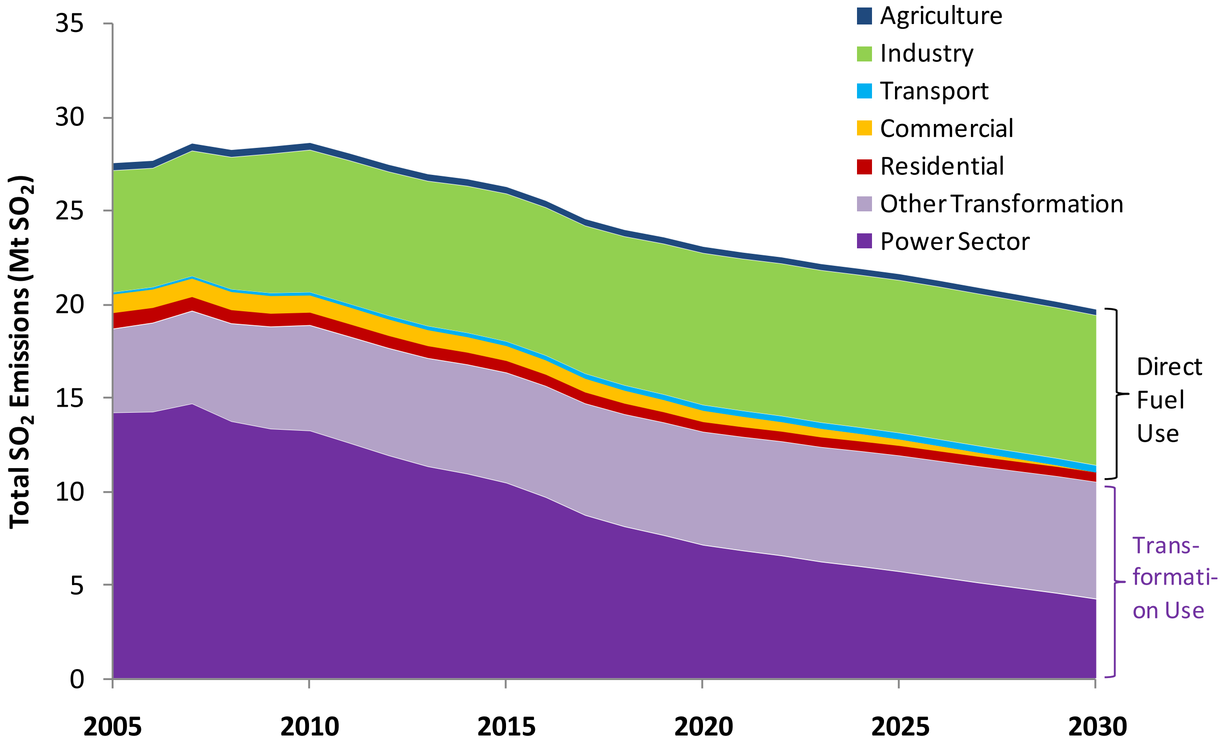
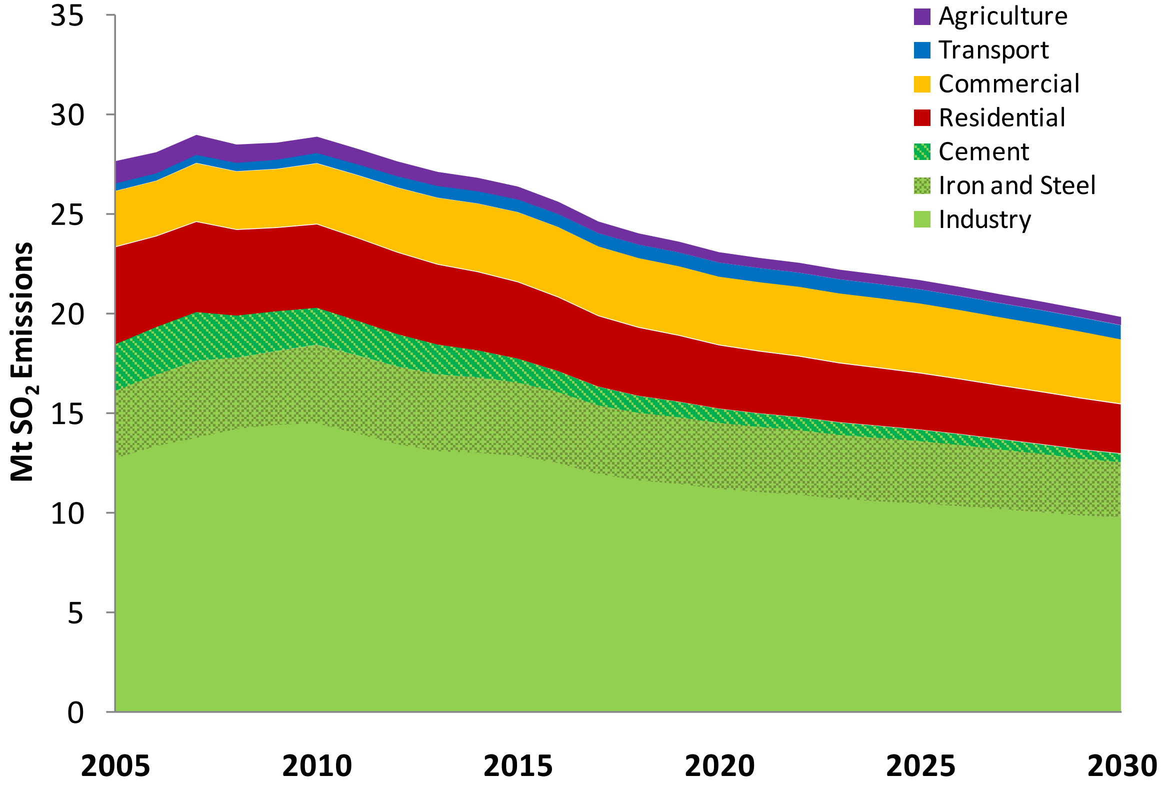


Figure 14 Total SO_2 Emissions Allocated to Demand Sector for Reference Scenario



5. Power Sector

Six scenarios were developed for the power sector to evaluate the potential and impact of the primary energy consumption and carbon emissions mitigation. The reference scenario / CI incorporates published Chinese government targets for non-fossil capacity growth as well as ongoing efficiency improvements and restructuring of small or out-of-date plants. The improvements in the coal generation efficiency scenario assume more aggressive improvements in the overall efficiency of coal-fired generation by concurrently retiring inefficient smaller generation units and adopting more efficient supercritical and ultra-supercritical units. Three additional scenarios are used to examine the different impacts of accelerating the installed capacity and utilization of non-fossil fuel generation including renewable power (solar and wind), hydropower and nuclear generation. The Carbon Capture and Sequestration (CCS) scenario examines the impact of installing sufficient capacity to capture and sequester 230 $MtCO_2$ in 2030 based on the China 450 ppm scenario in the 2009 World Energy Outlook (IEA 2009).

Table 2 CO_2 Mitigation Scenarios of Power Sector Development

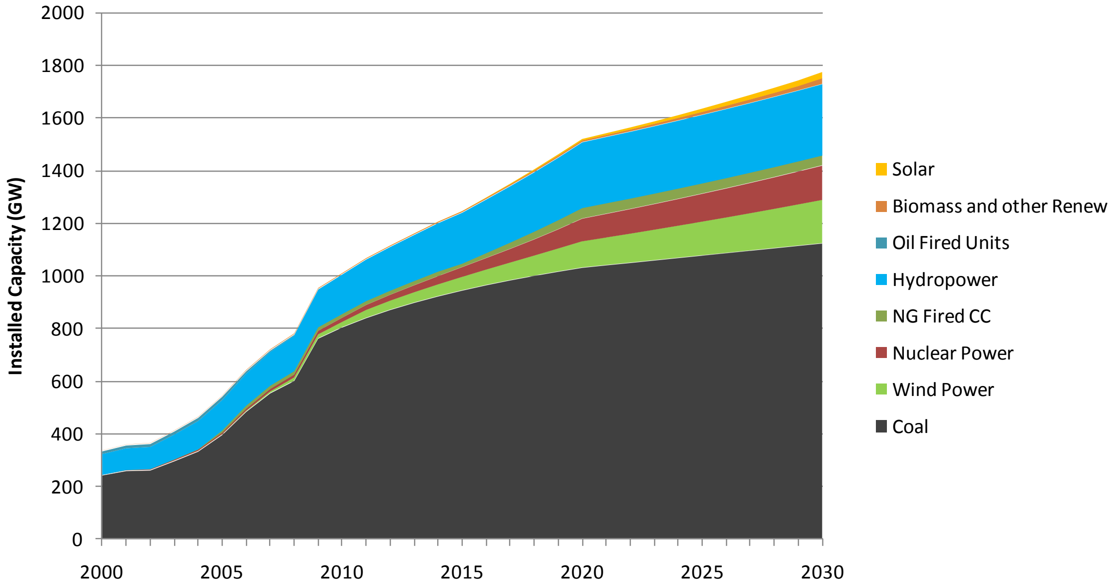
Scenario	Key Focus	2030 Primary Energy Requirement	2030 Power Sector CO_2 Emissions	2030 Power Sector SO_2 Emissions	2020 Installed Capacity	2030 Installed Capacity
Reference	Continuing efficiency improvements and fuel shifting	2066 Mtce	4127 Mt CO_2	4.60 Mt SO_2	Solar: 6 GW Wind: 100 GW Nuke: 86 GW Hydro: 250 GW	Solar: 24 GW Wind: 165 GW Nuke: 130 GW Hydro: 270 GW
Reference with CCS	Capture and sequestration of 500 Mt CO2 emissions by 2050	2109 Mtce	3902 Mt CO_2	6.95 Mt SO_2	Same as Reference	Same as Reference
Improvements in Coal Generation Efficiency	Accelerated retirement of small inefficient coal-fired units and adoption of ultra-critical and super-critical units	2047 Mtce	4138 Mt CO_2	4.86 Mt SO_2	Same as Reference	Same as Reference
Accelerated Renewable Generation	Accelerated solar and wind capacity	2026 Mtce	3949 Mt CO_2	4.32 Mt SO_2	Solar: 10 GW Wind: 135 GW	Solar: 24 GW Wind: 250 GW
Expanded Hydropower Generation	Greater hydropower capacity	2030 Mtce	3968 Mt CO_2	4.35 Mt SO_2	Hydro: 300 GW	Hydro: 330 GW
Expanded Nuclear Generation	Faster expansion of nuclear capacity after 2020	2066 Mtce	3948 Mt CO_2	4.32 Mt SO_2	Nuclear: 86 GW	Nuclear: 160 GW

Table 2 summarizes key aspects of the six power sector CO_2 mitigation scenarios. The third column shows the total primary energy requirement for the power sector in each scenario, expressed in terms of million tonnes of coal equivalent (Mtce). The fourth and fifth columns show the CO_2 and SO_2 emission implications of each scenario; this is discussed in more detail in the results section. Due to the higher energy requirement for carbon separation, pumping, and storage, the CCS scenario has the highest primary energy requirement and thus the highest SO_2 emissions but the lowest CO_2 emissions. The last two columns show the modeled 2020 and 2030 installed capacity for reference.

5.1 Reference Scenario

The reference scenario extrapolates existing policy and market-driven fuel switching and efficiency improvement trends to 2030. Figure 15 shows that renewable fuels (wind, biomass, and solar) increase their share of total installed capacity from less than 1% in 2009 to 7% in 2020 and 12% in 2030. By 2030, the reference scenario includes 165 GW of wind capacity, 22 GW of biomass, and 24 GW of installed solar capacity. Non-fossil fuels (renewable plus hydro and nuclear power) increase their share of total from 29% in 2020 to 34% in 2030.

Figure 15 China CIS Electricity Generation Capacity, 2000-2030



Not all of the generation capacity will be fully utilized. Under the reference scenario, fossil fuels have the highest capacity factors at 90%, followed by nuclear. Hydro, and renewable fuels have much lower capacity factors, as shown Table 3. In addition, in order to focus on fuel switching and efficiency improvements, the model uses merit order rather than economic or equally-distributed generation dispatch. As a result, the generation sources that are on the bottom of the priority order may not be fully utilized. In the reference scenario, it is assumed that the nuclear and renewable energy sources will be dispatched first for the decarbonization of the power sector, and coal will be dispatched last. Thus, the actual capacity factor will be lower than 90% when demand can be satisfied with other fuels. The intermittency of renewable electricity generation is reflected in their lower capacity factors.

Table 3 Reference Scenario Modeled Capacity Factors by Fuel

	Wind	Nuclear	Hydro	Biomass	Solar	Coal
Capacity Factor	30%	88%	39%	25%	19%	90%

Aside from fuel switching, the reference scenario features efficiency improvements in generation, transmission, and end-use. The average generation efficiency of nuclear power rises from 32% in 2005 to 38% in 2020 and 41% in 2030. Coal-fired power generation efficiency also rises with the continued replacement of small, out-of-date plants with state-of-the-art facilities. Transmission and distribution efficiency also continues to improve in line with China's large grid-improvement investments. For example, China's stimulus program is highly focused on modernizing the electricity grid: in 2010 the government targeted 8% of its annual budget towards grid improvement - $200 million more than federal smart grid investments in the U.S. (China Electricity Council 2010). One impact of China's large-scale grid investment is that average reference scenario transmission losses decline to 6% in 2030.

China has a stated target is to close 50 GW of power generation capacity during the 11th FYP period, from 2006 to 2010. It is estimated that if all the small coal-fired plants are replaced with large units, savings of 90 Mt of coal[1] and reductions of 1.8 Mt of SO_2 will be realized. This represents a decline of 10% and 13.5% in coal consumption and SO_2 emissions, respectively, based on 2005 data (NDRC 2007).

The closure plan focuses on small coal-fired (or oil-fired) electric power units including enterprises' self-supplied units and units for wholesale. There are five types of small units that are targeted: 1) coal-fired units with capacity under 50 MW/unit, 2) coal-fired units with capacity under 100 MW/unit that have been operating for twenty years, 3) all types of units that have completed the service duration with a capacity under 200 MW/unit, 4) coal-fired units that have a 10% higher coal consumption than the average provincial level or 15% higher than the national level, 5) all types of units that do not meet the environmental protection emissions requirements. Cogeneration plants that do not meet the local or national levels after renovation or have higher coal consumption when not supply heating should be closed as well (State Council 2007).

Table 4 below presents the up to date information on coal-fired plants annual targets, annual progress, and the aggregated capacity of closed small power plants.

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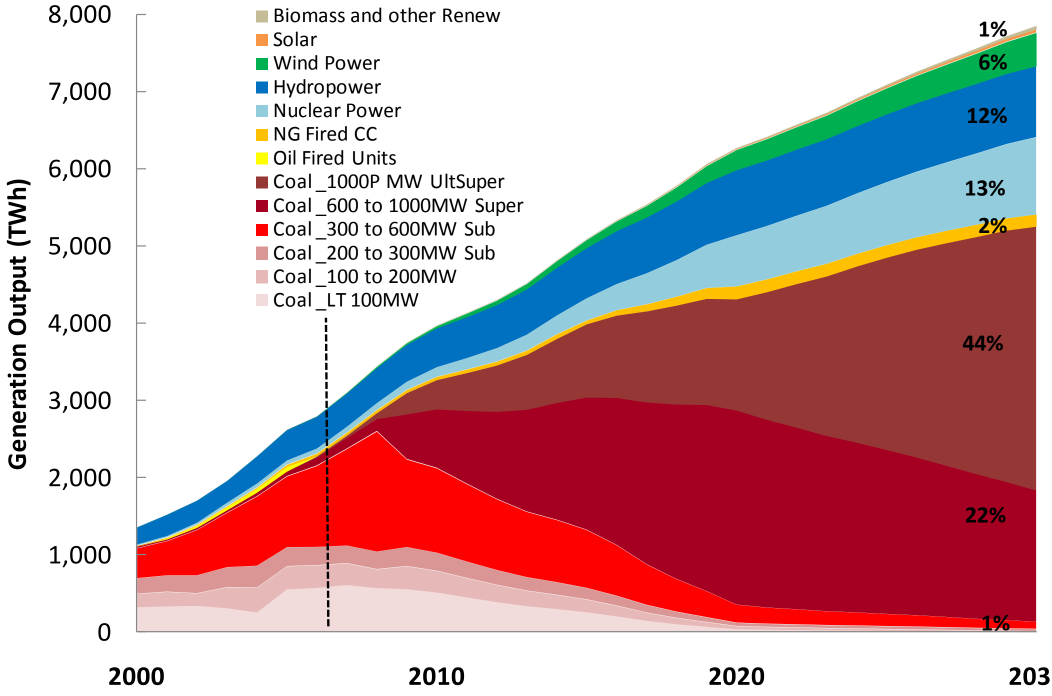
[1] This is equivalent to about 65 Mtce, assuming a conversion factor of 0.7143 kgce/kg raw coal.

Table 4 Coal-fired Power Plants Closure

Year	Targets	Closed Capacity	Aggregated Progress	Reference
2006	N/A	3.1398 GW	3.1398 GW	MEP 2009
2007	Total target for 11th FYP (2006-2010): 50GW by 2010 Target for 2007: 10 GW	14.38 GW	17.52 GW	SERC 2008
2008	Target for 2008: 13 GW	16.69 GW	34.21 GW	MEP 2009
2009	N/A	26.17 GW	60.37 GW	MIIT 2010
2010	Target for 11th FYP: 70 GW by 2010 Target for 2010: 10 GW	10.4 GW (as of July 15, 2010)	70.77 GW	People's Daily 2010

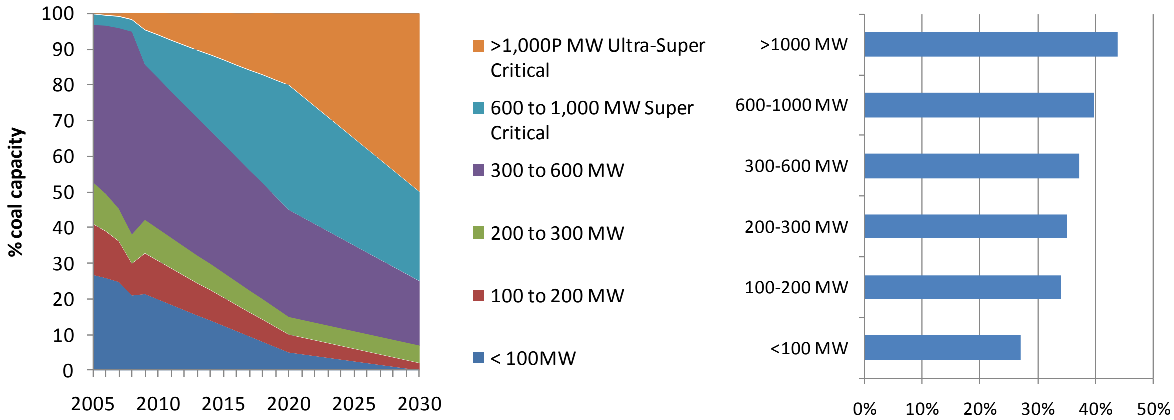
Figure 16 China Electricity Generation under Reference Scenario, 2000-2030



Actual electricity generation in the reference scenario expands at an average annual growth rate of 4%, from 2,600 TWh in 2005 to 7,900 TWh in 2030. By 2030, renewable fuels provide 7% of total generation and non-fossil fuels account for 31%, as illustrated in Figure 16. Actual generation shares are lower than installed capacity shares due to the intermittency of renewable electricity generation.

Average coal-fired efficiency improves to 323 grams coal equivalent (gce) per kilowatt-hour in 2020 and 304 gce in 2030. This is due to the increasing share of larger, more efficient plants as coal power restructuring policies continue to be implemented. Figure 17 shows the rapid increase of ultra-super critical units larger than 1 GW from less than 1% in 2005 to 50% of total installed coal capacity in 2030 with the complete phase-out of the least-efficient units with less than 100 MW capacity by 2030. Merit order dispatch is applied to coal generation technologies with the largest, most efficient units coming on-line first. Efficiency improvements are achieved through the structural shift to newer, larger-scale technologies as units larger than 1 GW have an average efficiency of 44% while those less than 100 MW are just 27% efficient.

Figure 17 China Coal-Fired Electricity Generation Technology Shares and Efficiencies under Reference Scenario, 2005-2030



In LBNL's China Energy-Use Energy Model, power sector CO_2 emissions are generated by combustion of oil and natural gas (heavy fuel oil electricity generation is completely phased out). The reference scenario's power sector emissions doubled from 2.1 $GtCO_2$ in 2005 to 4.0 $GtCO_2$ in 2030.

While the power sector share of total emissions remains fairly constant, the energy and carbon intensity of reference electricity production drop due to efficiency improvements and fuel switching. The average primary energy used to generate one kilowatt-hour drops from 330 gce in 2005 to 260 gce in 2030. Carbon intensity of electricity production is reduced from 820 grams carbon dioxide per kWh to 560 g CO_2 per kWh over the same period.

5.2 Improvements in Coal Generation Efficiency Scenario

Figure 18 shows the shift of coal-fired technology shares under the improvements in Coal Generation Efficiency scenario. Under this scenario, coal-fired electricity generation efficiency improves more aggressively with a total retirement of less-than-100 MW scale generators by 2020 and a 60% share of greater than one GW ultra-super critical plants by 2030. The aggressive shift of coal generation towards larger and more efficient plants under this scenario is reflected in the lower scenario average heat rate as seen in Figure 19.

Figure 18 China Coal-fired Technology Shares under Improved Coal Generation Efficiency Scenario, 2005-2030

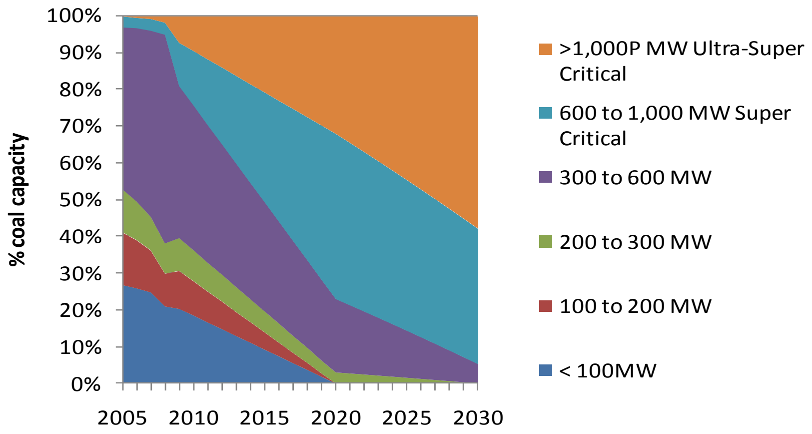
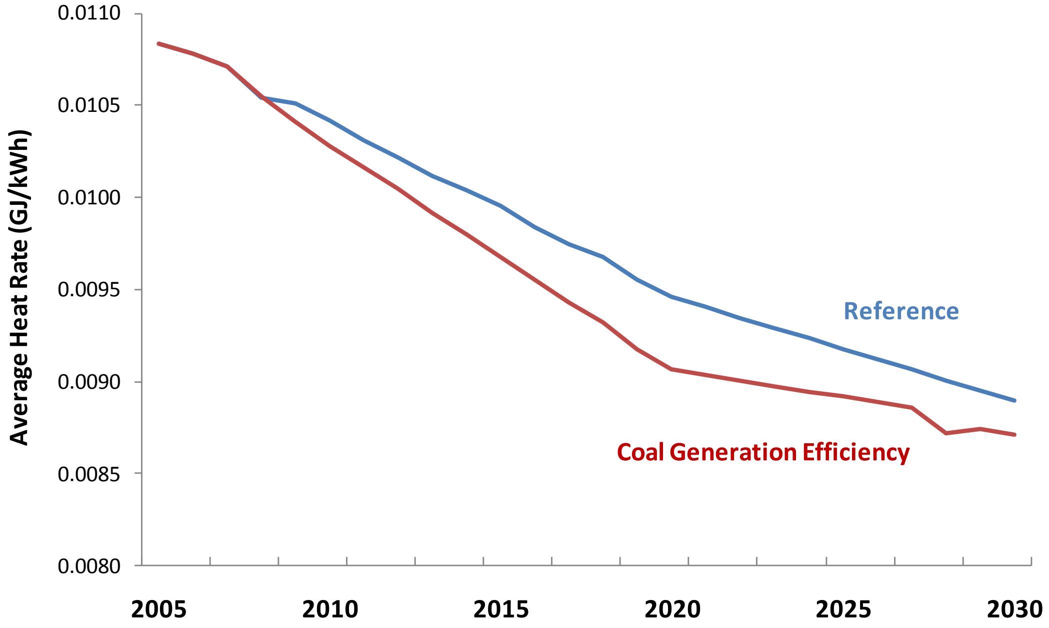


Figure 19 China Reference and Efficiency Improvement Scenario Coal-fired Fleet Average Heat Rate, 2000-2030



5.3 CO_2 Control Scenarios

5.3.1 Accelerated Renewable Generation Assumptions

Relative to the reference scenario, the Accelerated Renewable Generation scenario assumes that renewable generation will play a greater role in carbon mitigation with the installed capacity of solar and wind power increasing rapidly after 2010. In particular, solar capacity is greater with 10 GW (instead of 5 GW) in 2020 and wind capacity of 135 GW instead of 100 GW under the reference scenario. Additionally, the installed wind capacity in 2030 is 250 GW rather than 165 GW under the reference scenario.

5.3.2 Expanded Hydropower Generation Capacity Assumptions

Under this scenario, the installed capacity of hydropower is expanded by 300 GW by 2020 compared to 250 GW under the reference scenario. By 2030, this scenario assumes 330 GW of installed hydropower capacity versus 270 GW in the reference scenario.

5.3.3 Expanded Nuclear Generation Capacity Assumptions

Nuclear capacity growth through 2020 is identical to the reference scenario due to the physical building constraint limiting annual construction to no more than 13 GW of capacity per year. China's 86 GW nuclear capacity target for 2020 already requires annual capacity additions in excess of 2010 cumulative installed capacity. After 2020 however, the installed nuclear capacity grows more quickly under the expanded nuclear generation capacity scenario, reaching 160 GW in 2030, versus 130 GW in the reference scenario.

5.3.4 CCS Scenario Assumptions

Under the CCS scenario, CCS capacity is assumed to be divided between 600-1,000 MW super-critical, greater than 1 GW ultra super-critical, and integrated gasification combined cycle (IGCC) generation technologies. By 2030 pre-combustion IGCC accounts for 42% of total CCS-enabled capacity and 2% of total coal-fired capacity. This scenario also assumes that the amount of electricity required for post-combustion capture and sequestration of each tonne of CO_2 drops from 471 kWh in 2020 to 322 kWh for super-critical and ultra super-critical units in 2030, respectively.[2] This study assumes 90% capture of carbon emissions for pre- and post-combustion technologies. The additional energy requirement of CCS is calculated on the basis of the total electricity penalty per tonne CO_2 for each technology type as described above. By 2030, the CCS scenario requires 51 Mtce more primary energy than the reference scenario due to the energy requirements of carbon separation, pumping, and long-term storage. In order to supply 2030 electricity demand, the CCS scenario would also require 21 GW more coal-fired capacity, again due to the parasitic load.

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[2] Assuming CCS technology generational improvement as described in Feron (2010).

5.4 SO_2 Control Scenarios

5.4.1 Current Situation

For its 11th Five-Year Plan (FYP), China has established a national binding target of reducing 10% of SO_2 emissions by 2010 from the level of 2005. The caps on the total national SO_2 emissions and power sector SO_2 emissions by 2010 are 22.94 $MtSO_2$ and 9.517 $MtSO_2$, respectively. Power sector contributes a half of the total SO_2 emission in China, and the existing coal-fired power plants that were built before the end of 2005 are the main targets for SO_2 emission reduction. In the 11th FYP, the annual SO_2 emissions from the existing coal-fired power plants is set not to exceed 5.02 million tones, and the compliance of SO_2 emission requirements of all the existing coal-fired power plants should reach 90%. SO_2 emission intensity of coal-fired power plants by 2010 should decrease from 6.4 grams/kWh in 2005 to 2.7 grams/kWh, which means a 57.85% reduction in emission intensity. Total capacity of both installed and under-constructed desulfurization units is targeted to reach 230 GW (not including the capacity of circulating fluidized bed combustion boilers). In addition, all the small pure condensing turbines are going to be phased out, and the technology of flue gas desulfurization (FGD) shall be widely utilized. Priorities of applying FGD shall be given to medium-large cities and coal-fired plants that use high-sulfur content coal, or plants that didn't meet their SO_2 emission standards. To incentivize and facilitate the process, it is encouraged to conduct pilots of trading emission permits.

To estimate the potential of the SO_2 control technologies in the future, information and data on base year SO_2 emission factor, installation of SO_2 control technologies, the performance and energy penalty of the technology and the actual removal rate were collected and analyzed.

5.4.1.1 SO_2 emission intensity

SO_2 emission intensity (ton SO_2/tce of coal) from 2000 to 2008 is derived based on the total emissions of each type of power plant and the coal combusted. Coal input for combustion was calculated given production, capacity, efficiency and the load factor of the coal-fired unit. The derived average SO_2 emission factor is 0.01683 ton/tce in 2000 and the implied sulfur content of 1.2% is used as the baseline emission factor in the absence of any control technologies. This is consistent with the sulfur content of the coal commonly used in China, which is believed to be 1.1% around 2005 to 2008.[3] In addition, the SO_2 emissions from 1 ton of coal used for power generation are estimated to be between 16.78 and 17.04 in 2008, implying 1.05% to 1.07% of sulfur content (China State Environmental Protection Agency 2010) (see also Appendix B).

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[3] Various sources show sulfur content ranging from 0.95% to 1.2% with the sulfur content of coal varying significantly depending on where it is produced (see appendix of Table) so an average number is used in this study. These sources include Wen (2007) and Environment Protection Technology Company of Dimei International Group (2010).

5.4.1.2 SO_2 removal

The SO_2 removal rate could be calculated based on the historic trend of the emission intensity, given the installation rate of the technology, an actual operating rate of the technology and the derived absorption rate. Table 5 shows the derived and estimated rates for installation, operation, and SO_2 removal in facilities with SO_2 control technologies installed. The operating rate depends on the power plant, and the absorption rate depends on the actual performance of the technologies.

The installation rate is 2% in 2000, and increases to 6% in 2005. After the initiation of the 11th Five year Plan, it surged to 60% in 2008, and 80% in 2009 (CEC 2009). However, the absorption rate remained at only 79% in 2009 in contrast to the technical maximum removal rate of 95-98% of the technologies (Yang 2009). Based on an overall 46% removal rate derived from the SO_2 emission intensity, the ratio of the operating facility is estimated to be around 70% in 2009.

Table 5 Installation, Operation and SO_2 Removal Rates for Plants with SO_2 Control

	2000	2004	2005	2006	2007	2008	2009	2010
Operating and absorption rate	0%			57%	57%	57%	57.6%[4]	57.7%[5]
Installation rate	2%		6% (at least 7.9% based on LBNL estimate	30%	43%[6]	60%	80%	80%
Removal rate of all plants	0%	1.7%	7.9%	17%	24.6%	34.4%	46%	46%[7]

Coal power plants in the model have been disaggregated into different type and size of technologies in order to identify the impact of the technological change and efficiency improvement. Some small coal-fired units have been or are planned to be shut down under the government policy of closing down inefficient power plants, which has been in place since 1998. In support of the 11th Five Year Plan to reduce energy intensity by 20% by 2010, the State Council also approved a plan to close 50 GW of small coal-fired power plant capacity, where small plants are considered those with less than 100 MW of capacity. By the end of 2009, a total of 60.38 GW of capacity of small coal-fired power plants has already been shut down since 2006 (MIIT 2010). Therefore, no SO_2 control technologies were installed or planned to be installed for these plants in the model. On the other hand, the newly built large scale highly efficient units are required to add SO_2 control technologies. The shares of coal-fired power plants with SO_2 control technology running are broken down by the type and capacity of the units as shown in Table 6.

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[4] Derived

[5] Assuming 79% of the absorption rate based on interview (Yang 2009)

[6] Interpolated

[7] Derived based on the goal of achieving 9.517 million ton of SO_2 emissions from the power sector by 2010 stated in the 11th Five-Year Plan.

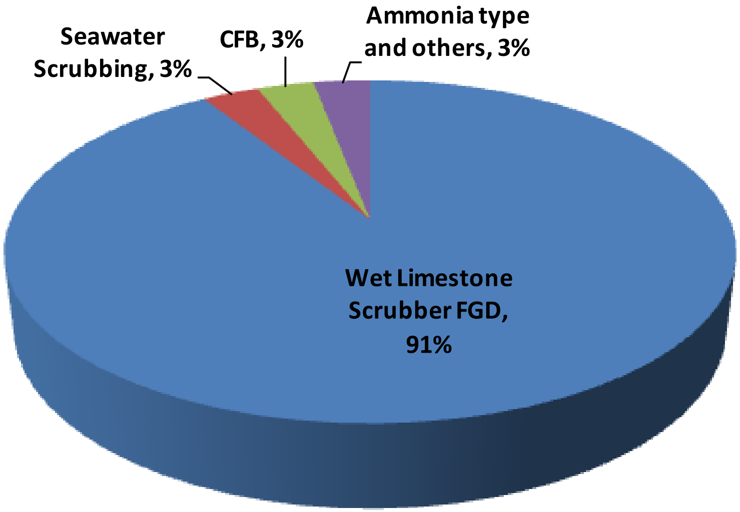
Table 6 SO_2 Technology Operation Rates by Plant Type

	2000	2004	2005	2006	2007	2008	2009	2010
Coal Fired Units: <100MW	0%	0%	0%	0%	0%	0%	0%	1.3%
Coal Fired Units: 100 to 200MW	0%	0%	14%	28.3%	39.3%	52.5%	61%	70.4%
Coal Fired Units: 200 to 300MW Subcritical	0%	0%	14%	28.3%	39.3%	52.5%	61%	70.4%
Coal Fired Units: 300 to 600MW Subcritical	0%	0%	14%	28.3%	39.3%	52.5%	61%	70.4%
Coal Fired Units: 600 to 1000MW Super critical	0%	0%	14%	71.4%	79%	85%	92%	100%

5.4.1.3 Technology

The general description of the SO_2 and CO_2 control technologies are provided in Appendix A. Where the data were available, associated cost information is also included. Today wet limestone scrubbers are the most widely used of all the FGD systems, with a share of 80 % of all the installed FGD capacity in the world. In China, based on China Electricity Council (CEC)'s report, 91% of the current installed technology is wet lime/ limestone scrubber FGD, with the remaining technology consisting of 3% seawater scrubbing, 3% Circulating fluid bed (CFB) dry scrubbers and 3% Ammonia type and others (Figure 20).

Figure 20 Installed SO_2 Technologies



Source: CEC 2009

The SO_2 emission control rate of the limestone FGD is 92% to 98 %, depending on the absorber type (EC 2006). Furthermore, the SO_2 control technology itself uses electricity. In the case of

FGD, approximately 1% to 3% of the total electricity output will be needed to run the facility, so an average of 2% was used in the model.

Switching to low sulfur fuel is another measure which can significantly reduce SO_2 emissions. In cases where supply is available, fuel switching may be a viable option and this may include fuels with high internal desulphurization due to the limestone (or other active compounds) content of the ash. However, in China, there is limited supply of low sulfur coal, and thus the option was not considered applicable for further reduction.

Biomass co-firing is a proven technology. Many coal plants have been converted or retrofitted to accommodate co-firing with limited impacts on efficiencies, operation, or lifespan. However, there is much more to co-firing than simply adding a secondary fuel. A power producer wishing to introduce bio-fuel at a plant must address complex technical, logistic, economic, and environmental considerations. In China, gathering biomass and transporting it to the power plant takes significant effort and energy. In addition, the rural population still uses large amounts of biomass for heating and cooking. If biomass is used to generate electricity, then rural residents will need to purchase more expensive coal to substitute for biomass. Thus biomass substitution in the power sector faces real constraints in the near future. Under the reference scenario, we looked at switching only 2% of the coal to biomass to evaluate its impact and effectiveness without explicitly accounting for transportation issues and costs.

5.4.2 Scenarios Assumptions

Two SO_2 control scenarios have been developed based on the technology applicability and potential in China. A base SO_2 control scenario takes into account the likely pace of improvement in China according to the government plan as well as technological potential. The accelerated SO_2 control scenario assumes China can achieve the 2020 goal by 2015. In terms of the removal rate, it implies 98% removal rate by 2015. In addition, 2% of the biomass is used for co-firing in the accelerated SO_2 control scenario.

Table 7 Historical and Projected SO_2 Removal Rates for Reference Scenario

	2000	2005	2008	2010	2015	2020
Coal Fired Units _LT 100MW	0	0	-6.3%	1%	68%	98%
Coal Fired Units _100 to 200MW	0	14%	41.5%	56%	81%	98%
Coal Fired Units _200 to 300MW Subcritical	0	14%	41.5%	56%	81%	98%
Coal Fired Units _300 to 600MW Subcritical	0	14%	41.5%	56%	81%	98%
Coal Fired Units _600 to 1000MW Supercritical	0	14%	67.1%	90%	94%	98%
Coal Fired Units _1000MW Ultra-supercritical	0					
Average removal rate of all plants				57.7%	81%[8]	98%[9]
Installation rate				80%	100%	100%

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[8] Assuming the facilities can achieve 90% operation rate and technical maximum absorption rate of 90% by 2015

[9] Assuming the facilities can achieve 100% operation rate and technical maximum absorption rate of 98% by 2020

Actual Removal rate				46%	81%	98%

5.5 Co-Control Scenarios

Beside the individual CO_2 mitigation and SO_2 control scenarios, four other scenarios were created to examine the emissions reduction potential and co-benefits of integrating CO_2 and SO_2 control measures in the power sector to different degrees.

5.5.1 Coal Generation Efficiency with SO_2 Control Scenarios

The coal generation efficiency with SO_2 control scenarios reflects maximum effort of controlling CO_2 and SO_2 in coal generation. Two scenarios are created to examine the emission reduction potential of improving the overall efficiency of coal generation fleet by technology switching and of installing base or accelerated SO_2 control technology to the more efficient plants. The underlying assumptions of these two scenarios are based on the coal generation efficiency improvement scenario and the two SO_2 control scenarios.

5.5.2 Coal Generation Efficiency with Decarbonization Scenario

The coal generation efficiency with decarbonization scenario is intended to represent the maximum CO_2 mitigation possible in the power sector by simultaneously adopting all the CO_2 mitigation measures of improved coal generation efficiency and accelerated and expanded renewable, hydropower and nuclear generation capacity and utilization. Besides maximizing the CO_2 emission reduction potential in this scenario, SO_2 emissions are also controlled by reducing the use of coal in the power sector through improved coal generation efficiency and more aggressive shift towards renewable and non-fossil fuel generation.

5.5.3 Maximum Co-control Scenario

The maximum co-control scenario represents the pathway of maximizing CO_2 mitigation and SO_2 control efforts by adopting all possible measures in the power sector. These measures include improved coal generation efficiency, maximum decarbonization through expanded renewable, hydropower and nuclear generation, and the accelerated installation of SO_2 control technologies in coal plants.

5.5.4 Expanded Biomass Generation Scenario

As an alternative fuel for generation, biomass has zero carbon and SO_2 emissions and its substitution for coal in power generation can have important benefits in both CO_2 and SO_2 reduction. As such, this scenario examines the potential emissions impacts of increasing biomass co-firing in large-scale coal power plants. It assumes that biomass co-firing has an average generation efficiency of 25%, which is a conservative assumption given that current co-firing in large-scale, modern coal power plants have efficiencies of 35% to 45% (IEA 2007). This scenario also assumes maximum availability of 150 million tonnes of biomass per year for generation, taking into consideration supply constraints from rural residential demand for direct biomass use.

5.6 Results

The scenario results and relative savings potential of each scenario is presented as relative to the reference scenario. However, the reference scenario in this study is not the business as usual or frozen scenario that is usually set as the baseline for examining savings potential. Rather, the reference scenario reflects a pathway in which China would continue its current and planned efforts to lower its energy intensity with efficiency improvements and fuel switching consistent with moderate pace of "market-based" improvements in all sectors. For the power sector, this incorporates planned renewable targets and efficiency improvements in coal-fired generation. As a result, the reference scenario already captures significant reduction in both CO_2 and SO_2 emissions in the power sector as a result of continued efforts to decarbonize the power sector. For instance, the total CO_2 emission from 2005 to 2030 under the reference scenario is 30% lower than the frozen scenario, or cumulative reduction of 40 billion tonnes of CO_2 (Figure 21). For SO_2 emissions, the 61% cumulative reduction of 456 million tonnes of SO_2 under reference scenario is even more evident with declining reference emissions after 2008 but rising emissions under the frozen scenario (Figure 22). Therefore, the savings potential examined for the control scenarios below represents savings *additional* to what China could achieve by following its current pathway of development with continued emphasis on efficiency and decarbonization.

Figure 21 Power Sector CO_2 Emissions for Frozen vs. Reference Scenario

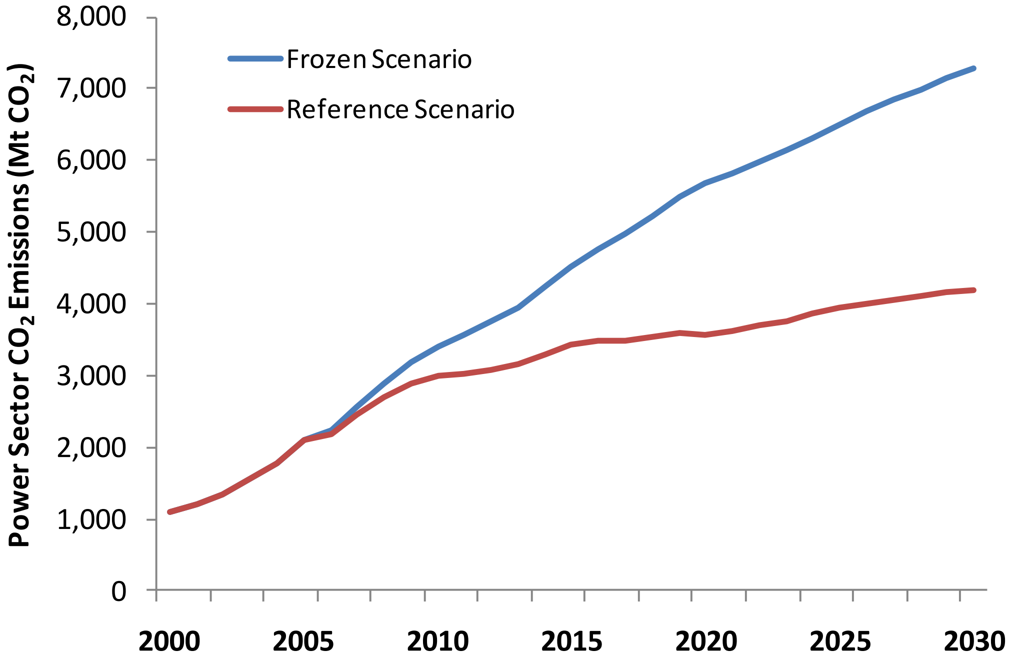
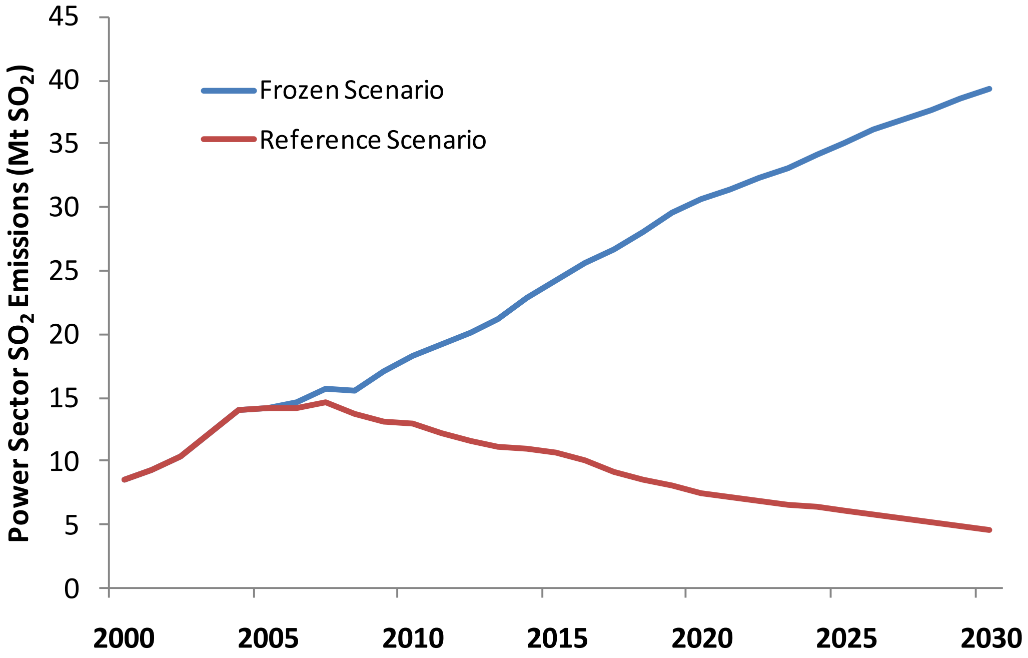


Figure 22 Power Sector SO_2 Emissions for Frozen vs. Reference Scenario

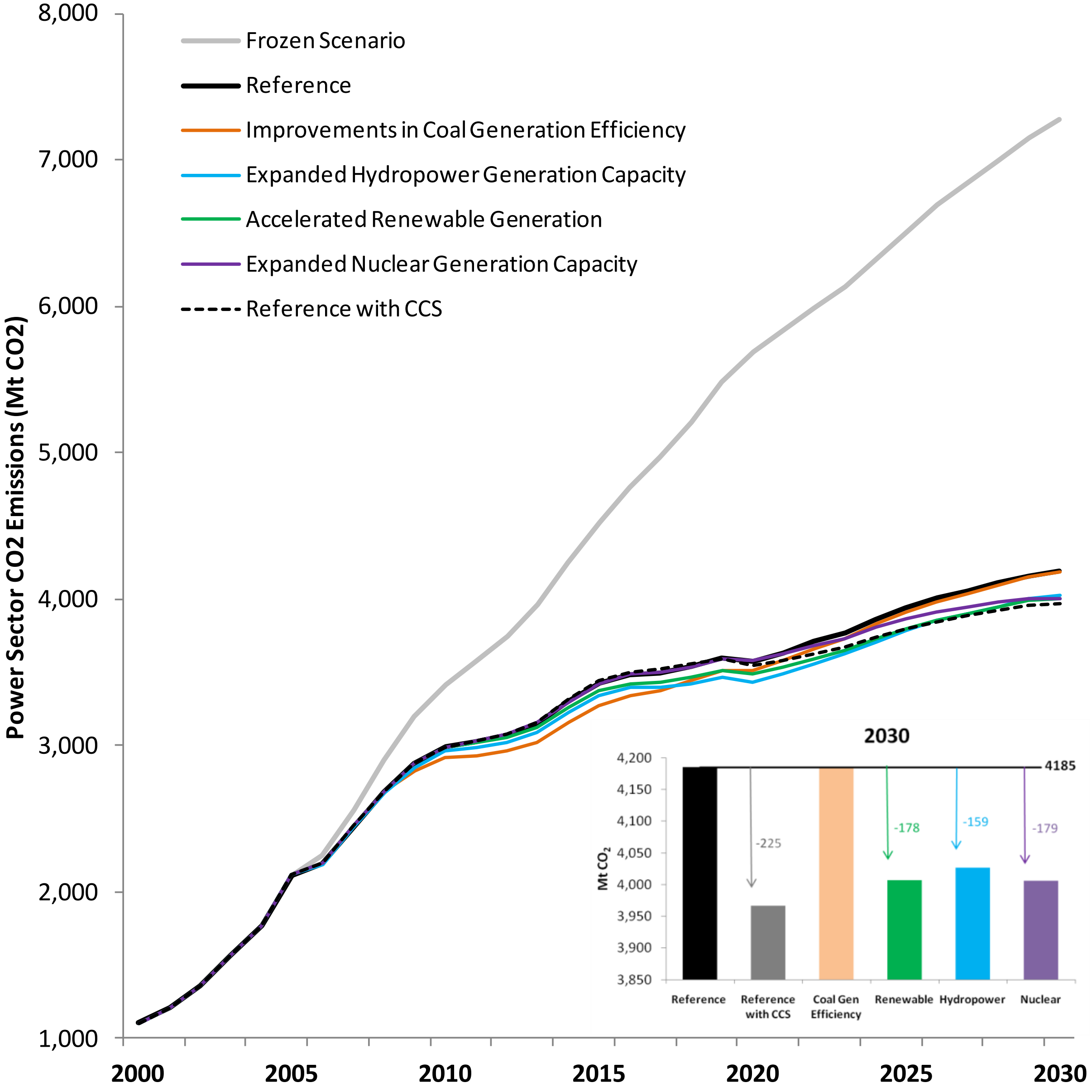


5.6.1 CO_2 Mitigation Scenarios

5.6.1.1 CO_2 emissions

Because the focus of the research is on CO_2 emission and SO_2 emission controls, the efficiency scenario is included as one of the CO_2 mitigation scenarios in the results. When assessing the individual five CO_2 mitigation scenarios, the CCS scenario seems to result in the greatest annual CO_2 emission reduction by 2030, with 225 million tonnes less CO_2 emissions in 2030 than the reference scenario (Figure 23). However, there is a 2% increase in the total primary energy requirement. CCS also does not have significant impact on CO_2 emission reductions in the initial years after 2005 and actually has a small net increase in CO_2 emissions prior to 2018. As a result, the cumulative CO_2 emissions reduction from CCS between 2005 and 2030 is actually ranked fourth out of the five CO_2 control options (Figure 25).

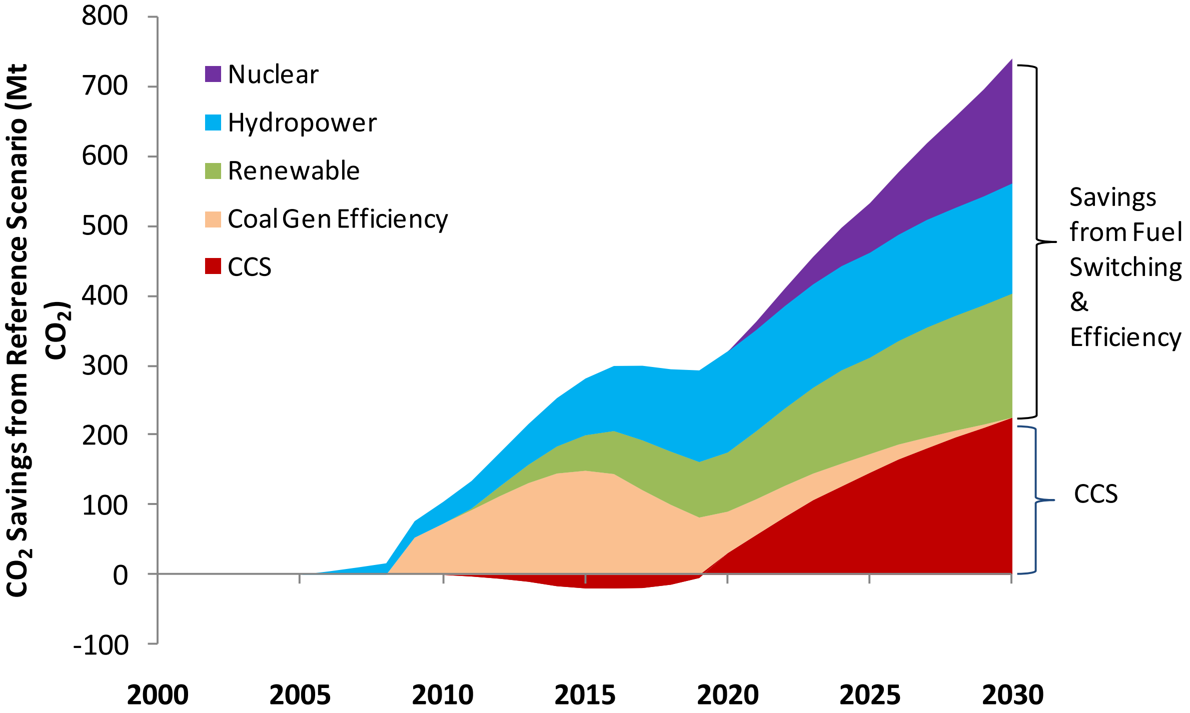
Figure 23 CO_2 Emissions of Power Sector CO_2 Control Scenarios, 2000-2030



Note: Y-axis scale not set to zero.

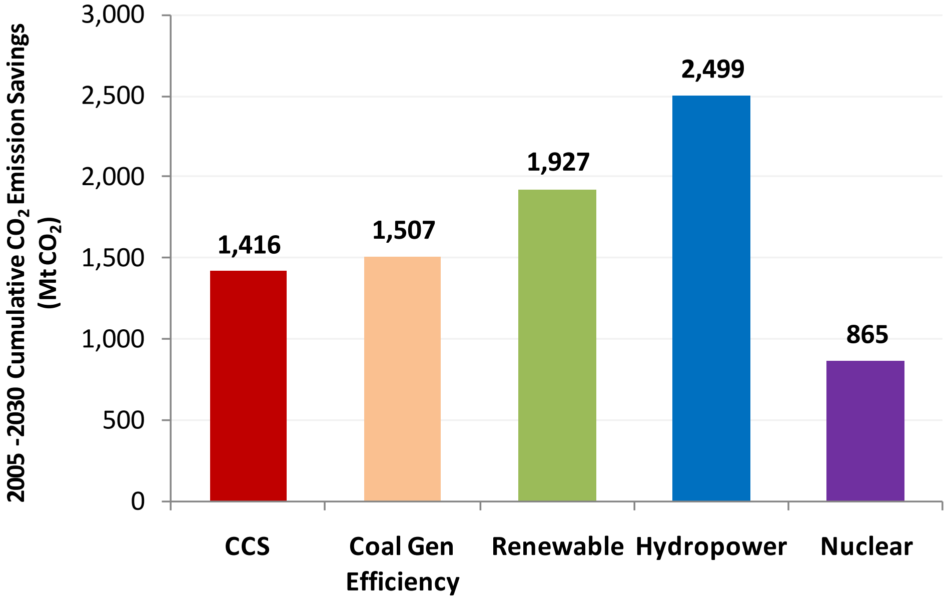
Compared to CCS, adopting larger hydropower and renewable capacity in order to decarbonize the power sector will have greater cumulative CO_2 reductions, with total emissions reduction of 2499 and 1927 Mt CO_2, respectively, from 2005 to 2030. As seen in Figure 24, expanded hydropower capacity and renewable capacity will both have continually growing emission reduction over time, albeit its 2030 annual reduction may not be as high as other mitigations options. In contrast, the CO_2 reduction from shifts in coal generation technology (i.e., greater use of supercritical coal generation) is initially large but declines over time after 2015 as a result of the accelerated phase out of the small and inefficient power plant by 2015 in the coal power plant efficiency scenario, most of the efficiency gain will have been captured in the early years. Nevertheless, the coal efficiency scenario still has slightly larger cumulative CO_2 reduction than CCS by 2030. Lastly, the expanded nuclear generation capacity after 2020 has rapidly growing emissions reduction and results in the same magnitude of reduction as renewable and hydropower capacity expansion by 2030.

Figure 24 CO_2 Emission Reduction by CO_2 Control Scenario, 2005 - 2030



Overall, increasing the capacity of non-fossil fuel generation by switching the power sector away from coal-fired generation as well as improving the efficiency of coal generation will have a much greater impact on CO_2 mitigation than CCS alone. More specifically, fuel switching and efficiency gains together account for 69% of total potential CO_2 savings from the five mitigation options in 2030 and an even larger share of 83% of cumulative potential CO_2 reduction from 2005 to 2030.

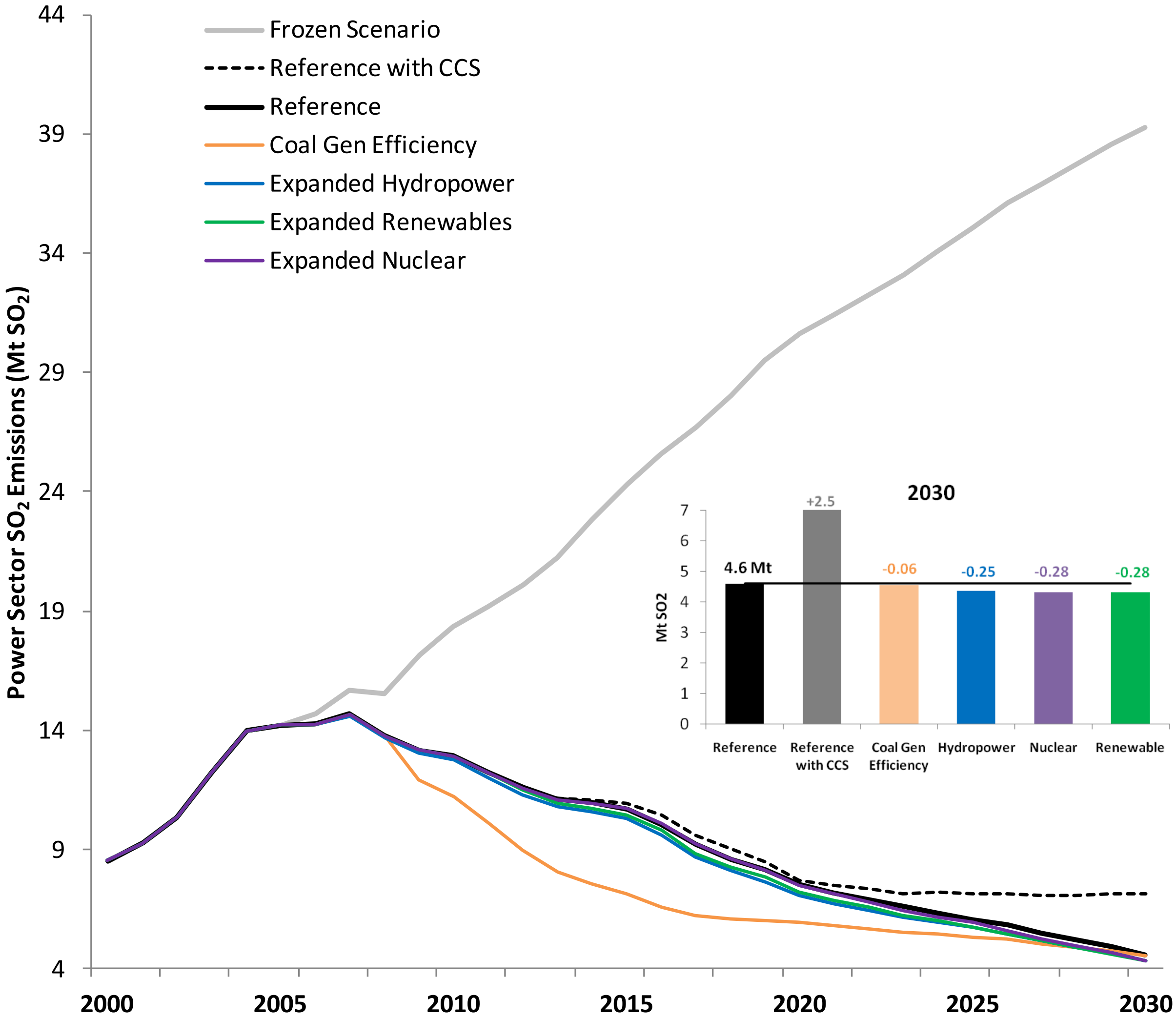
Figure 25 Cumulative CO_2 Emissions Reduction by CO_2 Control Scenario



5.6.1.2 SO_2 emissions

In terms of SO_2 emissions, improving coal generation efficiency for CO_2 mitigation has important co-benefits in significantly reducing SO_2 emissions by eliminating inefficient coal use. Prior to 2025, the coal generation efficiency scenario achieves significant SO_2 reduction with annual reduction of as much as 3.6 Mt SO_2 in 2015. After 2015, with all the small inefficient power plant being phased out or not dispatched and the share of the large and efficient technologies such as 1000P+ MW ultra-super critical plants and 600 to 1000 MW super critical plants remaining the same, SO_2 emission reduction potential declines over time to only 0.1 Mt SO_2 by 2030 . From a cumulative perspective, however, improving the coal generation efficiency has the largest reduction potential of 37 Mt of SO_2 compared to the reference scenario.

Figure 26 Total SO_2 Emissions for Power Sector CO_2 Control Scenarios



Note: Y-axis scale not set to zero.

Besides having the two largest cumulative CO_2 reduction potential of the five mitigation scenarios, expanding hydropower and renewable capacity also have important co-benefits in reducing cumulative SO_2 emissions. Although the annual SO_2 emissions reductions are relatively small compared to coal generation efficiency improvement for most years, hydropower and renewable capacity expansion are the only two CO_2 mitigation options that have relatively consistent annual SO_2 emissions reductions every year. As a result, hydropower and renewable capacity expansion have the second and third largest cumulative SO_2 reductions potential with 8 and 5.5 Mt SO_2, respectively, behind coal generation efficiency improvement (Figure 28). Finally, because it has higher energy requirements in terms of coal for carbon capture and sequestration, CCS results in more SO_2 emissions than the reference case with as much as 2.5 Mt increase in SO_2 emissions in 2030 and cumulative increase of 14.8 Mt by 2030.

Figure 27 SO_2 Emission Reductions by CO_2 Scenario, 2005 - 2030

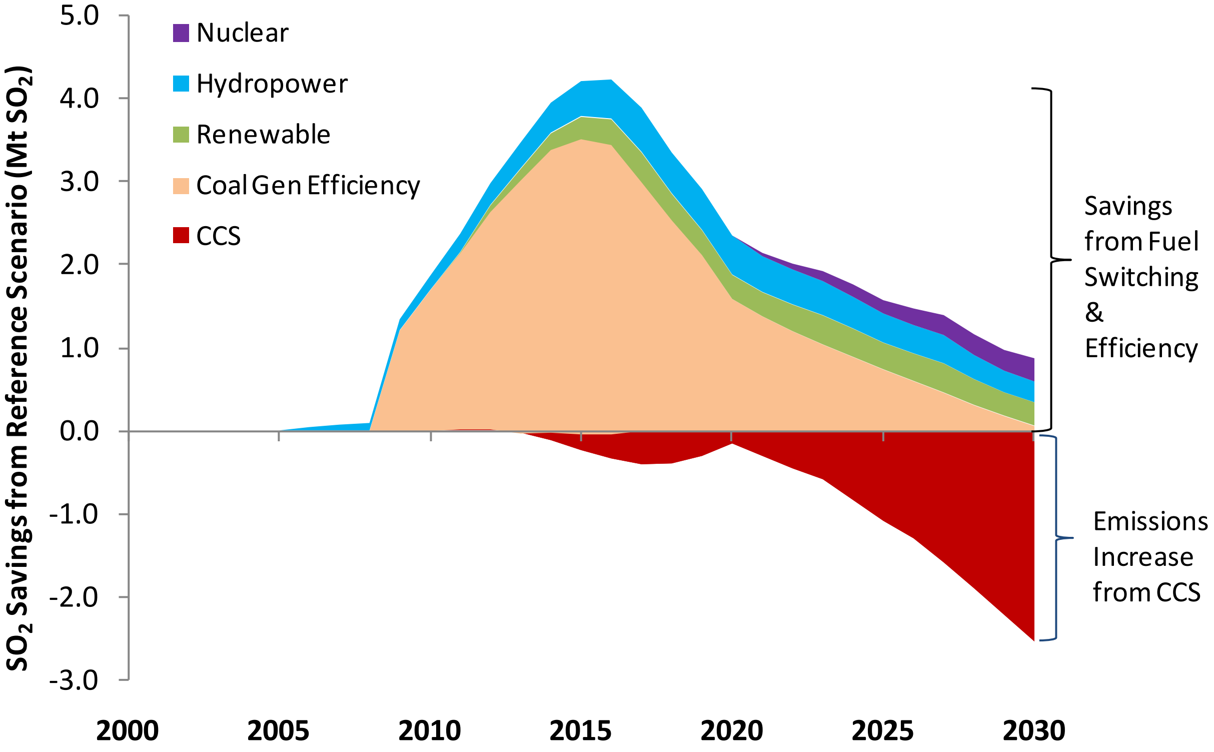
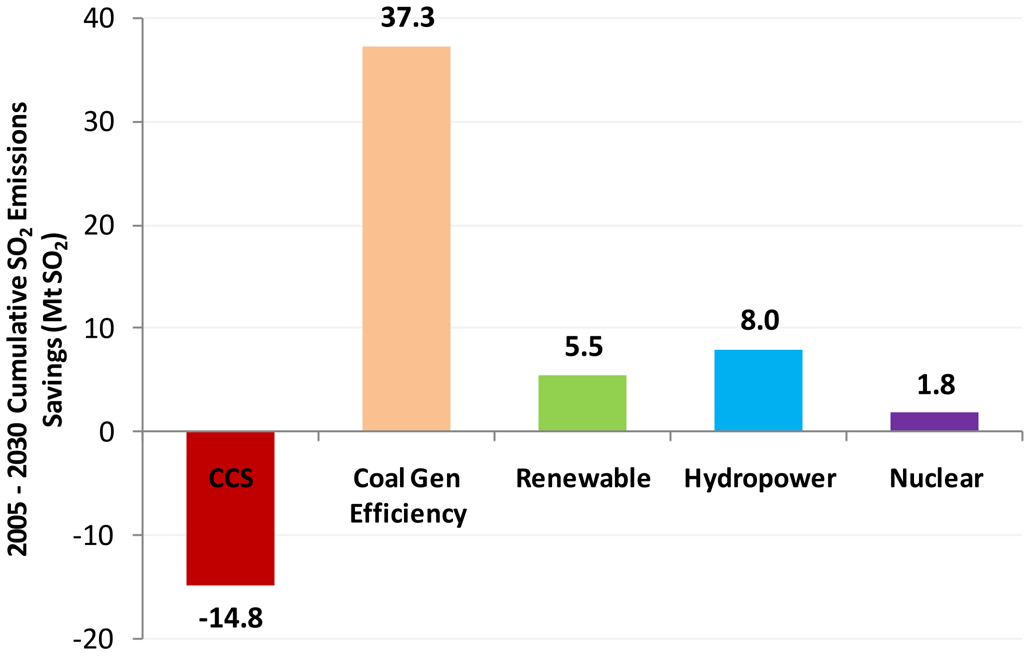


Figure 28 Cumulative SO_2 Emission Reductions by CO_2 Control Scenario

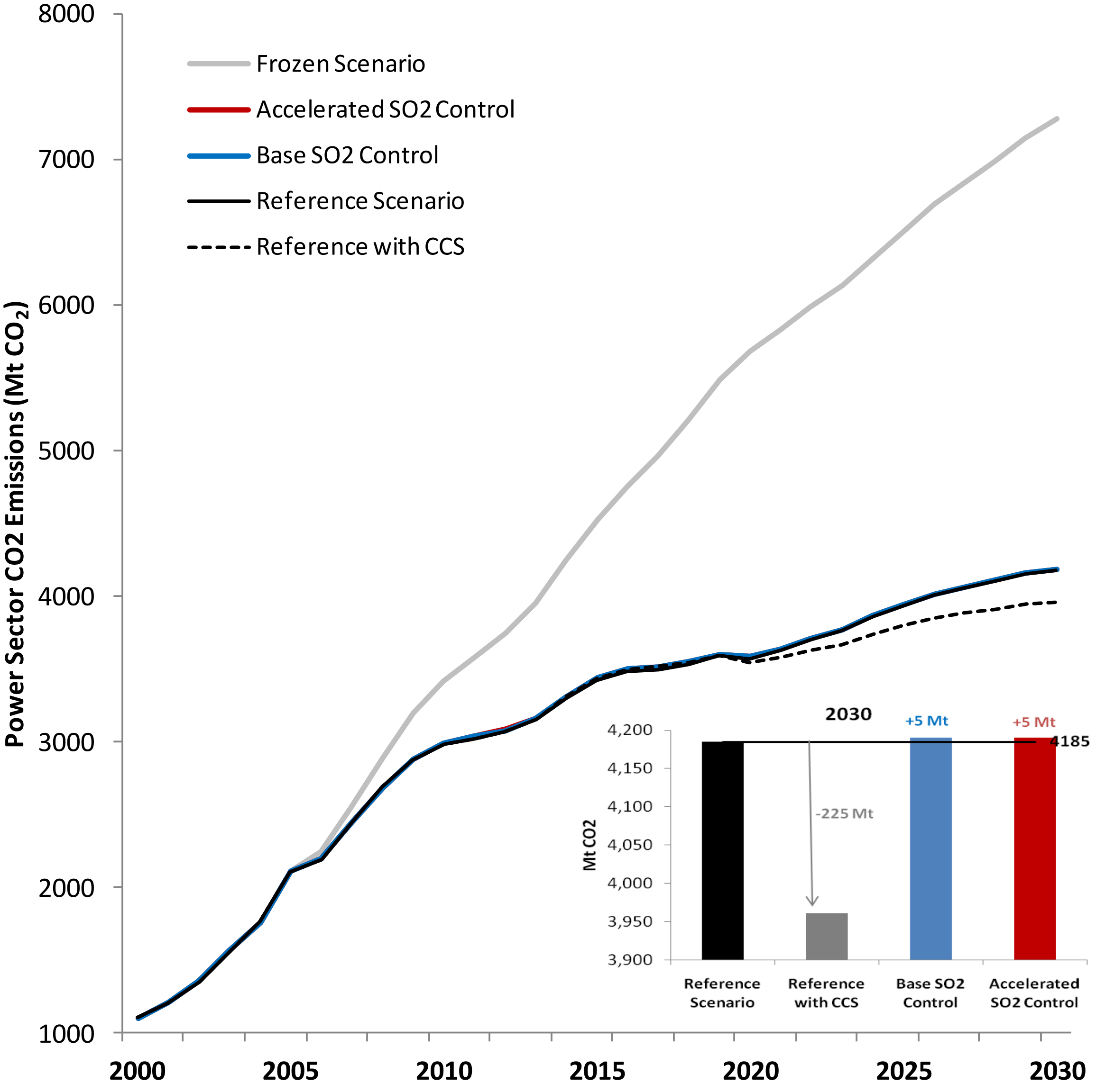


5.6.2 SO_2 Control Scenarios

5.6.2.1 CO_2 emissions

The base and accelerated SO_2 control scenarios have very small net effect of increasing CO_2 emissions relative to the reference case, with emissions gain of less than 1% of the total power sector emissions. The net gain in CO_2 emissions ranges from a low of 5 Mt CO_2 in 2030 to a high of 19 Mt CO_2 emissions for the accelerated SO_2 control case and 16 Mt CO_2 emissions for the base SO_2 control case in 2015 (Figure 29).

Figure 29 Total CO_2 Emissions for Power Sector SO_2 Control Scenarios

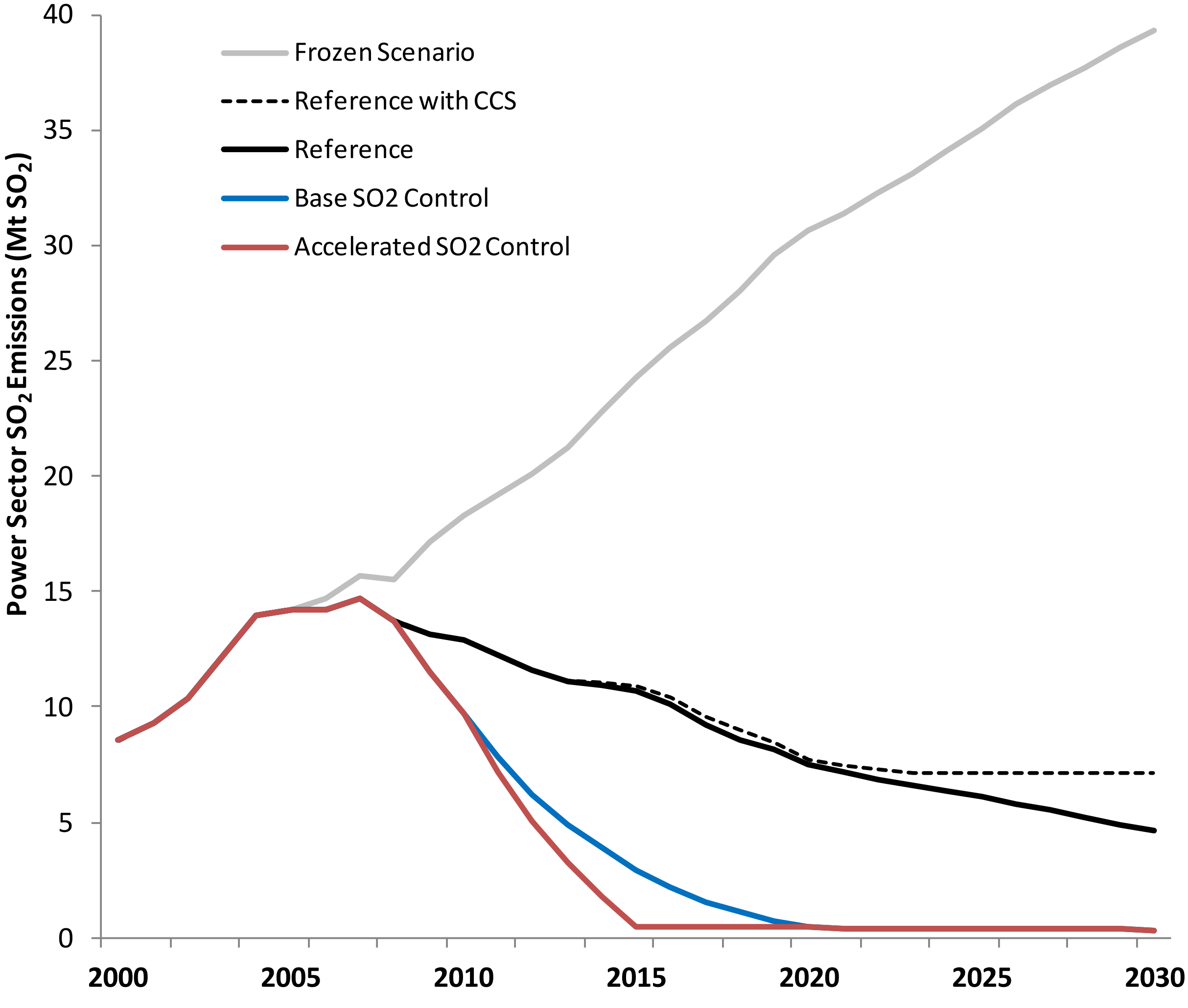


Note: Y-axis scale not set to zero.

5.6.2.2 SO_2 emissions

As expected, significant reductions in SO_2 emissions can be achieved under both the base control and accelerated control scenarios. Under the base control scenario, SO_2 emissions decrease significantly between 2010 and 2020 and actually achieve the same reductions as the 2015 accelerated control case by 2020 (Figure 30). In contrast, SO_2 emissions dramatically decrease in the accelerated control case between 2010 and 2015, and reaches the 0.46 Mt SO_2 emissions, or only 4% of reference SO_2 emissions, by 2015. Both control scenarios flatten out after 2020 with very small incremental reductions through 2030 as the SO2 control technology reaches full penetration and removal rate. Over the period from 2009 to 2030, cumulative SO_2 emission reductions total 128 Mt SO_2 under the base control case and total 140 Mt SO_2 under the accelerated case.

Figure 30 Total SO_2 Emissions for Power Sector SO_2 Control Scenarios

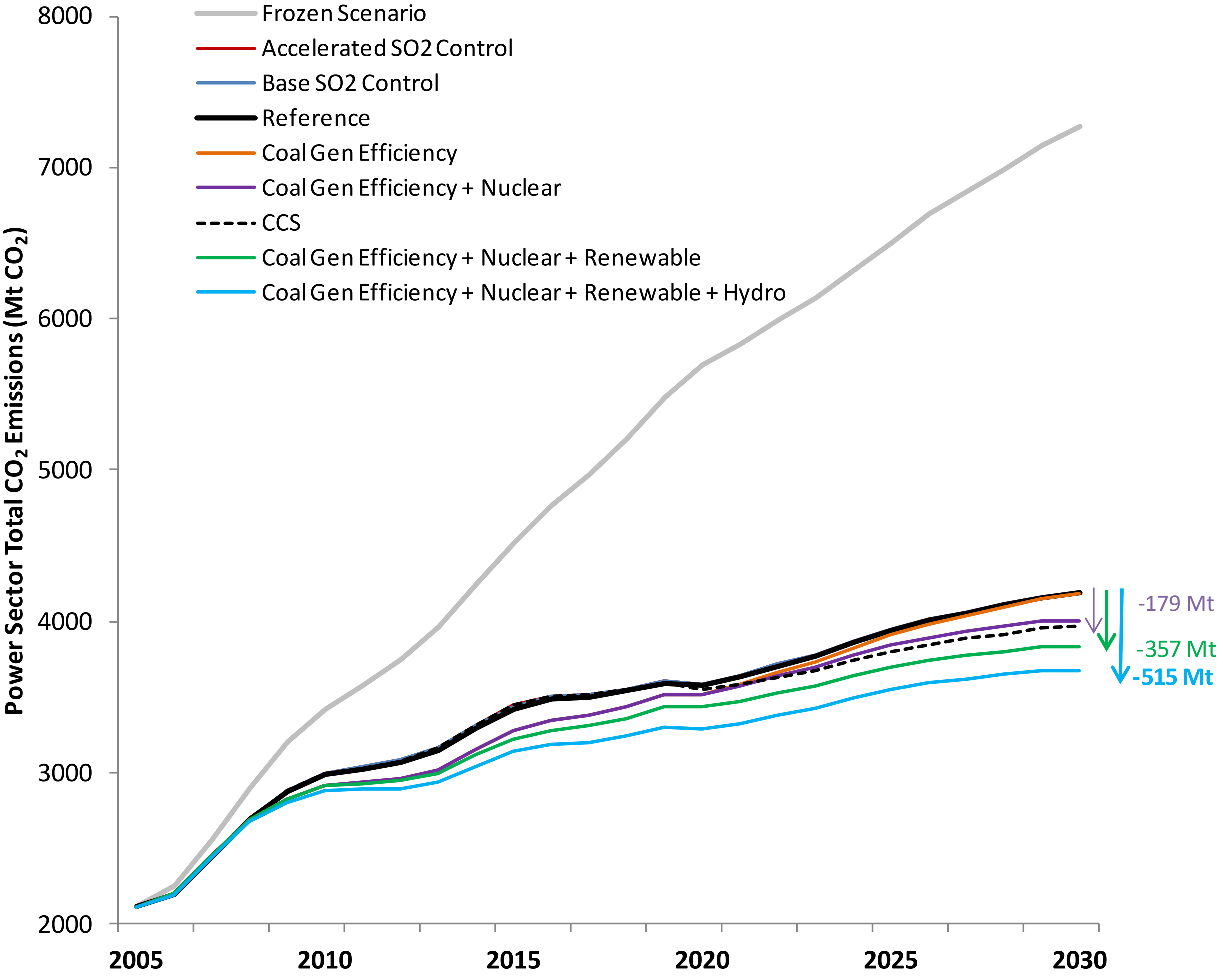


5.6.3 Integrated CO_2 and SO_2 Control Scenarios

5.6.3.1 CO_2 Emissions Reduction

Adopting SO_2 control at either pace without coal generation efficiency improvements or decarbonization will result in small net increase in CO2 emissions. However, if generation efficiency improvements and some form of decarbonization through expanded non-fossil fuel capacity are pursued, the resulting CO_2 emission mitigation will outweigh the benefits of adopting CCS at the assumed scale. Thus, of all the CO_2 and SO_2 control scenarios, the largest emission reductions potential arises from adopting efficiency improvements to coal generation and pursuing decarbonization through the expanded capacity of nuclear, renewable and hydropower generation, which leaves the reduction from CCS far behind.

Figure 31 Total CO_2 Emissions of CO_2 and SO_2 Control Scenarios, 2005-2030



Note: Y-axis not scaled to zero.

5.6.3.2 SO_2 Emissions Reduction

In terms of SO_2 emissions, both CO_2 and SO_2 control scenarios can have important impacts on reductions in the power sector. Although the base and accelerated SO_2 control scenarios will have the largest reduction potential on an annual and cumulative basis, the other CO_2 control options also have important co-benefits in reducing SO_2 emissions. This is especially true when coal generation efficiency improvements are undertaken with decarbonization. In fact, coal efficiency improvements along with hydropower, renewable and nuclear capacity expansion will achieve more than half of the SO_2 emission reductions as the base control scenario through 2016. At its peak reductions in 2015, coal efficiency with hydropower, renewable and nuclear capacity expansion will achieve reductions of 4.27 Mt SO_2 per year while accelerated SO_2 control can achieve 10.3 Mt SO_2 in reductions. Despite declines in reduction potential after 2015, power sector efficiency improvements and decarbonization can still reduce SO_2 emissions by nearly 0.9 Mt in 2030, or 20% of the reduction potential of accelerated base control. CCS is the only CO_2 control scenario that does not have any SO_2 reductions potential as a result of its higher primary energy requirements.

Figure 32 Total SO_2 Emissions of CO_2 and SO_2 Control Scenarios, 2005 – 2030

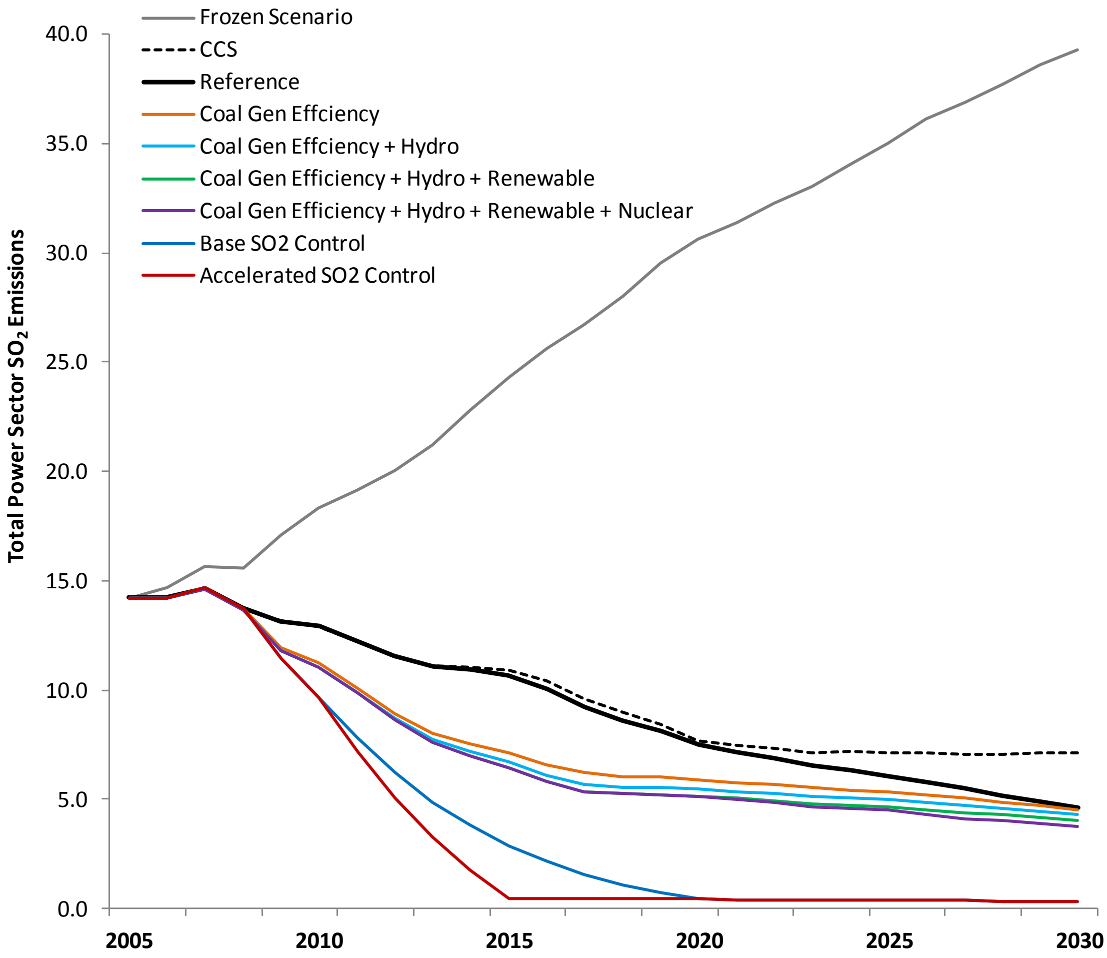
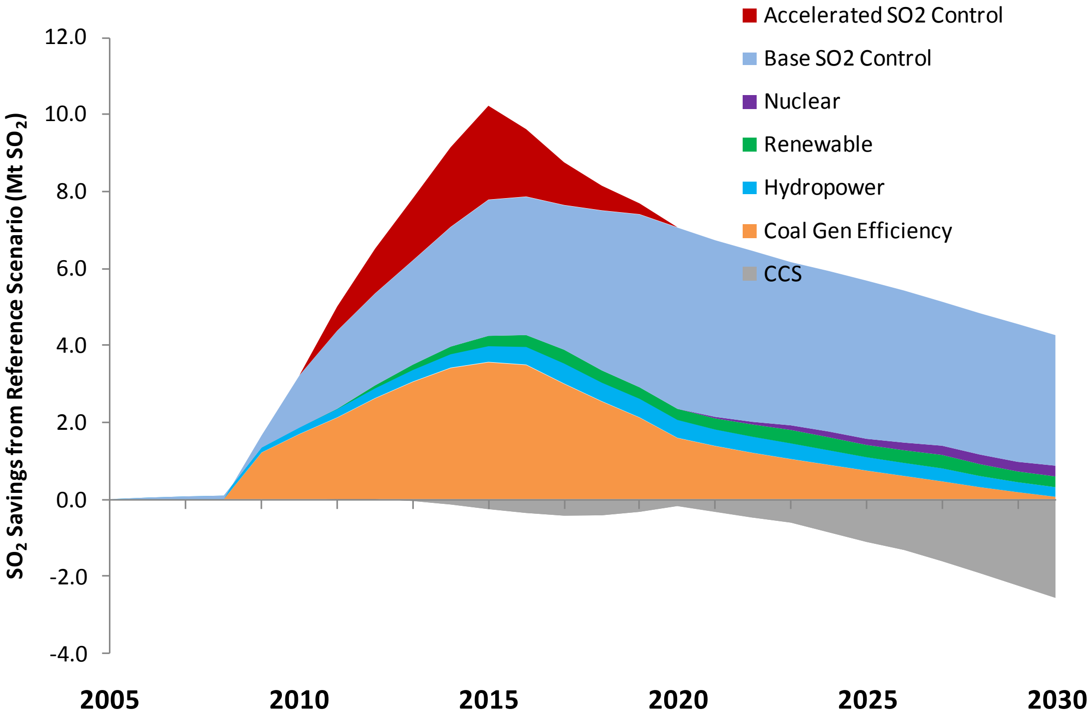


Figure 33 SO_2 Emission Reductions of CO_2 and SO_2 Control Scenarios



5.6.4 Emission Reductions Potential from Co-Control Scenarios

While some CO_2 control scenarios such as coal generation efficiency improvements and decarbonization have co-benefits in simultaneously reducing SO_2 emissions, co-control through the adoption of both CO_2 mitigation and SO_2 control measures can achieve greater emissions reductions than by pursuing only one type of control.

5.6.4.1 CO_2 Emissions

In terms of CO_2 emissions, adopting efficiency and decarbonization can achieve the maximum reductions. Combining it with accelerated SO_2 control has the added benefit of reducing much greater SO_2 emissions without significantly increasing CO_2 emissions. Without decarbonization, however, the power sector will not be able as achieve as significant CO_2 reductions, particularly in the later years. For example, annual SO_2 reductions under the base control with efficiency scenario will peak in 2015 with reductions of 139 Mt CO_2, and decline over time to no reduction potential by 2030 as all small inefficient plants have been phased out or are not utilized in coal generation. Increasing the use of biomass in generation will have growing annual CO_2 reductions over time, but its reductions potential is still much smaller than if coal efficiency and decarbonization are adopted. Decarbonization in particular has the greatest CO_2 emission reductions potential as a single co-control measure reduction (Figure 35). Nevertheless, fuel switching towards biomass can be added to accelerated SO_2 control, efficiency and decarbonization as another co-control measure to achieve even greater emissions reductions.

Figure 34 Power Sector CO_2 Emissions by Co-control Scenario

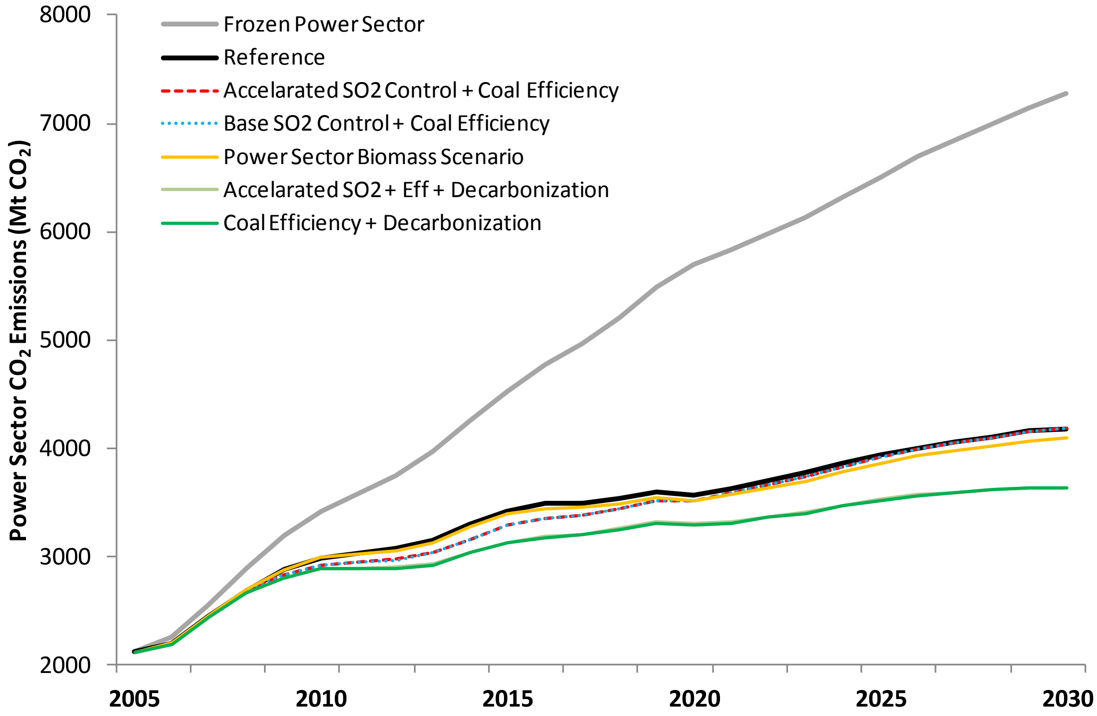
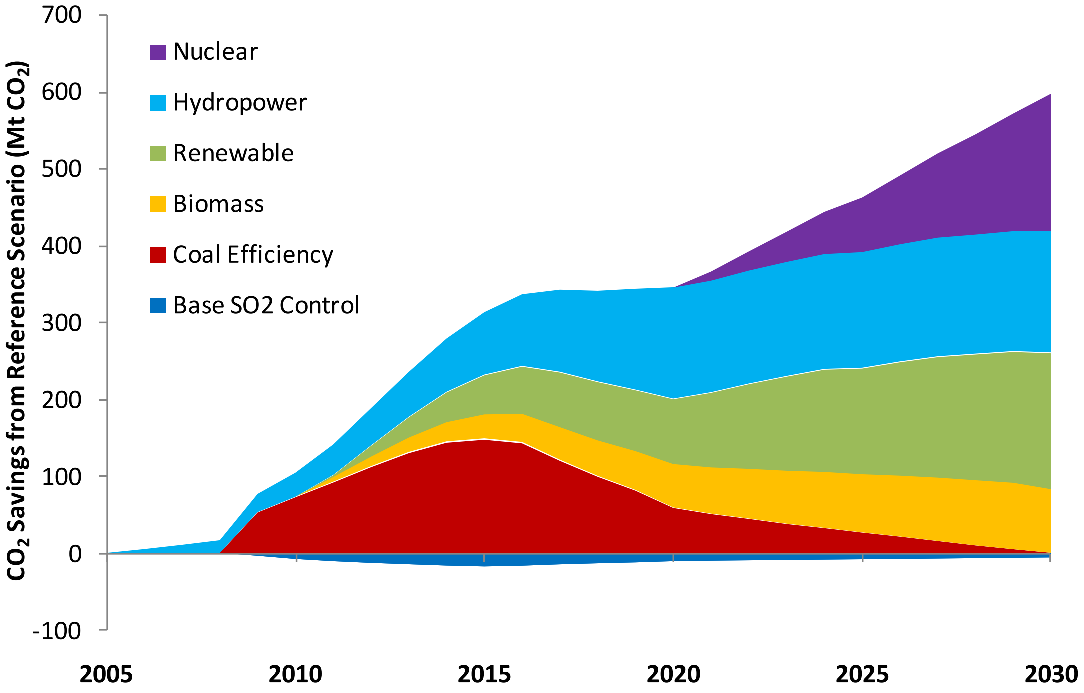


Figure 35 CO_2 Reductions Potential of Co-control Measures, 2005-2030



5.6.4.2 SO_2 Emissions

Of all the co-control scenarios, the expanded biomass generation scenario stands out as the only one that does not have significant potential for reducing SO_2 emissions, with annual reductions in the range of 0.1 to 0.2 Mt of SO_2. This is because coal, which is being replaced by biomass, has much lower sulfur content of approximately 1% than that of carbon content of up to 90% by weight. In contrast, the coal efficiency and decarbonization scenario had much larger SO_2 emission reductions with annual reductions potential of up to 4.2 Mt SO_2 in 2015 and 0.7 Mt SO_2 in 2030, or 40% and 15% of reference emissions, respectively. The base and accelerated SO_2 control with coal generation efficiency improvement scenarios still have the largest SO_2 emission reductions potential, with small incremental reductions in the same range as the biomass reductions for the maximum co-control effort scenario prior to 2015. All in all, annual reductions as high as 10.31 Mt SO_2 or as much as 96% of reference emissions are possible if SO_2 control technologies are adopted along with CO_2 control technologies. It can be seen from the two accelerated SO_2 control with efficiency scenarios that investing in decarbonization has SO_2 reductions when SO_2 control technology is not installed (Figure 27), but has very negligible additional SO_2 reductions when SO_2 control are already in place because most of the reductions potential has been captured by SO_2 control technology (Figure 36). However, adding decarbonization to SO_2 control and coal efficiency can play an important part in further reducing CO_2 emissions, especially from a cumulative perspective.

Figure 36 Power Sector SO_2 Emissions by Co-control Scenario, 2005-2030

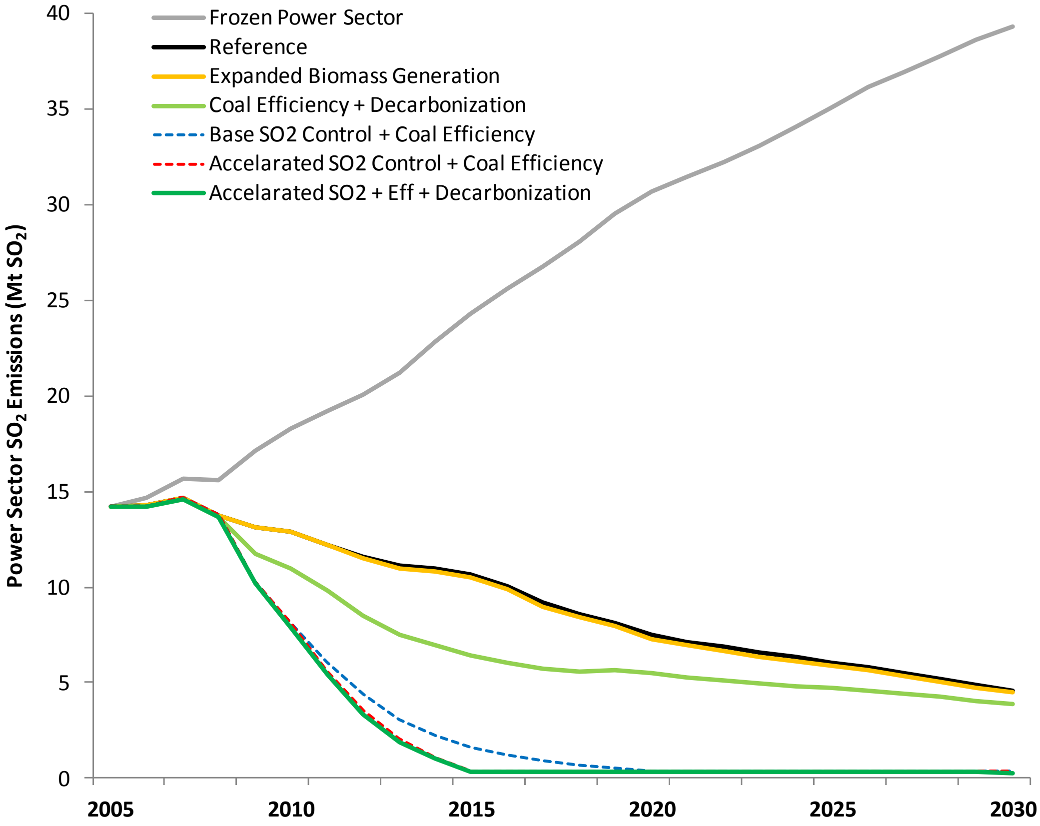
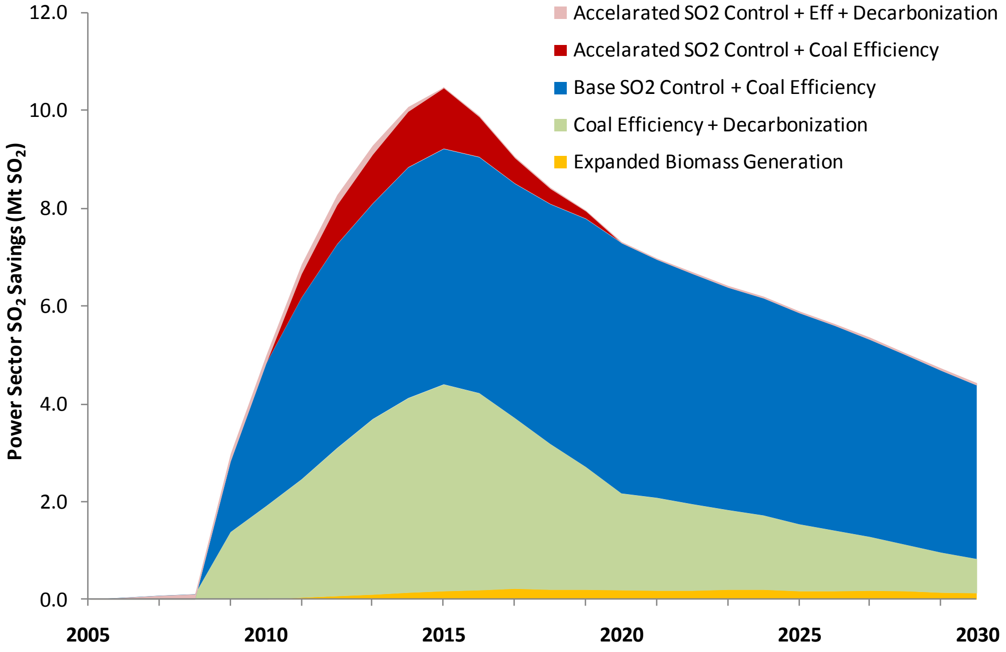


Figure 37 SO_2 Reductions by Co-control Scenario, 2005-2030



In terms of cumulative emission reductions, the greatest potential also lays with co-control scenarios that utilize both SO_2 and CO_2 control measures. While coal efficiency with decarbonization has slightly larger cumulative CO_2 reductions potential as the maximum co-control scenario, its SO_2 reductions potential is dwarfed by maximum co-control as it lacks SO_2 control technology. Of all the scenarios with SO_2 control technology, it is important to note that adding CO_2 control measures such as improving coal generation and shifting towards non-fossil fuel generation adds small incremental reductions in SO_2 and more substantial reductions in CO_2 emissions. Moreover, adopting more co-control measures increases the cumulative reductions potential of both CO_2 and SO_2 emissions. For example, while the two accelerated SO_2 with efficiency improvement scenarios have very similar SO_2 reductions potential with or without decarbonization, there is a significant difference in total CO_2 reductions potential if decarbonization is not included as a co-control measure (Figure 38, Figure 39).

Table 8 2005 – 2030 Cumulative Absolute and Relative Emission Reductions Potential of Co-control Scenarios

	SO_2 Savings		**CO_2 Savings**	
	Cumulative Savings (Mt)	***% of Ref Emissions***	**Cumulative Savings (Mt)**	***% of Ref Emissions***
Biomass Scenario	3.24	*1.3%*	1,098	*1.2%*
Coal Gen Efficiency Only	37.26	*15.4%*	1,507	*1.7%*
Coal Efficiency with Decarbonization	48.76	*20.2%*	7,124	*8.1%*
Base SO_2 Control	128.44	*53.1%*	-210	*-0.2%*
Base SO_2 Control with Efficiency	141.79	*58.6%*	1,361	*1.5%*
Accelerated SO_2 Control	140.13	*57.9%*	-226	*-0.3%*
Accelerated SO_2 Control with Efficiency	148.36	*61.3%*	1,355	*1.5%*
Accelerated SO_2 Control with Efficiency and Decarbonization	150.02	*62.0%*	6,986	*7.9%*

Figure 38 2005–2030 Cumulative CO_2 Reductions by Co-control Scenario

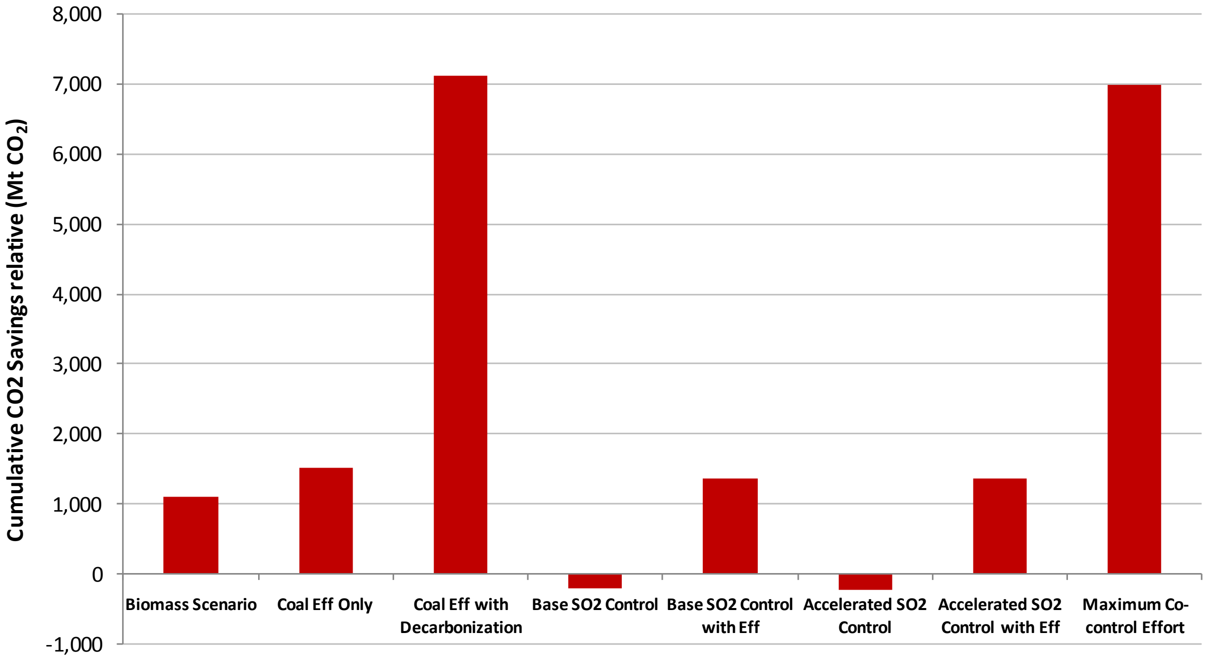
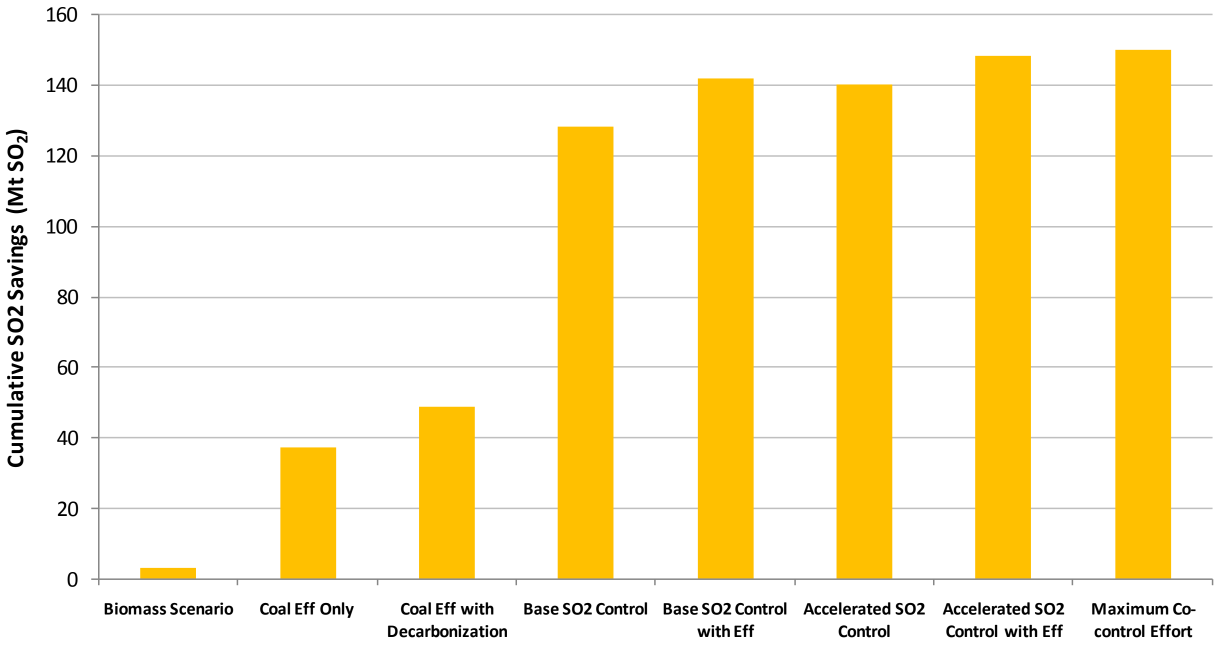
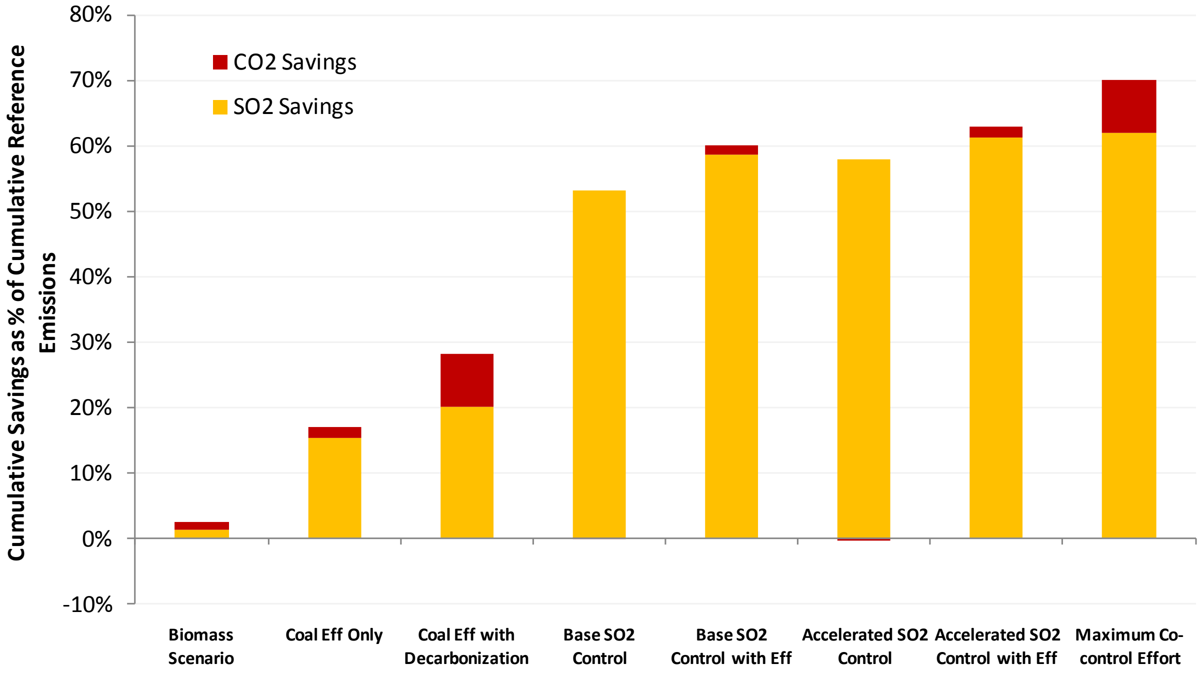


Figure 39 2005-2030 Cumulative SO_2 Reductions by Co-control Scenario



Therefore, the biomass scenario stands out as the co-control scenario with the smallest CO_2 and SO_2 emission reductions potential, primarily because it is only one control measure and has limited availability to substitute for coal as a key generation fuel. In contrast, improving the generation efficiency of coal generation could actually have a greater impact on reducing both types of emissions than by shifting towards biomass. SO_2 control can reduce the majority of SO_2 emissions from a reference case, but has net CO_2 emission increases if CO_2 control measures are not adopted concurrently. The maximum co-control scenario where accelerated SO_2 control is adopted along with efficiency improvements and power sector decarbonization will have the greatest potential on reducing cumulative SO_2 and CO_2 emissions from the power sector.

Figure 40 2005-2030 CO_2 and SO_2 Relative Emissions Reduction Potential of Co-control Scenarios



6. Cement Sector

China is the world's largest producer of cement, manufacturing more than 50% of total global cement in 2010 (USGS 2011a). The base year for the cement sector scenarios in this report is 2005; China's cement production that year was 1069 Mt (CCA 2007). In China, cement is produced by either a rotary kiln or a vertical shaft kiln (VSK). Modern new suspension preheater/precalciner (NSP) kilns are the most typical type of rotary kiln in China. Table 9 provides actual cement production in China 2005-2009 by kiln type (CCA 2008; CCA 2009; Digital Cement 2009; NBS 2010b; CIEE 2009; MIIT 2010b).

Table 9 Cement Production by Process in China, 2005-2009

	2005	2006	2007	2008	2009
Rotary (NSP) Kiln Production	481	606	721	861	1271
Vertical Shaft Kiln and Other Production	588	631	640	527	380
Total Production	1069	1237	1361	1388	1650

Sources: CCA 2008; CCA 2009; Digital Cement 2009; NBS 2010b; CIEE 2009; MIIT 2010b.

Future production of cement is based on LBNL's 2050 urban residential and commercial construction forecast, derived using the following formula:

$$P_c = [(CFSu + CFSr + RFSu + RFSr) \times CI1] + (PA \times CI2) + (H \times CI3) + (R \times CI4) + Ex$$

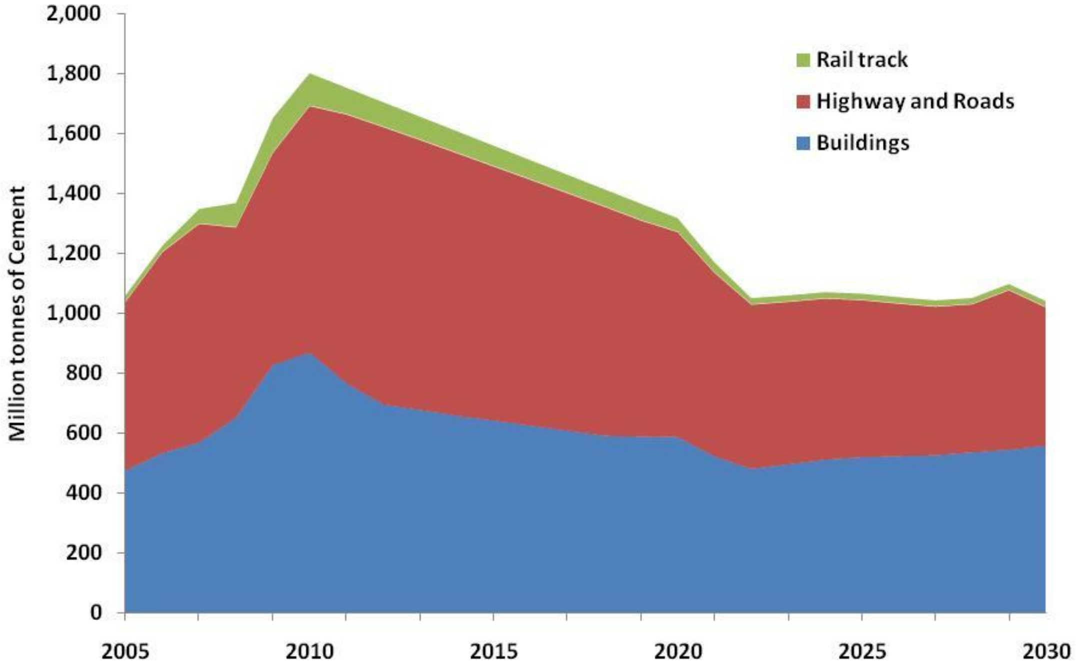
Where:

P_c = Annual cement production
$CFSu$ = Urban commercial floorspace (3 year rolling average)
$CFSr$ = Rural commercial floorspace (3 year rolling average)
$RFSu$ = Urban residential floorspace (3 year rolling average)
$RSFr$ = Rural residential floorspace (3 year rolling average)
$CI1$ = Building cement material intensity
PA = Urban paved area
$CI2$ = Paved area cement material intensity
H = Highways, specifically expressways, and Class 1 and 2 highways (3 year rolling average)
$CI3$ = Highway cement material intensity
R = Railroad track length, 3 year rolling average
$CI4$ = Railroad track cement material intensity
Ex = Net exports of cement

Figure 41 provides historical and projected cement consumption by end-uses to 2030. Figure 42 provides assumed cement production by kiln type (rotary and shaft) in China to 2030. Since VSKs are typically more energy-intensive and produce larger emissions of pollutants, use of these kilns is being phased out in China. Official government policy is that VSKs with a diameter less than 3.0 meters shall be phased out by 2012 (State Council 2010) and it is expected that the soon-to-be-released *Industrial Policy for Cement Industry* will indicate that China's cement sector should be comprised of 90% rotary kilns and 10% other, including VSKs, by 2015 (Li 2010;

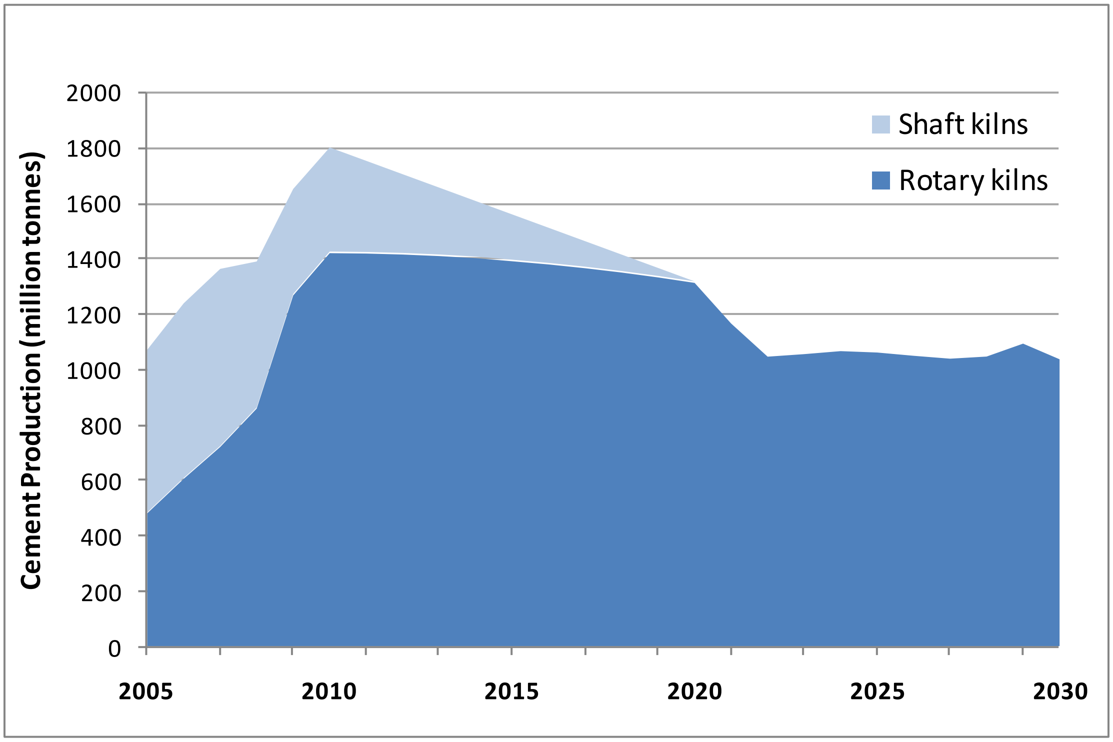
Wang 2010). Both figures show that cement production increases until 2010, when the annual production of about 1800 Mt begins to decline, reaching about 1040 Mt in 2030.

Figure 41 Historical and Projected Implied Cement Use by End-use, 2005-2030



Note: Implied cement use does not include net exports.

Figure 42 Historical and Projected Cement Production by Shaft and Rotary Kilns in China, 2005-2030.



6.1 Continuous Improvement Scenario

The base case for the cement sector is the Continuous Improvement (CI) scenario. This scenario uses the production values provided above and assumes continued improvement of energy efficiency and emissions reductions in the cement sector based on both autonomous improvements and continued implementation of policies and programs that provide information, financing, and incentives to cement enterprises to improve energy efficiency and reduce emissions.

Final energy intensity values in this scenario are based on meeting current (2005) world best practice of 100 kgce/t cement for Portland cement (Worrell et al. 2008)[10] by about 2025 and phasing out all shaft kilns by 2020. The assumed 2005 energy intensity value for all cement production in China is 125 kgce/t cement. This calculation is based on a reported energy intensity of 119 kgce/t clinker and electricity intensity of 97 kWh/t cement for rotary kilns and a reported energy intensity of 147 kgce/t clinker and electricity intensity of 87 kWh/t cement for vertical shaft kiln (VSK) production (Liu et al. 2007).[11] Based on NSP production of 481 Mt and

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[10] The minimum energy performance standard for large Chinese cement facilities (≥ 4,000 t/d) is ≤105 kgce/t cement (comparable comprehensive energy consumption) for existing facilities, ≤96 kgce/t cement for new facilities, and ≤93 kgce/t cement for "advanced" facilities (General AQSIQ and SAC 2007).

[11] This report provides detailed energy intensity information on 120 surveyed cement companies that accounted for 10.9% of total cement production in China in 2006. The report states that "the specific energy consumption for cement manufacturing in China was 142 kg-standard coal per ton in 2006". This value is comparable to other values for 2005 and 2006 that were based on an electricity conversion factor of 0.404 kgce/kWh. However, NBS

VSK production of 588 Mt in 2005, the weighted average final energy intensity is calculated to be 113 kgce/t cement for NSP kilns, 136 kgce/t cement for VSK kilns, and 125 kgce/t cement for the entire cement industry. Table 10 provides information on the assumed final energy intensity values for VSK, rotary kilns, and total cement production in China from 2005 to 2030 for the CI scenario.

Table 10 Energy Intensity (kgce/t cement) of Cement Production by Process in China in Continuous Improvement Scenario.

	2005	2010	2020	2030
Rotary Kiln Production	113	107	102	94
Vertical Shaft Kiln Production	136	118	Phased out	Phased out
Total Production	125	110	102	94

Regarding fuel shares, this scenario assumes a steady decline from the 2000 share of 85% coal to 60% coal by 2030 (see Table 11). Alternative fuels can be used as a substitute for coal in a cement kiln. It is assumed that China uses about 40% alternative fuels in 2030, slightly less than the current amount used in Norway (45%), the Czech Republic (45.3%), Austria (47%), Switzerland (47.8%), and Germany (50%) (Wang 2008). This scenario also assumes that the clinker-cement ratio remains at the 2005 level through 2025 and then declines by 5% in 2030.

Table 11 Fuel Shares (%) for Cement Production by Process in China in Continuous Improvement Scenario

	2005	2010	2020	2030
Rotary				
Coal (bituminous)	89.1	83.95	71.97	60
Electricity	9.82	10.79	12.4	14
Natural Gas	0	0	0	0
Biomass (unspecified)	0.1	1	1	1
Other Fuel	1.02	4.26	14.63	25
VSK and Other				
Coal (bituminous)	89.2	84.95	Phased out	Phased out
Electricity	9.82	10.79		
Other Fuel	1.02	4.26		

6.2 Accelerated Energy Efficiency Scenario

An "Accelerated Energy Efficiency (AEE)" scenario was developed to estimate the potential for increased energy efficiency in China's cement industry. For this scenario, both cement

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changed the electricity conversion factor from 0.404 kgce/kWh to 0.1229 kgce/kWh for the calculation of comprehensive energy consumption. Thus, a reported value of 153 kgce/t cement using the older conversion factor is 127 kgce/t cement using the new conversion factor (Zeng 2009). It is not possible, however, to replicate these values using the process-specific values reported in Liu et al. 2007, most likely because the surveyed plants represent more efficient plants than the national average. As such, an adjustment was made to increase the clinker-to-cement ratio in the calculation spreadsheets from the actual values to higher clinker-to-cement ratios to generate higher, more representative energy intensity values.

production levels and fuel shares are assumed to be the same as those in the CI scenario. The two variables that improve under this scenario are the final energy intensity values and the clinker-to-cement ratio. This scenario assumes the clinker-cement ratio remains at the 2005 level until 2010 and then declines by 5% in 2020 and 10% (relative to the 2005 value) in 2030.

Final energy intensity values in the AEE scenario are based on meeting the 2005 current world best practice of 100 kgce/t cement for Portland cement by about 2020 and current world best practice of 70 kgce/t for fly ash cement by about 2040. In addition, the final energy intensity value is based on phasing out all shaft kilns by 2020. Table 12 provides information on the assumed final energy intensity values for VSK, rotary kilns, and total cement production in China from 2005 to 2030 for the AEE scenario.

Table 12 Energy Intensity (kgce/t cement) of Cement Production by Process in China in Accelerated Energy Efficiency Scenario

	2005	2010	2020	2030
Rotary Kiln Production	113	107	100	85
Vertical Shaft Kiln Production	136	118	Phased out	Phased out
Total Production	125	110	100	85

Table 13 provides typical fuel and electricity savings, capital costs, and change in annual operations and maintenance (O&M) costs for 34 energy-efficiency measures applicable to the cement industry. An analysis of 16 NSP kiln cement plants in Shandong Province found that the annualized costs of 14 electricity-efficiency measures and all fuel-efficiency measures (taking the resulting energy savings into account) were below the annual costs of electricity and fuel, respectively, indicating that they are cost-effective (Price et al. 2009).

Table 13 Typical Fuel and Electricity Savings, Capital Costs, and Change in Annual Operations and Maintenance (O&M) Costs for 34 Selected Energy-Efficiency Technologies and Measures

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

No.	Technology/Measure	Typical Fuel Savings (GJ/t clinker)	Typical Electricity Savings (kWh/t clinker)	Typical Capital Cost (RMB/t clinker)	Typical Change in Annual O&M cost (RMB/t clinker)
22	Bucket elevators for kiln feed		1.24	2.41	0.0
23	Replacement of preheater fan with high efficiency fan		0.70	0.47	0.0
	Finish Grinding				
24	Energy management & process control in grinding		4.00	3.21	0.00
25	Replace ball mill with vertical roller mill		25.93	53.50	0.0
26	High pressure roller press as pre-grinding to ball mill		24.41	53.50	0.0
27	Improved grinding media for ball mills		6.10	7.49	0.0
28	High-Efficiency classifiers for finish grinding		6.10	21.40	0.0
29	Replacement of cement mill vent fan with high efficiency fan		0.13	0.06	0.0
	General Measures				
30	Use of alternative fuels	0.60		7.52	0.0
31	High efficiency motors		4.58	2.35	0.0
32	Adjustable Speed Drives		9.15	9.63	0.0
	Product Change [c]	**Fuel Savings (GJ/t cement)**	**Electricity Savings (kWh/t cement)**	**Capital Cost (RMB/t cement)**	**Change in Annual O&M cost (RMB/t cement)**
33	Blended cement (Additives: fly ash, pozzolans, and blast furnace slag)	1.77	-7.21[a]	4.92	-0.27
34	Portland limestone cement	0.23	3.30	0.82	-0.04

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

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

[c]: Since the "Share of production to which the measure applied" for product change measures is based on the "Share from total Cement Production Capacity in 2008", the calculations were made based on production of cement in contrast to the other measures for which the calculations were based on the clinker production capacity.

6.3 SO_2 Emissions Mitigation Scenarios

SO_2 emissions from cement production are directly related to combustion of coal in the kiln. The level of oxidation of sulfur varies significantly by kiln type. The more modern NSP kilns typically emit 2.9 g SO_2/kg of coal, due to the absorption of SO_2 during the reaction with calcium oxide in the kiln as well as the capture of SO_2 through the use of baghouse filters, which are common on NSP kilns. VSK and other rotary kilns typically emit 12.3 g SO_2/kg of coal (Liu, 2006 and Lei, 2010).

SO_2 emissions from Chinese cement kilns are provided in Table 14. Using the emissions factors provided above, SO_2 emissions from NSP and VSK kilns have been calculated.

Table 14 SO_2 Emissions from Chinese Cement Kilns.

	2005	2006	2007	2008	2009
Rotary Kiln Production	480	551	541	611	884
Vertical Shaft Kiln Production	706	681	562	432	299
Total Production	1186	1231	1103	1043	1183

Two SO_2 mitigation scenarios were developed. The first focuses on implementation of mitigation technology options including absorbent addition, wet scrubbers, and activated carbon. The second focuses on fuel switching, specifically increasing the share of biomass used in the cement kiln.

6.3.1 SO_2 Mitigation Technologies Scenario

For this scenario, all assumptions (production, final energy intensity, fuel shares, and clinker-to-cement ratio) are the same as in the CI scenario. In addition, this scenario assumes full implementation of SO_2 mitigation technologies by 2030. Full implementation of absorbent addition can reduce SO_2 emissions by 60-80%, full implementation of wet scrubbers can reduce SO_2 emissions by greater than 90%, and full implementation of activated carbon can reduce SO_2 emissions by up to 95%.

Table 15 shows that the capital costs of these measures range from 0.2 to 23 million Euro (1.9 to 219 million RMB) and that the annual operations and maintenance (O&M) costs range from 0.1 to 4 Euro/t clinker (1 to 38 RMB/t clinker).[12]

For this scenario, it is assumed that through the full adoption of a combination of these technologies, SO_2 emissions are reduced by 90% by 2030.

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[12] A recent study of 16 cement plants in Shandong Province found a range of annual clinker production capacity of 0.32 to 2.3 million metric tons (Price et al. 2009).

Table 15 SO_2 Emission Reduction Potential, Capital Costs, and Operations and Maintenance Costs of SO_2 End-of-Pipe Abatement Technologies

Technology	SO2 Emission Reduction	Costs	References
Absorbent addition	60-80%	Capital: 0.2-0.3 million Euro (1.9-2.9 mil RMB) O&M: 0.1 – 0.4 Euro/t clinker (1 – 3.8 RMB/t clinker)	EC 2010
		0.2 to 3.2 Euro/t clinker (1.9 to 30.5 RMB/t clinker)	Wesselink et al. 2010
Wet scrubber	> 90%	Capital: 5.8-23 million Euro (55-219 million RMB) O&M: 0.5 – 2 Euro/t clinker (4.8 – 19 RMB/t clinker)	EC 2010
		1.7 to 4.0 Euro/t clinker (16 to 38 RMB/t clinker)	Wesselink et al. 2010
Activated carbon	Up to 95%	Capital: 15 million Euro (143 million RMB) O&M: N/A	EC 2010
		4.7 Euro/t clinker (44.8 RMB/t clinker)	Wesselink et al. 2010

6.3.2 SO_2 Fuel Switching Scenario

For this scenario, all assumptions (production, final energy intensity and the clinker-to-cement ratio) are the same as in the CI scenario. This scenario assumes accelerated use of alternative fuels in rotary kilns such that the share of coal use drops from 85% to 50% in 2030. The reduction in SO_2 is equivalent to the share of fuel displaced. This option may be less expensive than using coal, but the costs and benefits will depend on the type of alternative fuel used (Murray and Price 2008). In addition, this scenario assumes that the share of biomass increases from 1% in 2005 to 25% in 2030.

6.4 CO_2 Scenario Assumptions

A CO_2 abatement scenario was developed that has the same production assumption as the CI scenario, but – in order to mitigate energy-related CO_2 – adopts the AEE scenario assumptions for final energy intensity and the clinker-to-cement ratio. This scenario assumes accelerated use of alternative fuels in rotary kilns such that the share of coal use drops from 85% to 60% in 2030.

Carbon capture and storage (CCS) for control of CO_2 in the cement sector was not considered in this report. One reason is that current analyses indicate that its use will not be significant before 2030. The International Energy Agency and the World Business Council for Sustainable Development, for example, projects CCS for the cement industry will not be commercially available before 2020 and that less than half of the global cement manufacturing capacity could be equipped with CCS between 2030 and 2050 assuming a 100% implementation rate for new large kilns, indicating that only a small share could potentially be constructed before 2030. Even if this capacity is installed, the costs for CCS are projected to be high, ranging from "EUR20 to over EUR75 per tonne of CO_2 captured (EUR20/t CO_2 is likely to be achievable only under very favorable circumstances and is not representative of the average cost of mass deployment of CCS)." Finally, CCS is not considered because it also has a high energy penalty, increasing plant electricity use by 50-120% (IEA/WBCSD 2009; ECRA 2009).

6.5 Optimal Co-Control Scenario

The optimal co-control scenario represents a combination of most of the accelerated variables presented in the above individual scenarios. As with all of the other scenarios, this scenario has the same production assumption as the CI scenario. This scenario adopts the AEE scenario assumptions for final energy intensity and clinker-to-cement ratio, assumes accelerated use of alternative fuels in rotary kilns such that the share of coal use drops from 85% to 50% in 2030, and includes fuel switching such that the share of biomass increases from 1% in 2005 to 25% in 2030.

Due to the high cost of SO_2 abatement mitigation technology measures, these technologies are not fully implemented in this scenario in order to determine the maximum SO_2 and CO_2 emissions reductions that can be realized using measures that "co-control" – or influence both types of emissions – at a minimum cost. If desired, additional SO_2 control could then be obtained by adding these measures.

6.6 Results

6.6.1 SO_2 Control Scenarios

Figure 43 illustrates the total SO_2 emissions for cement production for each of the six scenarios for 2005 to 2030. Overall, the SO_2 emissions trend follows the cement production trend shown in Figure 42 above which shows a continuing drop from the peak in 2010 to a plateau that begins between 2020 and 2025 and continues to 2030. The drop in SO_2 emissions between 2010 and 2020 shown in Figure 43 is more rapid than the drop in overall cement production during the same period because the more SO_2 intensive VSKs are being phased out during this period, resulting in greater reductions in SO_2 emissions. As noted above, modern NSP kilns typically emit 2.9 g SO_2/kg of coal while VSK and other rotary kilns typically emit 12.3 g SO_2/kg of coal (Liu 2006; Lei, et al. 2010).

Figure 43 through Figure 45 provide the results of the 6 scenarios, both annually and on a cumulative basis. The largest SO_2 emissions reductions are realized in the SO_2 abatement scenario in which a combination of absorbent addition, wet scrubbers, and activated carbon is implemented in order to reach 90% reduction in SO_2 by 2030. Achievement of this scenario, however, is costly.

In the co-control scenario, the application of SO_2 end-of-pipe abatement technologies is reduced in order to achieve maximum savings at a more reasonable cost. The co-control scenario, therefore, relies more heavily on lower-cost options such as energy efficiency and fuel switching, rather than full implementation of the more costly end-of-pipe SO_2 mitigation options.

Figure 43 Total SO_2 Emissions for Cement Production by Scenario, 2005-2030

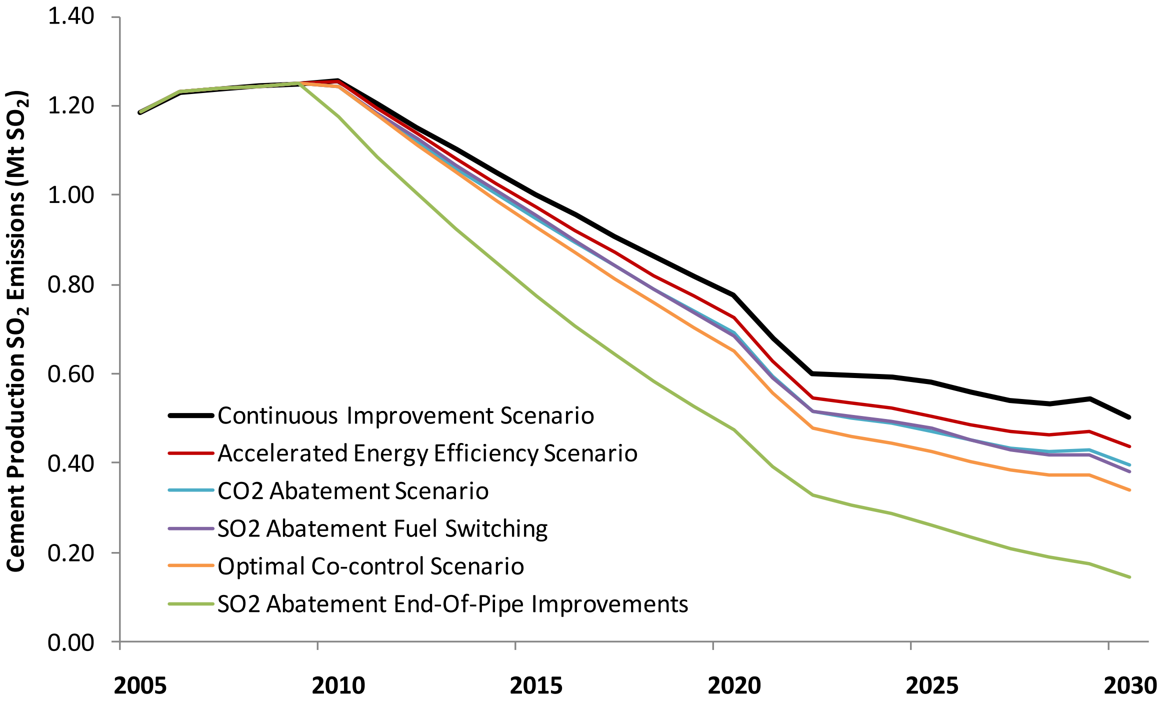


Figure 44 2030 SO_2 Emissions for Cement Production by Scenario

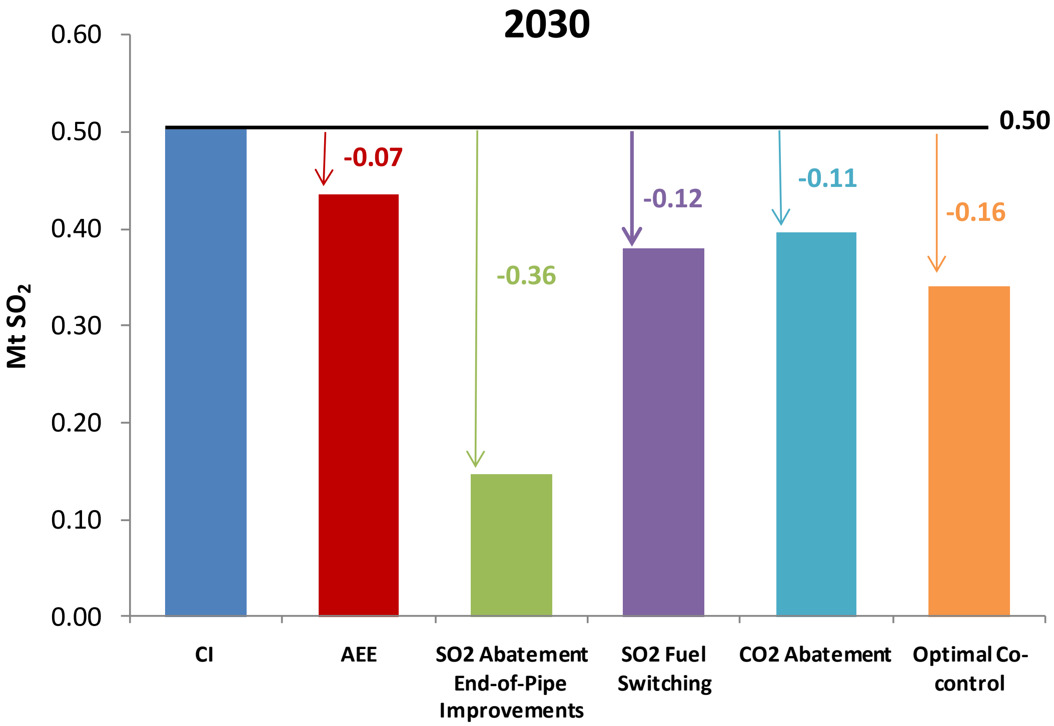
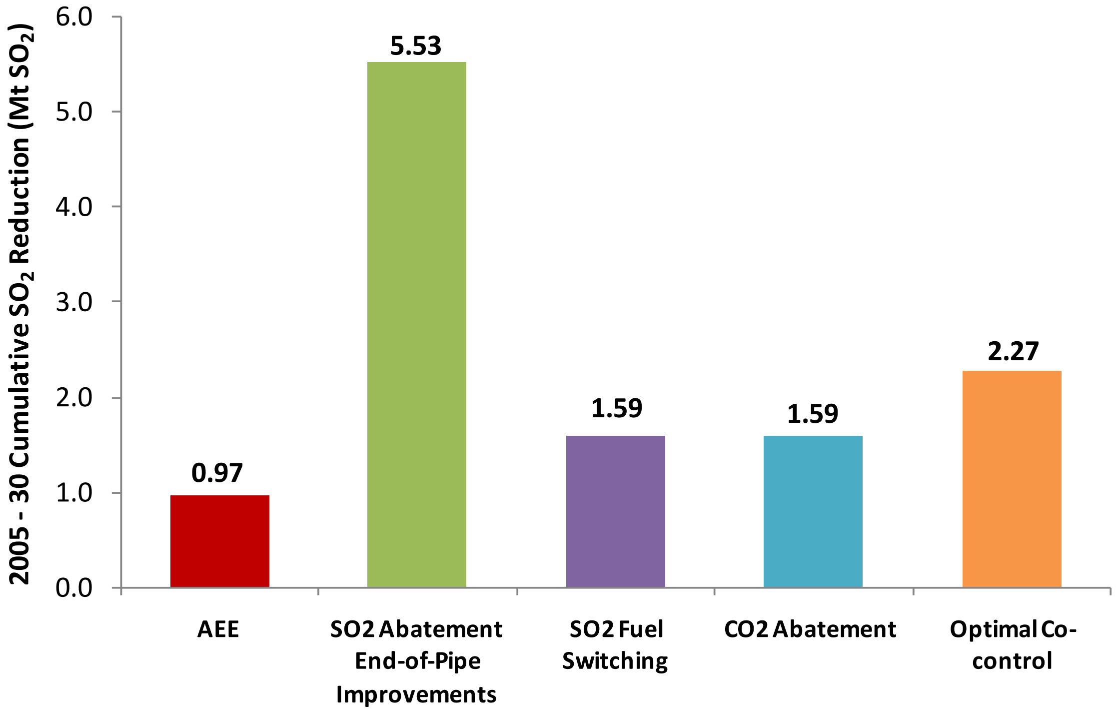


Figure 45 2005-2030 Cumulative SO_2 Reductions for Cement Production by Scenario



6.6.2 CO_2 Control Scenarios

CO_2 emissions from cement manufacturing are the result of combustion of fossil fuels in the kiln and for production of electricity use to power motors and other electrical equipment as well as the calcination of limestone in the kiln.

Figure 46 to Figure 47 show the results of the 6 scenarios in terms of achieved CO_2 emissions reductions from fuel combustion as well as process-related emissions. CO_2 emissions decline in all scenarios due to the projected decline in cement production in China between 2010 and 2030.

Emissions in the continuous improvement and the SO_2 abatement through mitigation technology scenarios decline at the same rate, since all of the scenario assumptions are the same except that SO_2 mitigation technologies are used in the SO_2 abatement scenario, which have no impact on CO_2 emissions.

CO_2 emissions reductions in the accelerated energy efficiency scenario and the CO_2 emissions abatement scenario are greater than those realized in the continuous improvement scenario since they both assume the increased penetration of energy-efficient technologies and measures. In addition, the CO_2 abatement scenario assumes that coal use declines to 50% in 2030, slightly lower than the assumed 60% share in the continuous improvement and accelerated energy efficiency scenarios.

Even greater CO_2 emissions reductions are seen in the SO_2 fuel switching scenario, due to the fact that this scenario also assumes that coal use in the kiln declines to 50% by 2030, but specifies that 25% of the replacement fuel for coal is biomass, which is assumed to be carbon neutral.

Finally, fuel-related CO_2 emissions are lowest in the optimal co-control scenario, which incorporates all of the assumptions outlined in the above scenarios.

Figure 46 Total CO_2 Emissions (Energy- and Process-Related) for Cement Production in China, 2005-2030

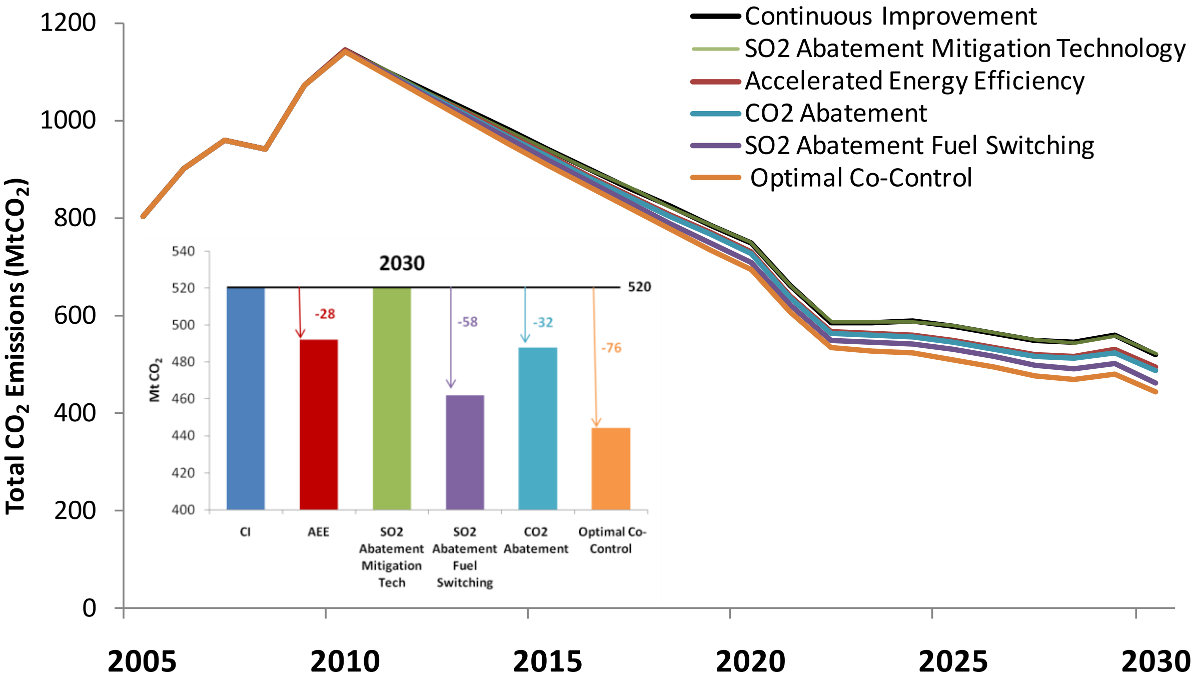
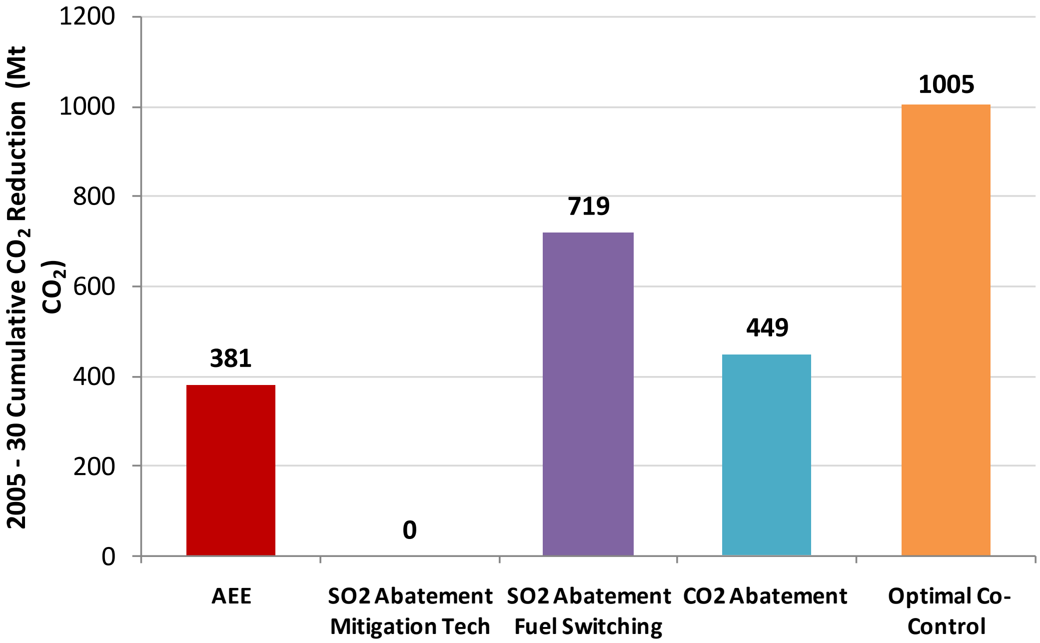


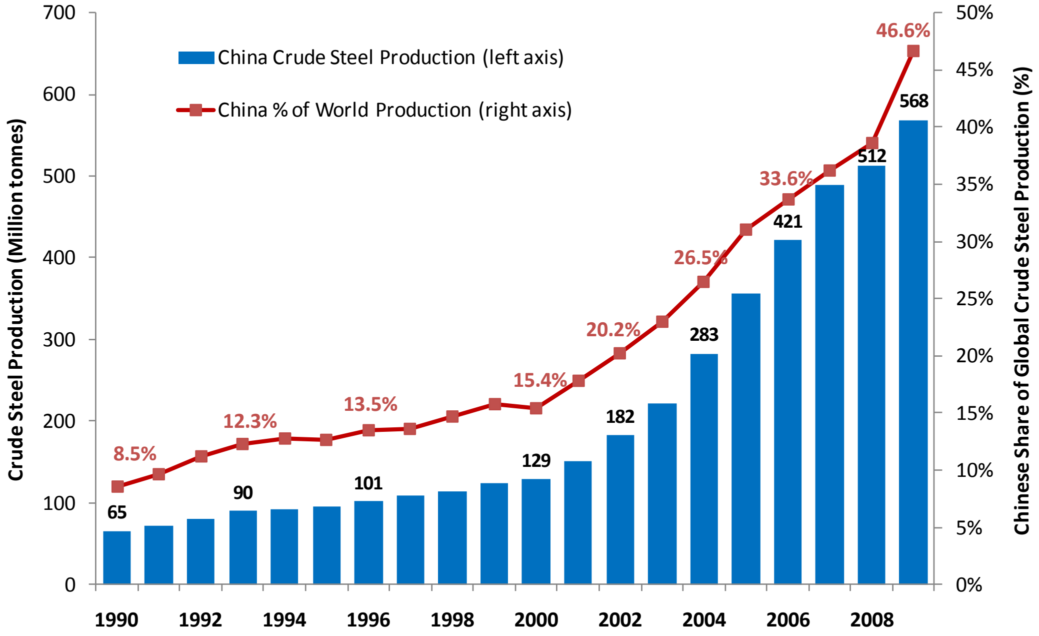
Figure 47 2005 – 2030 Cumulative CO_2 Reductions for Cement Production by Scenario



7. Iron and Steel Sector

China is the world's largest producer of iron and steel, manufacturing 45% of global steel in 2010 (USGS, 2011b). The base year for the steel sector scenarios in this report is 2005; China's steel production in that year was 353 Mt (NBS 2010a). There are two main processes for the production of steel: primary steel is produced using iron ores and secondary steel is produced using scrap steel. These two processes are referred to as blast furnace/basic oxygen furnace (BF/BOF) and electric arc furnace (EAF) steel production, respectively. A wide variety of steel products are produced by the industry, ranging from slabs and ingots to thin sheets, which are used in turn by many other manufacturing industries. Figure 48 shows China's crude steel production and share of global production from 1990-2009 (EBCISIY Various Years; worldsteel 2010).

Figure 48 China's Historical Crude Steel Production and Share of Global Production (1990-2009)



Sources: EBCISIY various years; worldsteel 2010

Future production of steel is based on LBNL's 2050 urban residential and commercial construction forecast, derived using the following formula:

$P_s = (\beta c \times Pc) + (\beta p \times GDPi) + Ex$

Where:

P_s = Annual steel production

βc = Structural steel to cement ratio, in kilograms of steel to kilograms of cement

P_c = Annual cement production

βp = Product steel to industry value-added GDP ratio, in tons of steel per million 2006 US Dollars

$GDPi$ = Industry value-added GDP

Ex = Net steel exports

Figure 49 Steel Production by Process, 2005 - 2030

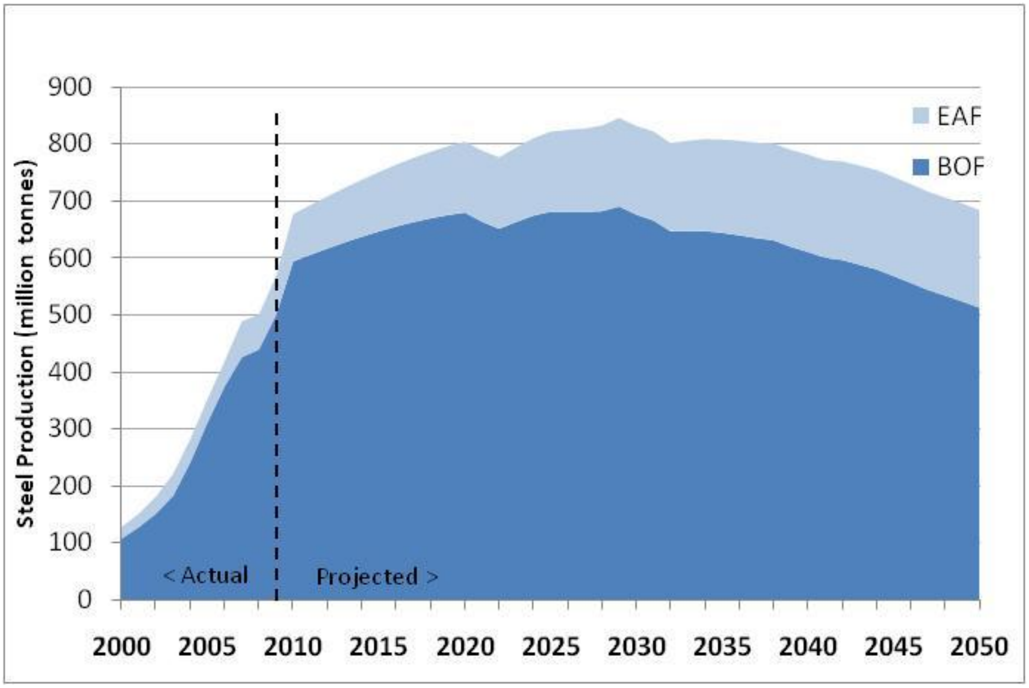


Figure 49 illustrates the assumed steel production by process in China to 2030.

Energy use (and related emissions) for cokemaking within the steel industry are not included in this analysis, since coke production is treated separately in the LEAP model. Energy values used for this analysis only include the energy used to produce crude steel from the EAF and do not include energy used for rolling and finishing steel products. Energy values are expressed in final (site) energy and do not include losses experienced in the generation, transmission, and distribution of electricity used to produce steel.

7.1 Continuous Improvement Scenario

The base case for the steel sector is the Continuous Improvement (CI) scenario. This scenario uses the production values provided above and assumes continued improvement of energy efficiency and emissions reductions in the steel sector based on both autonomous improvements and continued implementation of policies and programs that provide information, financing, and incentives to steel enterprises to improve energy efficiency and reduce emissions.

Final energy intensity values for steel production in this scenario are based on meeting current (2005) international best practice intensity by 2050. It is assumed that 50% of the steel products will be produced using thin slab casting and the remaining 50% will be produced using continuous casting by 2050. Table 16 provides information on the assumed final energy intensity values for BF/BOF, EAF, and total steel production in China from 2005 to 2030 in the CI scenario.

Table 16 Energy Intensity (kgce/t steel) of Steel Production by Process in China in Continuous Improvement Scenario

	2005	2010	2020	2030
BF/BOF Production	791	633	607	582
EAF Production	130	125	122	120
Total Steel Production	713	571	532	496

Regarding fuel shares, this scenario assumes a steady decline in coal use for steelmaking from a share of 26% in 2000 to 22% by 2030. Table 17 provides the fuel shares for steel production in China from 2005 to 2030. Fuel share information was derived from scenario 1 of Wang et al. (2007). This scenario also assumes that the share of EAF steel production in China increases from 16.3% in 2000 to 18.6% in 2030.

Table 17 Fuel Shares (%) for Steel Production by Process in China in Continuous Improvement Scenario

	2005	2010	2020	2030
BF/BOF Production				
Coal {bituminous}	25.5	24.98	22.85	21.96
Coke	61.8	61.37	61.51	60.21
Heavy Oil	2	1.8	1.43	2.13
Natural Gas	0.65	0.8	0.73	0.83
Electricity	10	11.05	13.48	14.85
EAF Production				
Electricity	98	98	98	98
Natural Gas	2	2	2	2

7.2 Accelerated Energy Efficiency Scenario

An Accelerated Energy Efficiency (AEE) scenario was developed to estimate the potential for increased energy efficiency in China’s steel industry. For this scenario, both steel production levels and fuel shares are assumed to be the same as those in the CI scenario. The two variables that improve under this scenario are the final energy intensity values and the share of EAF steel produced in China.

Final energy intensity values in the AEE scenario are based on meeting the 2005 current world best practice energy intensity for both BF/BOF and EAF steel production by about 2030. In addition, the share of EAF steel production grows from 16.3% in 2000 to 26.3% in 2030. Table 18 provides information on the assumed final energy intensity values for BF/BOF, EAF, and total steel production in China from 2005 to 2030 for the AEE scenario. Fuel shares are assumed to be the same as those in the CI scenario.

Table 18 Energy Intensity (kgce/t steel) of Steel Production by Process in China in Advanced Energy Efficiency Scenario

	2005	2010	2020	2030
BF/BOF Production	791	633	582	536
EAF Production	130	125	121	116
Total Steel Production	713	569	492	422

Appendix A.3 provides information on energy-efficiency technologies and measures for the steel industry. Information on the capital costs associated with these technologies can be found in the *State-of-the-Art Clean Technologies for Steelmaking Handbook* (APP 2007) and in Worrell et al. (2010).

7.3 SO_2 Emissions Mitigation Scenarios

SO_2 emissions from steel production are mostly from combustion of sulfur compounds in the sinter feed (coke breeze and iron ores). Additional SO_2 emissions are from the induration process (drying, heating, and cooling) in pelletization, and coke oven firing. SO_2 emissions from steel production can be mitigated by minimizing the sulfur content in the raw materials (especially the sinter feed) and coal, sinter waste gas recycling, sinter flue gas desulfurization, and use of other selected mitigation technologies such as fabric filters, dry-gas off-gas cleaning, fine wet scrubbers, and regenerative activated carbon (RAC) (IFC 2007; EC 2009).

Reported SO_2 emissions from Chinese steel mills are provided in Table 19. The steel sector is the second largest SO_2 emitter in China, after the power sector. The majority of SO_2 emissions from this sector are from the sintering process, which accounts for about 50% of total SO_2 emissions in the iron and steel industry. If self-generated power plants in the steel industry are excluded, SO_2 emissions from the sintering process represent around 90% of the total SO_2 emissions in this sector (Guo 2009; Rong 2010; Zhou 2010).

Table 19 SO_2 Emissions from Chinese Steel Mills ($MtSO_2$)

	2005	2006	2007	2008e	2009e
Total	1.465[1]	1.42[1]	1.72[1]	1.66[2]	1.58[2]

[1] Source: Yan 2008.

[2] 2008 and 2009 emissions are estimated using reported year-on-year reduction rates for 2008 and 2009. Sources: China Industrial News Network 2009; State Council Information Office 2010

Two SO_2 mitigation scenarios were developed. The first scenario focuses on full implementation of one of the mitigation technologies available for steel production: wet desulfurization. The second scenario assumes full implementation of sinter waste gas recycling.

7.3.1 SO_2 Mitigation Technologies Scenario – Wet Desulfurization

Large state-owned enterprises in China are required by the government to install flue-gas desulfurization technologies in sintering machines (Zhang 2010). China’s steel sector has about

400 sintering machines, but only around 20 companies have installed or planned to install desulfurization equipment. Currently the penetration of flue gas desulfurization (FGD) technologies is about 5% in China (Guo 2009; Rong 2010; Zhou 2010). China is in the initial stages of adopting FGD technologies for the sintering process and even though use of this technology is mature in the power industry, it is not completely mature in sintering machines (Zhang 2010), although more than ten different wet, semi-wet, and dry desulfurization technologies have been adopted. Regardless of which flue gas desulfurization technology is used, all require large investments equal to about 20~50% of the total investment for the sintering machine (Guo 2009; Rong 2010; Zhou 2010).

Estimated capital costs from implementation of wet desulfurization in European case studies are in the range of 442-708 million RMB (50-80 million €; 67-107 million US$) for a sinter plant with a capacity of 4 Mt/yr, a waste gas flow of 1 MNm3/h, 8640 operational hours per year and untreated SO_2 emissions of 1200 g/t sinter and 90% desulphurization efficiency (EC 2009). In addition, there are also costs of 4.4-9.7 RMB/t (0.5 - 1.1€ /t; 0.7-1.5US$/t) sinter associated with the operation and maintenance of wet desulfurization controls throughout the lifetime of this measure. The use of desulfurization also results in an increase in electricity consumption of 1.7 - 2 kWh/t sinter (EC 2009). In addition, there are also challenges related to the utilization of by-products from desulfurization, which pose serious concerns over secondary-pollution. Enterprises have little experience in applying these technologies, including project design, equipment procurement, and maintenance (Guo 2009; Rong 2010; Zhou 2010).

This scenario is based on the adoption of wet flue gas desulfurization in sinter plants. For this scenario, all assumptions (production, final energy intensity, fuel shares, and share of EAP production) are the same as in the CI scenario. It is assumed that only 5% of SO_2 emissions are currently mitigated through the use of FGD technologies in China. This scenario assumes, however, that 85% reduction of SO_2 emissions with full implementation of wet desulfurization is achieved by 2030.

7.3.2 Sinter Waste Gas Recycling Scenario

Sinter waste gas recycling can involve recycling of part of the mixed collected waste gas from the sinter strand back to the entire surface of the singer strand, recycling of waste gas from the end sinter strand combined with heat exchange, recycling of waste gas from part of the end sinter strand and use of waste gas from the sinter cooler, and recycling of part of the waste gas to other parts of the sinter strand. Capital costs for these various options range from 71-150 million RMB (8-17 million €; 11-23 US$), while operation and maintenance costs are typically decreased by 22 million RMB (2.5 million €; 3.3 million US$) per year. There are no increases in energy use associated with sinter waste gas recycling technologies (EC 2009).

For this scenario, all assumptions (production, final energy intensity, fuel shares, and share of EAP production) are the same as in the CI scenario. This scenario assumes full implementation of sinter waste gas recycling, resulting in a 30% reduction in SO_2 emissions in 2030. Fuel savings associated with implementation of this mitigation option (which only applies to BF/BOF steel) are included in the final energy intensity values.

7.4 CO_2 Scenario Assumptions

A CO_2 abatement scenario was developed that has the same production assumption as the CI scenario, but – in order to mitigate energy-related CO_2 – adopts the AEE scenario assumptions for final energy intensity and the share of EAF steel produced. This scenario assumes reduced use of coal and an increased use of natural gas from fuel shares of 0.84% in 2030 in the CI scenario to 2.1% in this scenario.

7.5 Optimal Co-Control Scenario

The optimal co-control scenario represents a combination of most of the accelerated variables presented in the above individual scenarios. As with all of the other scenarios, this scenario has the same production assumption as the CI scenario. This scenario adopts the AEE scenario assumptions for final energy intensity and share of EAF steel production. This scenario adopts the CO_2 mitigation scenario assumption regarding the reduced use of coal and increased use of natural gas for steel production. This scenario also assumes total SO_2 emissions reductions of 90% in 2030 comprised of SO_2 emissions reductions from energy efficiency and CO_2 emissions mitigation technologies and measures, full implementation of sinter waste gas recycling and the remaining reductions through the implementation of wet desulfurization.

7.6 Results

7.6.1 SO_2 Control Scenarios

Figure 50 show total SO_2 emissions for steel production under each scenario. As can be seen, SO_2 emissions are assumed to remain relatively stable in the CI Scenario, dropping slightly by 2030. Under the AEE and CO_2abatement scenarios, SO_2 emissions fall to 1.2 MtSO2/year and 1.1 MtSO_2/year, respectively, in 2030. All of these SO_2 emissions reductions are co-benefits from the implementation of energy efficiency and CO_2 mitigations technologies and measures.

The first scenario specifically designed to reduce SO_2 emissions, the sinter waste gas recycling scenario, results in emissions of 1.0 MtSO_2/year in 2030. The second SO_2 emissions reduction scenario, the wet desulfurization scenario, results in emissions of 0.2 MtSO_2/year in 2030, significantly lower than the first SO_2 emission reduction scenario. This scenario, however, is much more expensive to realize than the other scenarios presented above.

The optimal co-control scenario was designed to reduce SO_2 emissions by 90% while relying on the lowest cost options to the extent possible. Thus, cost-effective energy efficiency and CO_2 emissions mitigation technologies are combined with low-cost sinter waste gas recycling to the maximum extent possible. The more costly flue gas desulfurization, then, only needs to be implemented at a level of about 60% in this scenario. As a result of these combined efforts, SO_2 emissions in 2030 are about 0.1 $MtSO_2$/year.

Figure 50 Total SO_2 Emissions for Steel Production in China, 2005-2030

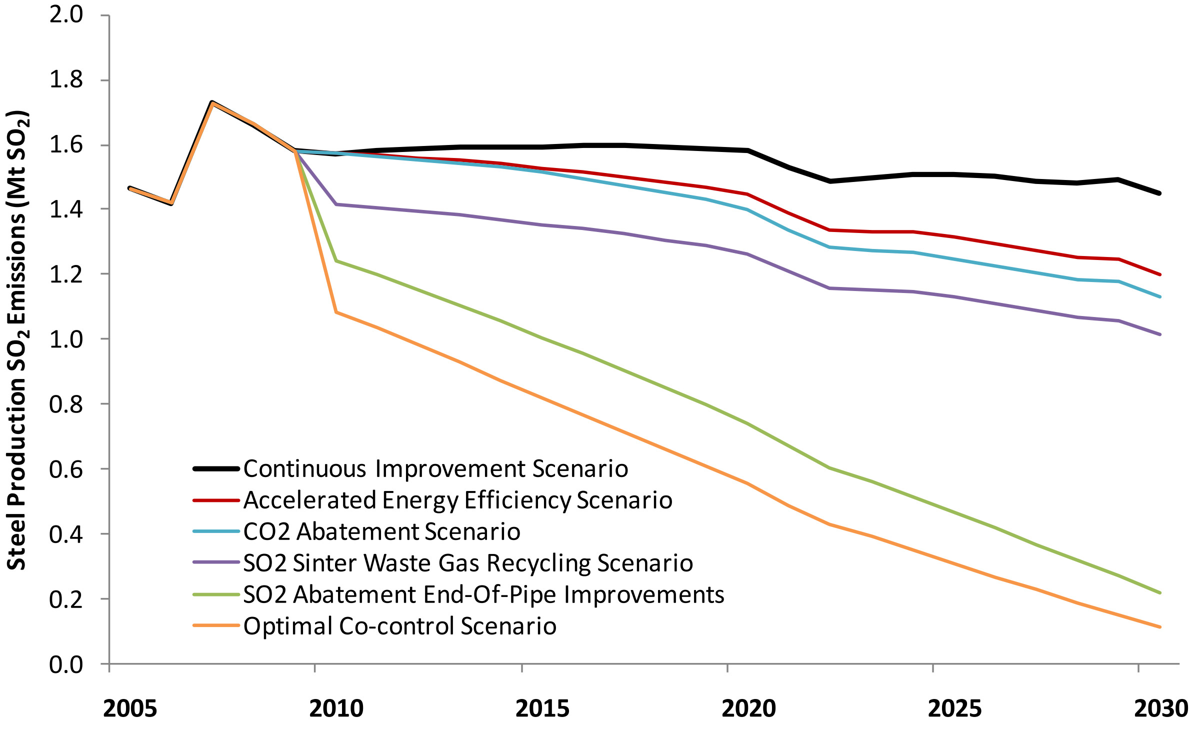


Figure 51 Total SO_2 Emissions for Steel Production by Scenario, 2030

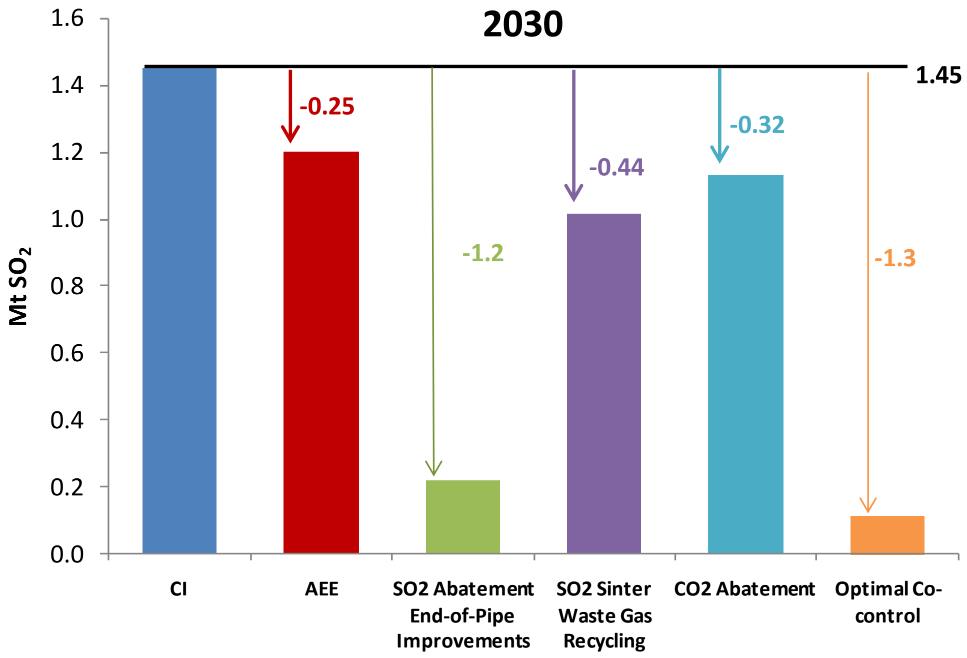
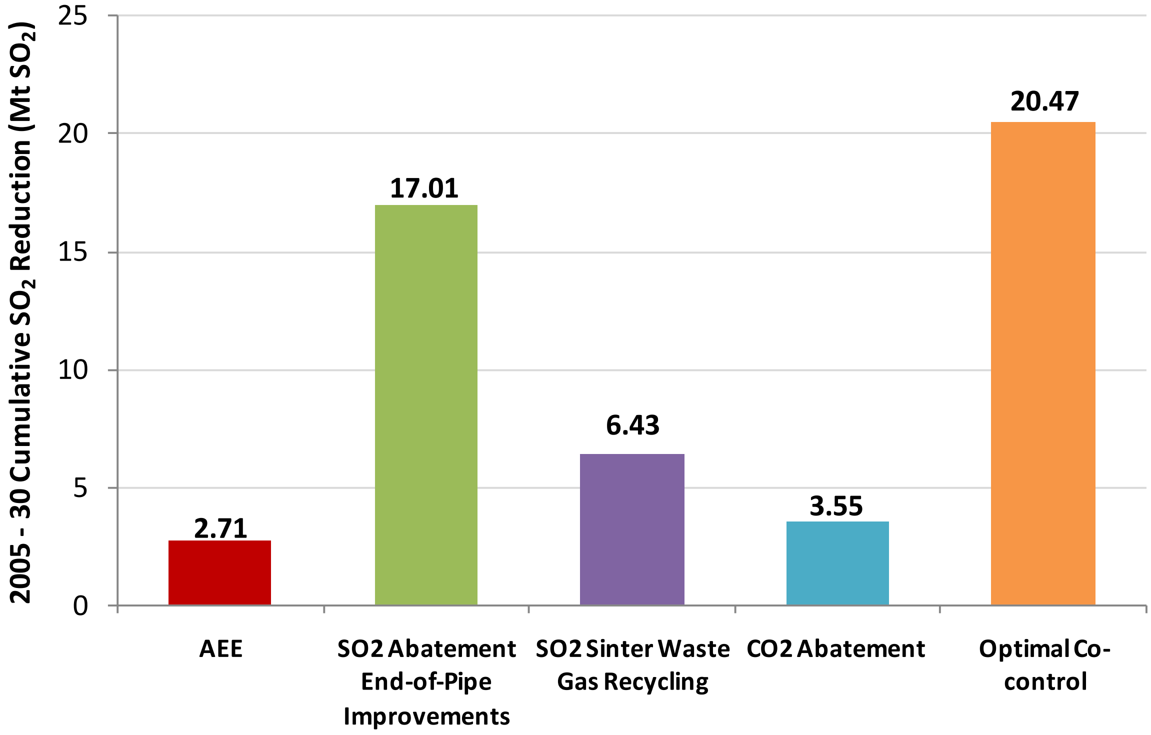


Figure 52 2005-2030 Cumulative SO_2 Reductions by Scenario for Steel Production



7.6.2 CO_2 Control Scenarios

Figure 53 through Figure 55 show the results of the six scenarios in terms of CO_2 emissions trends to 2030. The CO_2 emissions for the CI scenario and the two SO_2 mitigation scenarios exhibit the same trend and are about 990 $MtCO_2$ in 2030. Similarly, the CO_2 emissions for the AEE, CO_2 mitigation and optimal co-control scenarios also exhibit the same trend, with the CO_2 emissions from the AEE scenario reaching 818 $MtCO_2$ and the CO_2 emissions from the CO_2 abatement and Optimal Co-Control scenarios reaching 814 $MtCO_2$ in 2030.

Figure 53 Total CO2 Emissions for Steel Production in China, 2005-2030

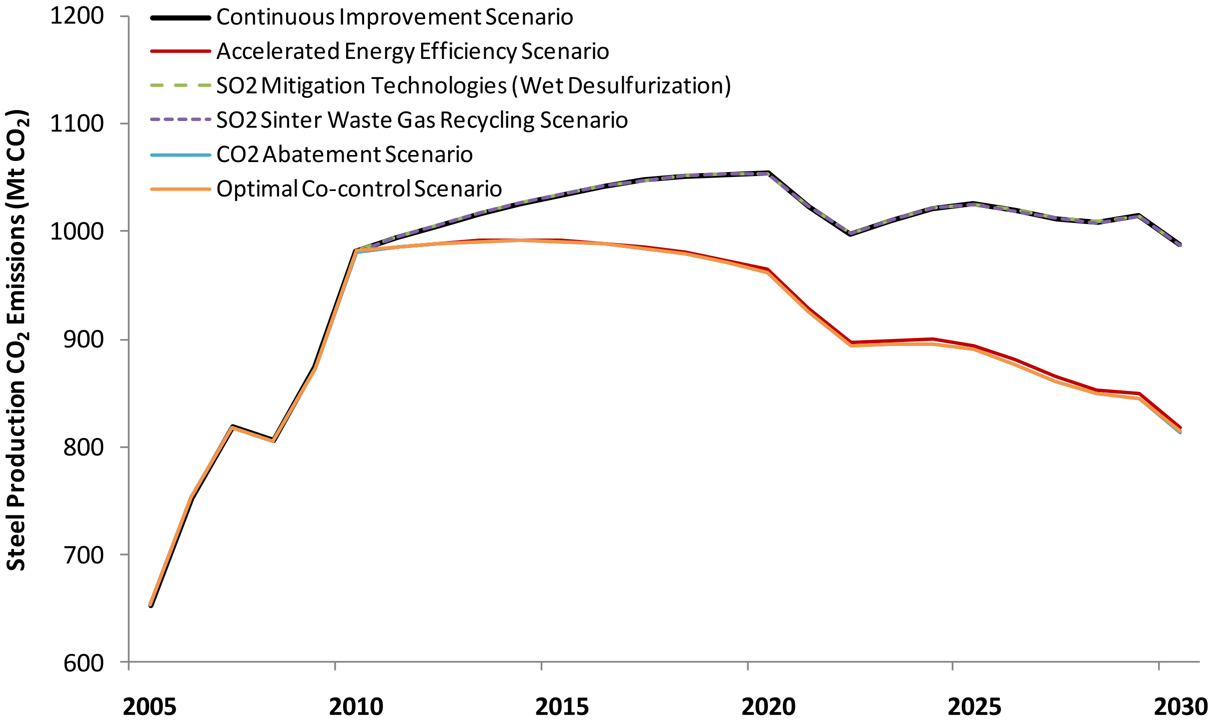


Figure 54 Total CO2 Emissions for Steel Production by Scenario, 2030

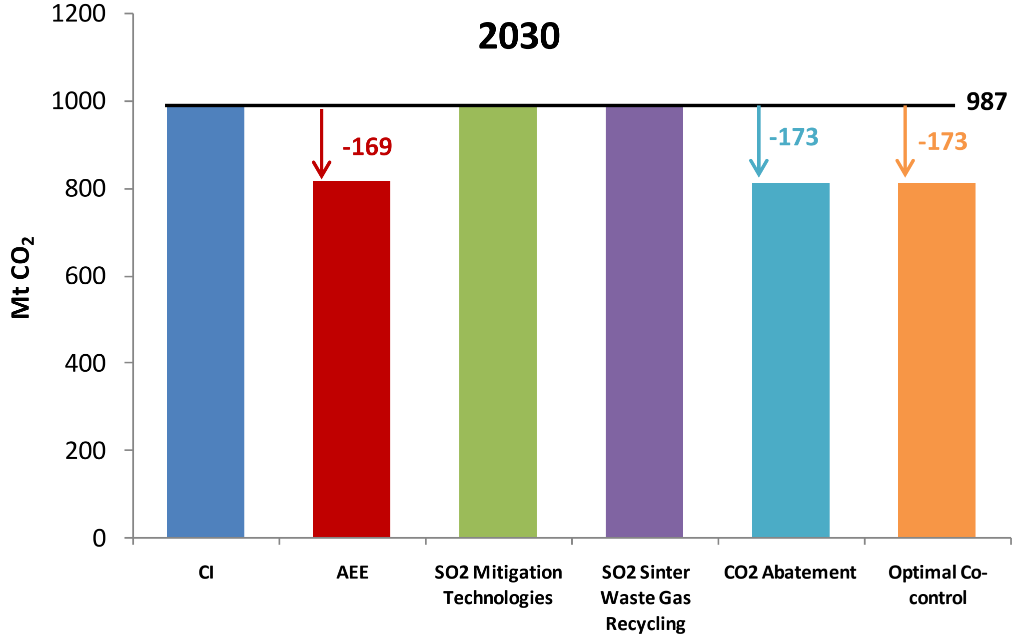
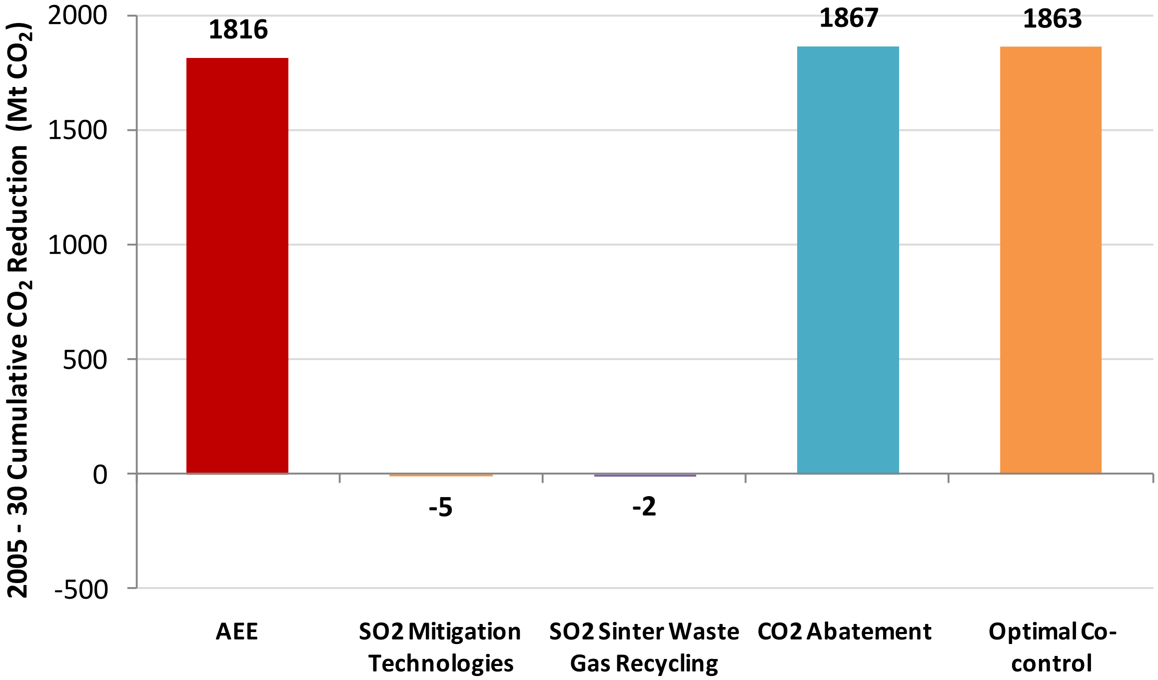


Figure 55 2005-2030 Cumulative CO_2 Reductions for Steel Production by Scenario



8. Conclusions

Power Sector

The reference scenario has incorporated the government plans to continue to improve efficiency and reduce emission, that already can cut over 67 billion tonnes of coal equivalent of energy demand between 2005 and 2030. Under the reference scenario, the industrial sector has the largest but slowly declining share of primary energy consumption, with 60% in 2020 and 55% in 2030. Of this, the iron and steel and cement subsectors together are responsible for a quarter of all industrial energy use. The share of commercial and transport sector primary energy demand both rise with growing demand for built environment, energy services and transport to accommodate the needs of the expanding urban population. Industry accounts for more than half of the total CO_2 emissions, followed by commercial and transport sectors. The iron and steel subsector accounts for 15% of national CO_2 emissions in 2030. While the industrial share declines over time, the transport and commercial shares of total CO_2 emissions rise quickly after 2010.

Despite decreasing absolute SO_2 emissions, the industrial sector still has the largest share, with total of 13 Mt SO_2 in 2030. Of this, the iron and steel subsector has the largest share at 30% of total industrial emissions or 2.82 Mt SO_2 emissions in 2030. However, when look at the emissions from where it occurs, then power sector accounts for close to 40% of the total CO_2 emission and over 46% of the SO_2 in 2010, and these share will decline over time, particularly SO_2 emission from power sector will only be 21% in 2030.

CCS scenario seems to result in the greatest annual CO_2 emission reduction by 2030 compared to other individual CO_2 mitigation scenarios, with 225 million tonnes less CO_2 emissions in 2030 than the reference scenario. However, the cumulative CO_2 emissions reduction from CCS between 2005 and 2030 is much less than efficiency improvement and decarbonization of the power sector. Decarbonization in particular has the greatest CO_2 emission reductions potential as a single co-control measure reduction.

In terms of SO_2 emission reduction, the base and accelerated SO_2 control scenarios have very small net effect of increasing CO_2 emissions relative to the reference case, which ranges from a low of 5 Mt CO_2 in 2030 to a high of 19 Mt CO_2 emissions for the accelerated SO2 control case and 16 Mt CO_2 emissions for the base SO_2 control case in 2015. Under the base control scenario, SO_2 emissions decrease significantly between 2010 and 2020 and actually achieve the 2015 accelerated control case by 2020. Both control scenarios flatten out after 2020 with very small incremental reductions through 2030 as the SO_2 control technology reaches full penetration and removal rate.

Although the base and accelerated SO_2 control scenarios will have the largest reduction potential on an annual and cumulative basis, the other CO_2 control options also have important co-benefits in reducing SO_2 emissions. Improving coal generation efficiency for CO_2 mitigation has important co-benefits in significantly reducing SO_2 emissions by eliminating inefficient coal use by as much as 3.6 Mt SO_2 in 2015, but declines after 2015 as all the inefficient plants will have been phased out. Expanding hydropower and renewable capacity also have important co-benefits in reducing cumulative SO_2 emissions. As the contribution from coal generation efficiency declines, decarbonizaiton will play much greater roles. hydropower and renewable capacity expansion have the second and third largest cumulative SO_2 reductions potential with 8 and 5.5 Mt SO_2, respectively. Coal efficiency improvements along with hydropower, renewable and nuclear capacity expansion will achieve more than half of the SO_2 emission reductions as the base control scenario through 2016. At its peak reductions in 2015, the reduction can still achieve 4.27 Mt SO_2 per year while accelerated SO_2 control can achieve 10.3 Mt SO2 in reductions. Despite declines after 2015, they can still reduce SO_2 emissions by nearly 0.9 Mt in 2030, or 20% of the reduction potential of accelerated base control.

CCS is the only CO_2 control scenario that has negative SO_2 reductions potential. Adopting efficiency and decarbonization can achieve the maximum CO_2 reductions. Combining it with accelerated SO_2 control has the added benefit of reducing much greater SO_2 emissions without significantly increasing CO_2 emissions. Without decarbonization, however, the power sector will not achieve significant CO_2 reductions, particularly in the later years.

As co-control scenarios, the base and accelerated SO_2 control with coal generation efficiency improvement will have the largest SO_2 emission reductions potential. Decarbonization, however, has very negligible additional SO_2 reductions when SO_2 controls are already in place because most of the reductions potential has been captured by SO_2 control technology. The expanded biomass generation scenario does not have significant potential for reducing SO_2 emissions, with annual reductions in the range of 0.1 to 0.2 Mt of SO_2 because its much lower sulfur content than that of carbon content of up to 90% by weight, and its limited availability.

The maximum co-control scenario where accelerated SO_2 control is adopted along with efficiency improvements and power sector decarbonization will have the greatest potential on reducing cumulative SO_2 and CO_2 emissions from the power sector.

Cement Sector

There are numerous options for reducing SO_2 and CO_2 emissions in the cement sector in China. Both SO_2 and CO_2 emissions reductions can be realized through the accelerated adoption of energy efficiency options. Numerous energy efficiency technologies and measures were identified that have not been fully implemented in China's cement industry.

SO_2 emissions can also be reduced through the implementation of SO_2 abatement end-of-pipe technology options (such as absorbent addition, wet scrubbers, and activated carbon) and through increasing the share of biomass used in the cement kiln. Given the assumptions outlined in this report, the SO_2 mitigation scenarios resulted in annual savings in 2030 of 0.07 Mt SO_2 from accelerated adoption of energy efficiency, 0.12 Mt SO_2 from fuel switching, and 0.36 Mt SO_2 from implementation of SO_2 abatement end-of-pipe technology options.

In addition to the implementation of energy efficiency measures that have not yet been adopted, CO_2 emissions reduction options also include reduced use of clinker through increased blending of additives in cement production, and reduction of coal use in the cement kiln through the substitution of coal with alternative fuels. Given the assumptions outlined in this report, an Accelerated Energy Efficiency scenario, that includes the energy efficiency and clinker substitution measures, resulted in annual savings in 2030 of 28 Mt CO_2. A CO_2 Abatement scenario that also reduces the use of coal from 85% to 60% by 2030 resulted in annual savings in 2030 of 32Mt CO_2. It should be noted that carbon capture and storage (CCS) for control of CO_2 in the cement sector was not considered in this report due to uncertainty regarding its commercialization, cost, and the fact that its use could increase plant electricity use significantly, resulting in an energy penalty that could significantly reduce the overall amount of sequestered CO_2.

A combined approach that relies on full or nearly full adoption of each of these measures by 2030 results in the greatest combined SO_2 and CO_2 emissions reductions for the cement industry. This Optimal Co-Control scenario includes accelerated adoption of energy efficiency measures, decreased use of clinker in cement production, increased use of alternative fuels and fuel-switching to biomass. Due to the high cost of SO_2 abatement mitigation technology measures, these technologies are not fully implemented in this scenario in order to determine the maximum SO_2 and CO_2 emissions reductions that can be realized using measures that "co-control" – or influence both types of emissions – at a minimum cost. If desired, additional SO_2 mitigation could be realized by more fully adopting these measures. The optimal co-control scenario results in annual SO_2 emissions reductions in 2030 of 0.16 Mt SO_2 and annual CO_2 emissions reductions of 76 Mt CO_2.

Iron and Steel Sector

It was also possible to identify numerous options for reducing SO_2 and CO_2 emissions in the iron and steel sector in China. As with the cement industry, many energy efficiency technologies and measures were identified that have not been fully implemented in China's steel industry.

SO_2 emissions from steel production can also be mitigated by minimizing the sulfur content in the raw materials (especially the sinter feed) and coal, sinter waste gas recycling, sinter flue gas desulfurization, and use of other selected mitigation technologies such as fabric filters, dry-gas off-gas cleaning, fine wet scrubbers, and regenerative activated carbon (RAC). Two SO_2 mitigation scenarios were developed. The first scenario, which focuses on full implementation of wet desulfurization which is one of the mitigation technologies available for steel production, resulted in annual 2030 SO_2 emissions reductions of 1.2 Mt SO_2. The second scenario assumes full implementation of sinter waste gas recycling and resulted in annual SO_2 emissions reductions in 2030 of 0.44 Mt SO_2.

CO_2 emissions reductions can be realized through adoption of energy efficiency measures, increasing the share of steel made using the electric arc furnaces (EAFs), and reducing the share of coal used for all types of steel production. An Accelerated Energy Efficiency scenario was developed that increases the adoption of energy efficiency measures so that China's steel industry reaches the 2005 international best practice energy intensity level by 2030 and assumes that steel produced by EAFs in China grows from slightly over 16% in 2000 to slightly over 26% in 2030. Annual CO_2 emissions reductions from this scenario in 2030 are 169 Mt CO_2. Another CO_2 Abatement scenario adopts the same measures as the AEE scenario, but also includes reduced use of coal and increased use of natural gas. This scenario results in annual 2030 CO_2 emissions reductions of 173 Mt CO_2.

A combined approach that represents a combination of most of the accelerated variables presented in the above individual scenarios results in the greatest combined SO_2 and CO_2 emissions reductions for the steel industry. This Optimal Co-Control scenario includes accelerated adoption of energy efficiency measures, increased share of EAF steel production, and reduced use of coal and increased use of natural gas in steel production. This scenario also assumes total SO_2 emissions reductions of 90% in 2030 comprised of SO_2 emissions reductions from energy efficiency and CO_2 emissions mitigation technologies and measures, full implementation of sinter waste gas recycling and the remaining reductions through the implementation of wet desulfurization. The Optimal Co-control scenario results in annual SO_2 emissions reductions in 2030 of 1.3 Mt SO_2 and annual CO_2 emissions reductions of 173 Mt CO_2.

Based on the findings, the following policies are recommended:

1. Continue to promote energy efficiency improvement in coal power plants by accelerating the phase out of inefficient power plants, strengthening efficiency standards for coal power plants, and promoting the installation of the most efficient power generation technologies such as ultra-supercritical technology.
2. Accelerate the adoption of renewable technologies including wind and solar. Policies that could help removing barriers and facilitating the adoption include: implementing Mandatory Market Rate (MMR) for renewables; resolve interconnection issues; establish net metering schemes and adequate feed in tariff.
3. Strengthen the enforcement of the emission standard for new and existing power plants. Currently most of the new and old plants have installed SO2 removal equipment but the removal rate is low due to both technical issues and weaker enforcement.
4. Accelerate adoption of various energy efficiency measures in the cement and Iron & steel sectors through target setting, benchmarking, efficiency standards, energy auditing, fiscal policies such as tax relief, rebates, and utilization of ESCOs.
5. Develop incentive polices for decreased use of clinker in cement production, increased use of alternative fuels, and fuel-switching to biomass.
6. Develop incentive polices for the use of electric arc furnace steel production, encourage the use of natural gas in steel production for replacement of coal.
7. Promote the full implementation of sinter waste gas recycling and wet desulfurization in the iron & steel sector.

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Appendix A. SO_2 and CO_2 technologies

A-1. Power Sector

A-1.1. SO_2 Technologies

This section provides a description of the SO_2 emissions control technologies and measures used in the power sector scenarios.

A-1.1.1. Wet lime/ limestone scrubber

The European Commission (2006) provides the following information about wet limestone scrubbers:

> Wet limestone scrubbers are the most widely used of all the FGD systems, with a share of c. 80 % of all the installed FGD capacity. Limestone is commonly used as a reagent because it is present in large amounts in many countries and is usually around three or four times cheaper than other reagents. The flue-gas leaving the particulate control system usually passes through a heat-exchanger and enters the FGD absorber, in which SO_2 is removed by direct contact with an aqueous suspension of finely ground limestone whereas limestone should have more than 95 % of $CaCO_3$. Fresh limestone slurry is continuously charged into the absorber. The scrubbed flue-gas passes through the mist eliminator and is emitted to the atmosphere from a stack or a cooling tower. Reaction products are withdrawn from the absorber and are sent for dewatering and further processing. The wet limestone scrubber is generally divided into two categories according to the type of oxidation: forced oxidation and natural oxidation mode. The mode of oxidation is determined by the chemical reactions, the pH of the reagent slurry and the resulting by-product.

A-1.1.2. Seawater scrubber

The European Commission (2006) provides the following information about seawater scrubbers:

> Seawater scrubbing utilises seawater's inherent properties to absorb and neutralise sulphur dioxide in flue-gases. If a large amount of seawater is available near a power plant, it is most likely to be used as a cooling medium in the condensers. Downstream of the condensers the seawater can be re-used for FGD. The flue-gas from the power plant leaves the dust collector, normally a fabric filter or an electrostatic precipitator. The flue-gas is then fed to the SO_2 absorber, where it comes into contact with a controlled proportion of the seawater, taken from the cooling water outflow of the steam turbine condenser. Due to the presence of bicarbonate and carbonates in the seawater, the sulphur

> dioxide of the flue-gas is absorbed. The acidified absorber effluent is mixed with additional seawater to ensure that the pH is at optimal level for the oxidation process. The introduced air forces the oxidation of the absorbed sulphur dioxide from bisulphite to bisulphate and removes dissolved CO_2. The water will be nearly saturated with oxygen and the pH value will be restored to neutral before the seawater is discharged back to the sea.

A-1.1.3. Circulating fluid bed (CFB) dry scrubber

The European Commission (2006) provides the following information about circulating fluid bed (CFB) dry scrubbers:

> The flue-gas from the boiler air preheater enters the CFB reactor at the bottom and flows vertically upwards through a venturi section. The venturi is designed to achieve the proper flow distribution throughout the operating range of the vessel. Inside the venturi, the gas is first accelerated, and then decelerated before entering the upper cylindrical vessel. The upper height of the vessel is designed to accommodate the mass of bed material required for the desired Ca and SO_2 contact time. The increased effective surface area of the circulating bed permits successful capture of virtually all of the SO_3 in the gas, eliminating the possibility of gas path corrosion from condensate SO_3 aerosol mist.

There are also other SO_2 control technologies that are used in the power sector. These technologies are listed below and detail explanations can be found in the references provided.

- Use of a low sulphur fuel or fuel with basic ash compounds for internal desulphurization (EC 2006)
- Use of adsorbents in fluidised bed combustion systems (EC 2006)
- Spray dry scrubbers (EC 2006)
- Furnace sorbent injection (EC 2006)
- Duct sorbent injection (dry FGD) (EC 2006)
- Hybrid sorbent injection (EC 2006)
- Sodium sulphite bisulphite process (EC 2006)
- Coal preparation (Kaminski 2003)
- Boiler modernization (Kaminski 2003)

A-1.2. CO_2 Control Technologies

Carbon capture and sequestration (CCS) will be an important CO_2 control technology option for China as it allows China to partially mitigate its carbon emissions while continuing to burn prodigious amounts of coal due to its domestic abundance and benefits for energy security. At present, however, the costs of CCS, both in terms of capital requirements and additional energy input, have slowed the commercial deployment of CCS.

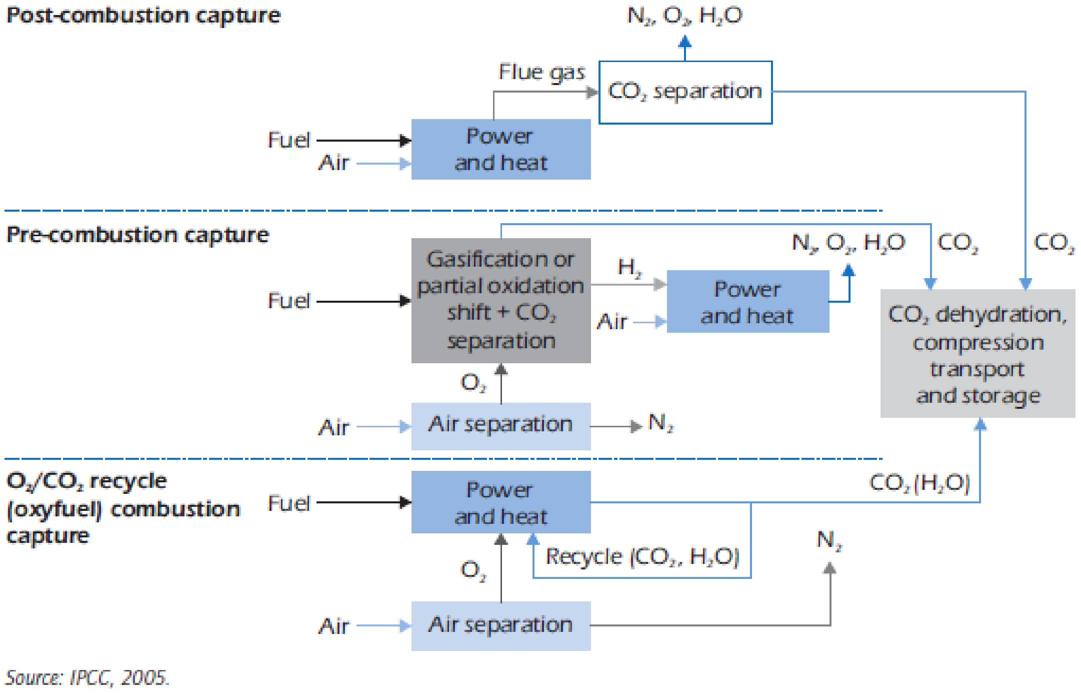
Table 20 Energy Efficiencies and Penalties by Technology

	Net Plant HHV Efficiency	Total Estimated Penalty
	%	kWh/kg CO_2
Sub-critical PC	24.9	1.01
Super-critical PC	27.2	0.83
IGCC pre-combustion	32.5	0.27

Source: House et. al., 2009a.

As shown in the table above, published estimates of the energy penalty of post-combustion CCS range from 20% to 80%, with new construction experiencing a smaller penalty than retrofitted plants (House et al. 2009b). There are two reasons for new plants' smaller penalty: they have a lower primary energy requirement for compression due to their higher efficiency; new plants are designed to more easily capture and utilize waste heat for CO_2 separation. The vintage and efficiency of coal-fired power plants influences the CCS energy penalty: the 2007 US fleet ranged from 18.7% to 46.4% thermal efficiency, which would result in energy penalties of 52% and 34%, respectively (House et al. 2009b). As such, the scale of CCS utilization in this scenario would likely require extensive policy support.

Figure 56 CCS Technology Types



A-2. Cement Sector

This section provides a description of the energy efficiency, SO_2 emissions control, and CO_2 emissions reduction technologies and measures used in the cement industry scenarios.

A-2.1. Energy-Efficiency Technologies and Measures

There are a number of energy-efficiency technologies and measures that can be applied in the cement industry in China to realize the 2005 international best practice energy intensity of 0.100 tce/t cement for Portland cement and 0.70 tce/t for fly ash cement (Worrell et al. 2008).[13] The assumptions related to international best practice values are provided below.[14] There are many energy-efficiency technologies and measures that can be used to reach the international best practice levels. Table A-2.1 provides a list of these options; full discussion of each option is provided in Worrell and Galitsky (2004).

A-2.1.1. Raw materials and fuel preparation

Energy-consuming steps in the preparation of raw material consist of pre-blending (pre-homogenization and proportioning), crushing, grinding and drying (if necessary) the raw meal which is mostly limestone. All materials are also homogenized before entering the kiln. Solid fuels input to the kiln must also be crushed, ground, and dried. Best practice for raw materials preparation is based on the use of a longitudinal pre-blending store with either bridge scraper or bucket wheel reclaimer or a circular pre-blending store with bridge scraper reclaimer for pre-blending (pre-homogenization and proportioning) using 0.5 kWh/t raw meal (Cembureau 1997), a gyratory crusher using 0.38 kWh/t raw meal (PCA 2004), an integrated vertical roller mill system with four grinding rollers and a high-efficiency separator using 11.45 kWh/t raw meal for grinding (Schneider 1999), and a gravity (multi-outlet silo) drying system using 0.10 kWh/t raw meal for homogenization (PCA 2004). Based on the above values, the overall best practice value for raw materials preparation is 12.05 kWh/t of raw material.

Ideally the best practice value should take into account the differences in moisture content of the raw materials as well as the hardness of the limestone. Higher moisture content requires more energy for drying and harder limestone requires more crushing and grinding energy. If drying is required, best practice is to install a pre-heater to dry the raw materials, which decreases the efficiency of the kiln. Solid fuel preparation also depends on the moisture content of the fuel. It is assumed that only coal needs to be dried and ground and that the energy required for drying or grinding of other materials is insignificant or unnecessary. Best practice is to use the waste heat from the kiln system, for example, the clinker cooler (if available) to dry the coal (Worrell and Galitsky 2004). Best practice using an MPS vertical roller mill is 10-36 kWh/t anthracite, 6-12 kWh/t pit coal, 8-19 kWh/t lignite, and 7-17 kWh/t petcoke

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[13] These values are expressed in final (or site) energy and do not account for generation, transmission, and distribution losses associated with the electricity used on-site.

[14] The descriptions are excerpted from Galitsky et al. 2008.

(Kraft and Reichardt 2005) or using a bowl mill is 10-18 kWh/t product (PCA 2004). Based on this, it is assumed that best practice for solid fuel preparation is 10 kWh/t product.

Table A-2.1. Energy-Efficient Practices and Technologies in Cement Production.

Raw Materials Preparation
Efficient transport systems (dry process) Slurry blending and homogenization (wet process) Raw meal blending systems (dry process) Conversion to closed circuit wash mill (wet process) High-efficiency roller mills (dry process) High-efficiency classifiers (dry process) Fuel Preparation: Roller mills
Clinker Production
Energy management and process control Seal replacement Kiln combustion system improvements Kiln shell heat loss reduction Use of waste fuels Conversion to modern grate cooler Refractories Heat recovery for power generation Low pressure drop cyclones for suspension pre-heaters Optimize grate coolers Addition of pre-calciner to pre-heater kiln Long dry kiln conversion to multi-stage pre-heater kiln Long dry kiln conversion to multi-stage pre-heater, pre-calciner kiln Efficient kiln drives Oxygen enrichment
Finish Grinding
Energy management and process control Improved grinding media (ball mills) High-pressure roller press High efficiency classifiers
General Measures
Preventative maintenance (insulation, compressed air system, maintenance) High efficiency motors Efficient fans with variable speed drives Optimization of compressed air systems Efficient lighting
Product & Feedstock Changes
Blended Cements Limestone cement Low Alkali cement Use of steel slag in kiln (CemStar®) Reducing fineness of cement for selected uses

A-2.1.2. Additives preparation

In addition to clinker, some cement plants use additives in the final cement product. While this reduces clinker production (the most energy-intensive stage of cement production), as well as the carbonation process which produces additional CO_2 as a product of the reaction, some additives require additional electricity for blending and grinding (such as fly ash, slags and pozzolans) and/or additional fuel for drying (such as blast furnace and other slags). Additional requirements from use of additives are based on the differences between blending and grinding Portland cement (5% additives) and other types of cement (up to 65% additives). Portland Cement typically requires about 55 kWh/t for clinker grinding, while fly ash cement (with 25% fly ash) typically requires 60 kWh/t and blast furnace slag cement (with 65% slag) requires about 80 kWh/t (these are typical grinding numbers only used to determine the additional grinding energy required by additives, not best practice; for best practice refer to data below in cement grinding section). It is assumed that only fly ash, blast furnace and other slags and natural pozzolans require additional energy. Based on this, fly ash will require an additional 20 kWh/t of fly ash ground and slags will require an additional 38 kWh/t of slag. It is assumed that natural pozzolans have requirements similar to fly ash. These data are used to calculate cement grinding requirements (Van Heijningen et al. 1992).

For additives which are dried, best practice requires 0.75 GJ/t (26 kgce/t) of additive. Generally, only blast furnace and other slags are dried. Those additives that need to be dried (the default is all slags, although the user can enter this data as well in the production input sheet) best practice requires an additional 0.75 GJ/t (26 kgce/t) of additive (Worrell et al. 1995).

A-2.1.3. Kiln

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

A-2.1.4. Final grinding

Best practice for cement grinding depends on the cement being produced, measured as fineness or Blaine (cm2/g). In 1997, it was reported that the Horomill required 25 kWh/t of cement produced for 3200 Blaine and 30 kWh/t cement produced for 4000 Blaine (Buzzi 1997). The following assumptions are made regarding Chinese cement types: 325 = a Blaine of less than or equal to 3200; 425 = a Blaine of approximately 3500; 525 = a Blaine of about 4000; and, 625 = a Blaine of approximately 4200. More recent estimates of Horomill energy consumption range between 16 and 19 kWh/t (Hendricks et al. 2004). Best practice values are used for the Horomill for 3200 and 4000 Blaine and interpolated and extrapolated values are then based on an assumed linear distribution for 3500 and 4200 Blaine. It is estimated that the lowest quality cement requires 16 kWh/t and that 3500 Blaine is 8% more than 3200 Blaine (17.3 kWh/t), 4000 Blaine is 20% more than 3200 Blaine (19.2 kWh/t), and 4200 Blaine is 24% more than 3200 Blaine (19.8 kWh/t). These values are then used to estimate the values of other types of cement, based on more or less grinding that would be needed for any additives. It is assumed that common Portland cement grinding required similar energy as pure Portland cement, that blended slag and fly ash cements were on average, 65% slag and 35% fly ash, that grinding pozzolans required similar energy as grinding slags (at a similar ratio of 65%) and that limestone cement contained 5% extra limestone with grinding requirements similar to grinding slag (Buzzi 1997; Hendriks et al. 1998).

A-2.1.5. Other production energy uses

Some cement facilities have quarries on-site, and those generally use both trucks and conveyors to move raw materials. If applicable to the cement facility, quarrying is estimated to use about 1% of the total electricity at the facility (Warshawsky, 1996). Other production energy includes power for auxiliaries and conveyors within the facility (packaging is excluded from this analysis). Total power use for auxiliaries is estimated to require about 10 kWh/t of clinker at a cement facility. Power use for conveyors is estimated to require about 1 to 2 kWh/t of cement (Worrell and Galitsky 2004). Lighting, office equipment, and other miscellaneous electricity uses are estimated to use about 1.2% of the total electricity at the facility (Warshawsky 1996).

A-2.2. SO_2 Control Technologies

SO_2 emissions from cement manufacturing are the result of oxidation of sulfide or elemental sulfur contained in the fuel or raw materials during combustion (at temperatures of 300 to 600 degrees C) when certain levels of oxygen are present or through localized reducing conditions (Greer 2003; Miller et al. 2001). Raw materials such as limestone, sand, shale, or wastes from other industries (steel mill scale or fly ash from power plants) and bituminous coal all can contain sulfates, sulfides (metallic and organic), and elemental sulfur which are oxidized to SO_2 during combustion (Greer 2003).

SO_2 emissions from cement manufacturing can be controlled through process optimization of the clinker burning process to ensure an oxygen level that is adequate to achieve the desired product quality but controlled to reduce formation of sulphates. Sulphates are formed in the bottom section of the cyclone pre-heater or the hot gas chamber of the grate pre-heater and are released through the clinker (EC 2010).

While there are a number of SO_2 control technologies available,[15] this report focuses on three emissions mitigation technologies (absorbent addition, wet scrubber, and activated carbon) as

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[15] For information on additional SO_2 control technologies, see Greer (2003) and EC (2010).

well as fuel switching due to availability of information on SO_2 emissions reductions, energy use or savings, and costs associated with each of these technologies.

Figure A-2.2.1 illustrates the primary (process optimization) and secondary (absorbent addition, wet scrubber, and activitated carbon) options for reduction of SO_2 emissions from a cement facility with preheater/precalciner kilns (Wesselink et al. 2010).

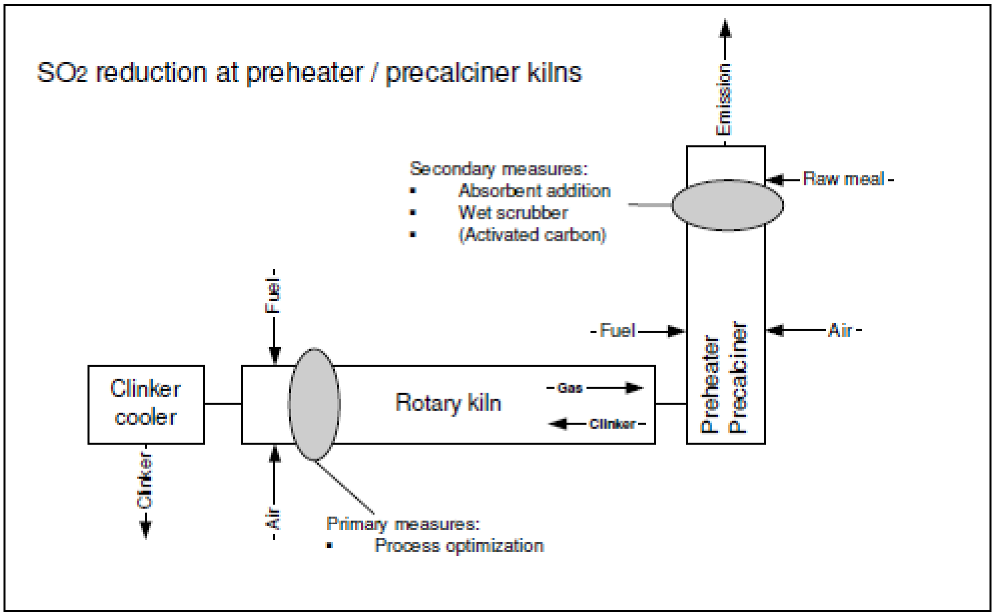

Figure A-2.2.1 SO_2 reduction Technologies for Preheater/Precalciner Kilns.
Source: Wesselink et al. 2010.

A-2.2.1. Absorbent addition[16]

Addition of hydrated lime (calcium hydroxide) within the cement manufacturing process to react with the SO_2 or to act as a scrubbing reagent can be an effective means to capture SO_2 (Greer 2003). The addition can be made to the raw material, the upper stages of the preheater tower or the raw gas duct, or into the clinker-burning process.

Hydrate or slaked lime ($Ca(OH)_2$), quicklime (CaO) or activated fly ash with a high CaO content, is injected into the exhaust gas path at temperatures close to the water dew point, which results in more favourable conditions for SO_2 capture. In cement kiln systems, this temperature range is available in the area between the raw mill and the dust collector. The hydrate-of-lime reacts with the SO_2 in the upper cyclone stages and is carried out of the system as raw gas dust (dust collector) which is returned to the downstream grinding-drying unit with the raw gas. Factors limiting the reduction efficiency of this process are the short gas retention times in the upper cyclone stages (minimum two seconds) and the high exhaust gas CO_2 levels of over 30%.

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[16] Partially excerpted from EC (2010).

Absorbent addition is, in principle, applicable to all kiln systems, although it is mostly used in suspension preheaters. For preheater kilns it has been found that direct injection of slaked lime into the exhaust gas is less efficient than adding slaked lime to the kiln feed. The SO_2 will react with the lime to $CaSO_3$ and $CaSO_4$, which then enters the kiln together with the raw material and is incorporated into the clinker. This technique is suitable for cleaning gas streams with moderate SO_2 concentrations and can be applied at an air temperature of more than 400 °C. The highest reduction rates can be achieved at temperatures exceeding 600 ºC. It is recommended that a $Ca(OH)_2$ based absorbent with a high specific surface area and high porosity should be used. Slaked lime does not have a high reactivity, therefore $Ca(OH)_2/SO_2$ molar ratios of between 3 and 6 have to be applied. Gas streams with high SO_2 concentrations require 6 – 7 times the stoichiometric amount of absorbent, implying high operational costs.

Absorbent addition is in use at several plants to ensure that the limits are not exceeded in peak situations. This means that, in general, it is not in continuous operation, but only when required by specific circumstances. With an initial SO_2 concentration of up to 3000 mg/Nm3, a reduction of up to 65% and a slaked lime cost of EUR 85 per tonne, the investment costs for a 3000 tonne clinker/day preheater kiln are about EUR 0.2 million – 0.3 million and the operating costs are about EUR 0.1 – 0.4 per tonne clinker.

A recent study of the costs of using absorbent addition in the EU found costs of 0.2 to 3.2 Euro/t clinker, which includes fixed operation costs as well as variable costs related to implementation of the measure (Wesselink et al. 2010).

A-2.2.2. Wet scrubber[17]

The wet scrubber is the most commonly used technique for flue-gas desulphurization in coal-fired power plants. For cement manufacturing processes, the wet process for reducing SO_2 emissions is an established technique. Wet scrubbing is based on the following chemical reaction:

$SO_2 + \frac{1}{2} O_2 + 2 H_2O + CaCO_3$eH $CaSO_4 \bullet 2 H_2O + CO_2$

The SOx is absorbed by a liquid/slurry which is sprayed in a spray tower. The absorbent is calcium carbonate. Wet scrubbing systems provide the highest removal efficiencies for soluble acid gases of all flue-gas desulphurisation (FGD) methods with the lowest excess stoichiometric factors and the lowest solid waste production rate. However, wet scrubbers also significantly reduce the HCl, residual dust and, to a lesser extent, metal and NH_3 emissions. The basic principle of the working system of a wet scrubber is shown in Figure A-2.2.2.

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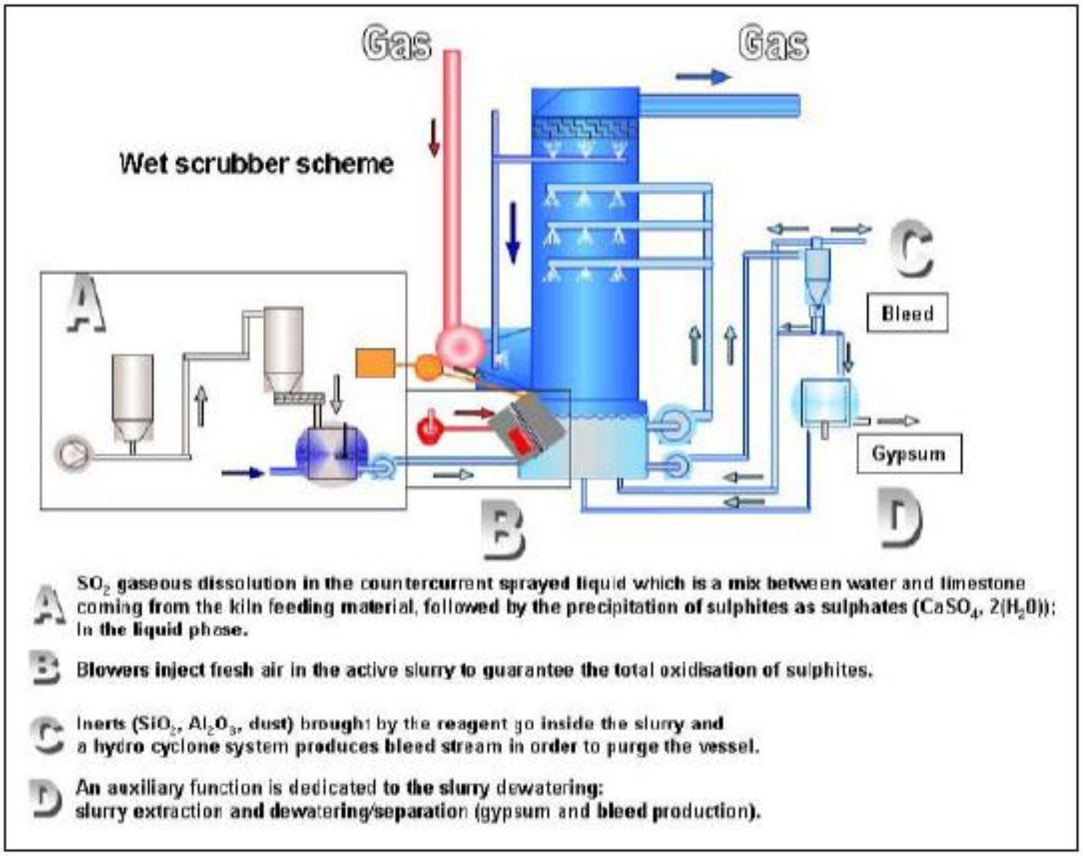
[17] Excerpted from EC (2010).



A SO_2 gaseous dissolution in the countercurrent sprayed liquid which is a mix between water and limestone coming from the kiln feeding material, followed by the precipitation of sulphites as sulphates ($CaSO_4$, $2(H_2O)$); in the liquid phase.

B Blowers inject fresh air in the active slurry to guarantee the total oxidisation of sulphites.

C Inerts (SiO_2, Al_2O_3, dust) brought by the reagent go inside the slurry and a hydro cyclone system produces bleed stream in order to purge the vessel.

D An auxiliary function is dedicated to the slurry dewatering: slurry extraction and dewatering/separation (gypsum and bleed production).

Figure A-2.2.2 Basic operational features of a wet scrubber

There are seven wet scrubbers currently in use in 2008 and one is planned to be used in the European cement industry, all of them spray towers. The slurry is sprayed in counter currently to the exhaust gas and collected in a recycle tank at the bottom of the scrubber where the formed sulphite is oxidised with air to sulphate and forms calcium sulphate dihydrate. The dihydrate is separated and depending upon the physico-chemical properties of gypsum this material can be used in cement milling and the water is returned to the scrubber.

In comparison to the dry scrubber, the potential to generate cement kiln dust (CKD) in a wet process is much lower and natural gypsum recourses are saved. In Untervaz, Switzerland, the only installed circulating fluidised bed dry scrubber in Europe was retired in 2003, due to economic – and to a lesser extent – technical reasons. Normally, during the cement manufacturing process or from gas scrubbing applications, the aim is not to generate waste dust. In wet desulphurisation processes, $CaSO_4 \bullet 2\ H_2O$ is formed – which is used as a natural gypsum replacement and in the follow-up integrated as a modulating agent in the cement. In a dry/semi-dry desulphurisation process, a large quantity of the product $CaSO_3 \bullet ½\ H_2O$ is formed, the latter of which is harmful for the cement quality and integration possibilities in the cement are limited. The majority of the dry scrubber product would therefore have to be taken either back to the kiln or would need to be disposed of.

Use of this technology can result in increased energy consumption, increased waste production from flue-gas desulphurization, increased CO_2 emissions, increased water consumption, emissions to water and increased risk of water contamination, and increased operational costs.

A wet scrubber can be fitted to all cement kiln types with appropriate (sufficient) SO_2 levels in order to manufacture the gypsum.

In 2008, capital expenditure costs for a wet scrubber of Ribblesdale works, Castle Cement in the UK, were estimated by the supplier to be around EUR 23 million, when considering inflation. In 2000, the investment costs for the scrubber of Castle Cement (including plant modifications) were reported to be EUR 7 million and the operating costs were about EUR 0.9 per tonne clinker. In 1998 for Cementa AB in Sweden, the investment costs were about EUR 10 million and the operating costs were about EUR 0.5 per tonne clinker. With an initial SO_2 concentration of up to 3000 mg/Nm^3 and a kiln capacity of 3000 tonne clinker/day, the investment costs in the late 1990s were EUR 6 million – 10 million and the operating costs EUR 0.5 – 1 per tonne clinker. Furthermore in 1998 at an Austrian cement plant, the investment costs for a wet scrubber (SO_2 emissions reduction to less than 200 mg/Nm^3) were EUR 5.8 million and until 2008, the yearly operational costs were EUR 140000. In 2008, the European cement industry reported investment costs of between EUR 6 million and 30 million and operational costs of between EUR 1 – 2 per tonne clinker.

A recent study of the costs of using a wet scrubber in the EU found costs of 1.7 to 4.0 Euro/t clinker, which includes fixed operation costs as well as variable costs related to implementation of the measure (Wesselink et al. 2010).

A-2.2.3. Activated carbon[18]

Pollutants such as SO_2, organic compounds, metals, NH_3, NH_4 compounds, HCl, HF and residual dust (after an ESP or fabric filter) may be removed from the exhaust gases by adsorption on activated carbon. The activated carbon filter is used for the injection technique or is constructed as a packed-bed with modular partition walls. The modular design allows the filter sizes to be adapted for different gas throughputs and kiln capacity. The used activated coke is periodically extracted to a separate silo and replaced with fresh adsorbent. By using the saturated coke as fuel in the kiln, the trapped substances are returned to the system and to a large extent become fixed in the cement clinker. An activated carbon filter can be fitted to all dry kiln systems. Wastes, such as used activated carbon with PCDD/Fs and other pollutants like mercury, have to be managed as hazardous wastes. Monitoring and control of temperature and CO are especially important for such processes, to prevent fires in the coke filter.

The system at Siggenthal also includes an SNCR process and in 1999, the city of Zürich financed about 30 % of the total investment cost of approximately EUR 15 million. The investment in this

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[18] Partially excerpted from EC (2010).

abatement system was made to enable the cement works to use digested sewage sludge as fuel. Operating costs may increase as well.

A recent study of the costs of using activated carbon in the EU found costs of 4.7 Euro/t clinker (Wesselink et al. 2010).

A-2.2.4. Use of biomass fuels instead of fossil fuels

Since SO_2 emissions result from the oxidation of sulfide or elemental sulfur contained in the fuels burned in the kiln, replacement of a portion of those fuels with biomass will reduce SO_2 emissions. Biomass is injected into the kiln as a secondary fuel. Agricultural and non-agricultural biomass accounted for nearly 30% of the solid-fuel substitutes used in the cement industry globally (CSI, 2005). Agricultural biomass includes rice husks, wheat straw, corn stover, sugarcane leaves and bagasse, rapeseed stems, and the shells of hazelnuts and palmnuts. Non-agricultural biomass includes dewatered and dried sewage sludge, paper sludge, paper, sawdust, waste wood, and animal waste such as bones, meal, and fat (Murray and Price 2008). Substitution of fossil fuels in cement kilns with low-sulfur biomass can result in reduced SO_2 emissions, although the impact may be small since the raw meal in a cement kiln naturally scrubs out SO_2 (Choate 2003).

A-2.2.5. Summary data for SO2 abatement measures/techniques for the cement industry

Table A-2.2 provides summary information on the four SO_2 abatement techniques discussed above. While specific information is available for the first three abatement options, the costs associated with the use of biomass as a substitute fuel vary too much to easily characterize, although they are typically lower than using an equivalent amount of fossil fuels.

Table A-2.2 Summary Data for SO_2 Abatement Measures

Technology	**SO_2 Emission Reduction**	**Costs**	**References**
Absorbent addition	60-80%	Capital: 0.2-0.3 million Euro O&M: 0.1 – 0.4 Euro/t clinker	EC 2010
		0.2 to 3.2 Euro/t clinker	Wesselink et al. 2010
Wet scrubber	> 90%	Capital: 5.8-23 million Euro O&M: 0.5 – 2 Euro/t clinker	EC 2010
		1.7 to 4.0 Euro/t clinker	Wesselink et al. 2010
Activated carbon	Up to 95%	Capital: 15 million Euro O&M: N/A	EC 2010
		4.7 Euro/t clinker	Wesselink et al. 2010
Biomass fuels	Reduction	May be less expensive, but	CSI 2005

	equivalent to % of fuel displaced	costs vary with type of waste[19]	

A-2.3. CO_2 Control Technologies

CO_2 emissions from cement manufacturing are the result of combustion of fossil fuels in the kiln and for production of electricity use to power motors and other electrical equipment as well as the calcination of limestone in the kiln. Approximately 50% of the CO_2 emissions are from combustion of fossil fuels and 50% are from the calcination process. Fuel-related CO_2 emissions are dependent upon the type of fuel burned in the kiln (e.g. coal, fuel oil, natural gas, petroleum coke, alternative fuels). Process-related CO_2 emissions of clinker production are estimated to be about 0.5 $kgCO_2$/kg clinker, but the process emissions per tonne of cement are dependent upon the amount of blending, or the clinker-to-cement ratio, which ranges from 0.5 to 0.95 (Worrell et al. 2001).

The CO_2 emissions abatement technologies and measures evaluated in this report include increased energy efficiency to reduce the use of fossil fuels, increased use of alternative fuels to replace fossil fuels, and increased clinker-to-cement ratio.

A-2.3.1. Increased Energy Efficiency

Improved thermal efficiency reduces the use of fossil fuels in the cement kiln, in turn reducing energy-related emissions of CO_2. Improved electricity efficiency reduces fossil fuels required for production of off-site electricity at power plants. Sometimes, fossil fuels are used to produce electricity on-site, either alone or in combination with on-site waste heat. In either case, energy-related CO_2 emissions are also reduced.

International best practice values for energy intensity of cement production were provided in Section A-2.1 above. Additional information on the energy savings, CO_2 emissions reduction, and costs of a number of energy-efficiency technologies and measures is provided in Table A-2.3 below.

A-2.3.2. Increased Use of Alternative Fuels[20]

Countries around the world are adopting the practice of using waste products and other alternatives to replace fossil fuels in cement manufacturing. Industrialized countries have over 20 years of successful experience (GTZ and Holcim 2006). Figure A-2.3 shows that a number of European countries are world leaders in this practice (CSI 2005; Wang 2008). In the U.S., it is common for cement plants to derive 20-70% of their energy needs from alternative fuels (PCA 2006). In the U.S., as of 2006, 16 cement plants were burning waste oil, 40 were burning scrap

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[19] Additional considerations include that biomass fuels may need to be pre-treated, additional environmental equipment may need to be installed to control emissions, and additional costs may be incurred to maintain safety, quality, and environmental standards (CSI 2005).

[20] Excerpted from Murray and Price (2008).

tires, and still others were burning solvents, non-recyclable plastics and other materials (PCA 2006). Cement plants are often paid to accept alternative fuels; other times the fuels are acquired for free, or at a much lower cost than the energy equivalent in coal. Thus the lower cost of fuel can offset the cost of installing new equipment for handling the alternative fuels. Energy normally accounts for 30-40% of the operating costs of cement manufacturing; thus, any opportunity to save on these costs can provide a competitive edge over cement plants using traditional fuels (Mokrzycki and Uliasz-Bochenczyk 2003).

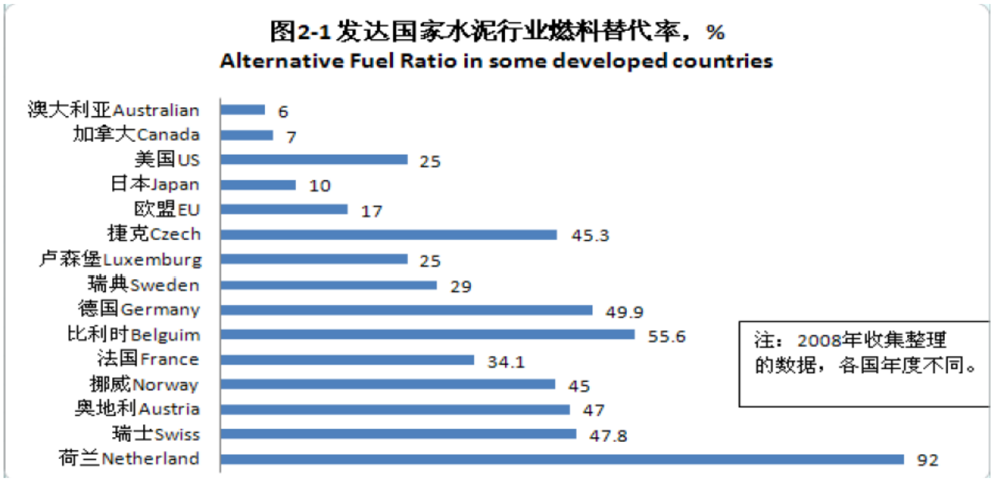

Figure A-2.3 Share of Alternatives Fuels Used for Cement Production in Selected Countries.
Source: Wang 2008.

Using alternative fuels in cement manufacturing is recognized for far-reaching environmental benefits (Cembureau 1999). The embodied energy in alternative fuels that is harnessed by cement plants is the most direct benefit, as it replaces demand for fossil fuels like coal. The amount of coal or other fossil fuel demand that is displaced depends on the calorific value and water content of the alternative fuel in comparison to coal. Additionally, the fuel substitutes often have lower carbon contents (on a mass basis) than fossil fuels. The cement industry is responsible for 5% of global CO_2 emissions, nearly 50% of which are due to the combustion of fossil fuels (IPCC 2007; Karstensen 2008). Therefore, another direct benefit of alternative fuel substitution is a reduction in CO_2 emissions from cement manufacturing.

A-2.3.3. Increased Clinker-to-Cement Ratio (Increased Use of Blended Cement)

Increasing the clinker-to-cement ratio, by inter-grinding the clinker with additives such as fly ash, pozzolans, granulated blast furnace slag, silica fume, or volcanic ash, reduces the amount of clinker that needs to be produced per tonne of cement. This in turn results in lower energy consumption and both energy- and process-related (calcinations) CO_2 emissions per tonne of cement despite the need for some additional electricity for grinding of the additives. Increasing production of this “blended” cement, then, can significantly reduce CO_2 emissions. Blended cements typically have higher long-term strength and improved resistance to acids and sulfates. While short-term strength (measured after less than one week) can be reduced, cement containing less than 30% additives will generally have setting times comparable to Portland cement (Worrell and Galitsky 2004).

Blended cements are very common in Europe where the share increased from 13.1% in 1994 to 72.5% in 2004 (Cembureau 2007). In 2007, 5.4% of the cement produced in China was Pure Portland Cement, which is defined as either being comprised of 100% clinker and gypsum or >95% clinker and gypsum with <5% of either granulated blast furnace slag (GGBS) or limestone. Common Portland Cement, comprised of >80% and <95% of clinker and gypsum combined with >5% and <20% of additives (GGBS, pozzolana, fly ash, or limestone), made up 54% of the cement produced in China that year. Slag Portland Cement, that blends anywhere from >20% to <70% GGBS with clinker and gypsum, constituted 36% of 2007 cement production. The remaining 5% of cement was Pozzolana (>20% to <40% pozzolan additives), fly ash (>20% to <40% fly ash), or other blended cement (>20% to <50% other additives) (Wang 2009).

A-2.3.4. Summary data for CO2 abatement measures/techniques for the cement industry

Table A-2.3 provides the estimated fuel and electricity savings as well as the associated energy-related CO_2 emissions reduction from the energy-efficiency measures listed previously in Table A-2.1 above. In addition, estimated capital costs along with operations and maintenance (O&M) costs are provided (Worrell and Galitsky. 2004).

Table A-2.3 Typical Energy Savings, Energy-Related CO_2 Emissions Reductions, Capital Costs and O&M Costs of Energy-Efficiency Measures for the Cement Industry[21]

Technology/Measure	Fuel Savings (GJ/t clinker)	Electricity Savings (kWh/t clinker)	Primary Energy Savings (GJ/t-cl) [a]	CO_2 Emission Reduction (ktCO2/t-cl) [b]	Capital Cost (RMB/t clinker)	Change in Annual O&M cost (RMB/t clinker)
Fuel Preparation						
New efficient coal separator for fuel preparation		0.26	0.003	0.27	0.08	0.0
Efficient roller mills for coal grinding		1.47	0.016	1.51	0.32	0.0
Install variable frequency drive & replace coal mill bag dust collector's fan		0.16	0.002	0.16	0.18	0.0
Raw Materials Preparation						
Raw meal process control for Vertical mill		1.41	0.016	1.45	3.52	0.0
High Efficiency classifiers/separators		5.08	0.057	5.23	23.54	0.0
High Efficiency roller mill for raw materials grinding		10.17	0.114	10.45	58.85	0.0
Efficient (mechanical) transport system for raw materials preparation		3.13	0.035	3.22	32.10	0.0
Raw meal blending (homogenizing) systems		2.66	0.030	2.73	39.59	0.0
Variable Frequency Drive in raw mill vent fan		0.33	0.004	0.34	0.17	0.0
Bucket elevator for raw meal transport from raw mill to homogenizing silos		2.35	0.026	2.42	1.56	0.0
High efficiency fan for raw mill vent fan with inverter		0.36	0.004	0.37	0.23	0.0
Clinker Making						
Kiln shell heat loss reduction (Improved refractories)	0.26		0.260	24.60	1.71	0.0
Energy management/process control systems for clinker	0.15	2.35	0.176	16.61	6.84	0.0
Adjustable speed drive for kiln fan		6.10	0.068	6.27	1.57	0.0
Optimize heat recovery/upgrade clinker cooler	0.11	-2.00 [c]	0.088	8.35	1.37	0.0
Low temperature waste heat recovery power generation		30.80	0.345	31.66	9132 RMB/ kWh-Capacity	5.58
Efficient kiln drives		0.55	0.006	0.57	1.50	0.0
Upgrading preheater from 5 to 6 stages	0.11	-1.17 [c]	0.098	9.30	17.37	0.0

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[21] Excerpted from Price et al. (2009).

Technology/Measure	Fuel Savings (GJ/t clinker)	Electricity Savings (kWh/t clinker)	Primary Energy Savings (GJ/t-cl) [a]	CO_2 Emission Reduction (ktCO2/t-cl) [b]	Capital Cost (RMB/t clinker)	Change in Annual O&M cost (RMB/t clinker)
Upgrading preheater kiln to a preheater/precalciner Kiln	0.43		0.430	40.68	123.12	-7.52
Low pressure drop cyclones for suspension preheater		2.60	0.029	2.67	20.52	0.0
VFD in cooler fan of grate cooler		0.11	0.001	0.11	0.08	0.0
Bucket elevators for kiln feed		1.24	0.014	1.27	2.41	0.0
Replacement of preheater fan with high efficiency fan		0.70	0.008	0.72	0.47	0.0
Finish Grinding						
Energy management & process control in grinding		4.00	0.045	4.11	3.21	0.00
Replace ball mill with vertical roller mill		25.93	0.290	26.66	53.50	0.0
High pressure roller press as pre-grinding to ball mill		24.41	0.273	25.09	53.50	0.0
Improved grinding media for ball mills		6.10	0.068	6.27	7.49	0.0
High-Efficiency classifiers for finish grinding		6.10	0.068	6.27	21.40	0.0
Replacement of cement mill vent fan w/high efficiency fan		0.13	0.001	0.13	0.06	0.0
General Measures						
Use of alternative fuels	0.60		0.600	56.76	7.52	0.0
High efficiency motors		4.58	0.051	4.70	2.35	0.0
Adjustable Speed Drives		9.15	0.102	9.41	9.63	0.0
Product Change [c]	**Fuel Savings (GJ/t cement)**	**Electricity Savings (kWh/t cement)**	**Primary Energy Savings (GJ/t-cem)** [a]	**CO_2 Emission Reductions (kg CO_2/t-cem)** [b]	**Capital Cost (RMB/t cement)**	**Change in Annual O&M cost (RMB/t cement)**
Blended cement (fly ash, pozzolans, and blast furnace slag)	1.77	-7.21[c]	1.689	160.02 [d]	4.92	-0.27
Portland limestone cement	0.23	3.30	0.266	25.10 [d]	0.82	-0.04

[a] Primary energy saving is calculated based on China's national average efficiency of thermal power generation including transmission and distribution losses (32.15%) (NBS 2007; Anhua and Xingshu 2006; Kahrl and Roland-Holst 2006). The calculated primary energy savings could be different in other countries.

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

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

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

A-3. Iron &Steel Sector

This section provides a description of the energy efficiency, SO_2 emissions control, and CO_2 emissions reduction technologies and measures used in the iron and steel industry scenarios.

A-3.1. Energy-Efficiency Technologies and Measures

There are a number of energy-efficiency technologies and measures that can be applied in the steel industry in China to realize the 2005 international best practice energy intensity of 505 kgce/t steel for steel produced using a blast furnace and basic oxygen furnace (BOF) and 88 kgce/t for steel produced from scrap in an electric arc furnace (Worrell et al. 2008).[22] The assumptions related to international best practice values are provided below.[23] There are many energy-efficiency technologies and measures that can be used to reach the international best practice levels. Table A-3.1.1 provides a list of cross-cutting energy-efficiency improvement options and Table A-3.1.2 provides a list of process-specific energy-efficiency improvement options for the steel industry; full discussion of each option is provided in Worrell et al. (2010).

A-3.1.1. Blast furnace – basic oxygen furnace steelmaking

Best practice calculations are based on the following assumptions: 1.389 t sinter are required to produce 1 t hot rolled steel, 90% pig iron and 10% scrap, 0.9923 t pig iron required to produce 1 t hot rolled steel, 1.05 t crude steel required to make 1 t hot rolled steel.

The best practice coke plant is a modern coke plant using standard technology, including electrical exhausters, high-pressure ammonia liquor spray for oven aspiration, as well as variable speed drives on motors and fans. Coke dry quenching saves an additional 1.44 GJ/t (49 kgce/t) coke (beyond the Ecotech value). The best practice does not include a Jumbo Coke Reactor or non-recovery coke ovens. The best practice sinter plant is a state-of-the-art sinter plant using a bed depth of 500 mm on a moving grate, using coke and breeze as fuel, and gas as ignition furnace fuel. Waste heat is recovered from the sinter exhaust cooler, and air leakage is controlled.

During the ironmaking process, sintered or pelletized iron ore is reduced using coke in combination with injected coal or oil to produce pig iron in a blast furnace.[24] Limestone is added as a fluxing agent. Reduction of the iron ore is the largest energy-consuming process in the production of primary steel. The best practice blast furnace is a modern large scale blast furnace. Fuel injection rates are similar to modern practices found at various plants around the world (equivalent to about approximately 125 kg/t hot metal, slight oxygen enrichment, as well

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[22] These values are expressed in final (or site) energy and do not account for generation, transmission, and distribution losses associated with the electricity used on-site.

[23] The descriptions are excerpted from Worrell et al. 2008.

[24] Best practice energy use is also determined by the concentration and quality of the ore used. As ore is traded internationally (and to China), it is assumed that plants around the world have access to similar qualities of raw materials.

as pressurized operation (4 bar) allowing for power recovery using a top gas power recovery turbine (wet type). Furthermore, the hot blast stoves have a heating efficiency of 85% using staggered parallel operation with three or four stoves per furnace. Combustion air is preheated. The stoves use a mixture of coke oven and blast furnace gas without oxygen enrichment.

The BOF process operates through the injection of oxygen, oxidizing the carbon in the hot metal. Several configurations exist depending on the way the oxygen is injected. The steel quality can be improved further by ladle refining processes used in the steel mill. The scrap input is rather small for the BOF-route, typically about 10-25%. The process needs no net input of energy and can even be a net energy exporter in the form of BOF-gas and steam. In the best practice case BOF gas and sensible heat are recovered.

A-3.1.2. Electric arc furnace steelmaking

In the EAF steelmaking process, the coke production, pig iron production, and steel production steps are omitted, resulting in much lower energy consumption. To produce EAF steel, scrap is melted and refined, using a strong electric current. Several process variations exist, using either AC or DC currents and fuels can be injected to reduce electricity use.

Table 2.1.6 provides best practice energy consumption values by fuel for the EAF route. The best practice EAF plant is state-of-the-art facility using 100% high quality scrap. The EAF is equipped with eccentric bottom tapping, ultra high power transformers, oxygen blowing, full foamy slag operation, oxy-fuel burners, and carbon injection. Scrap preheating is not assumed, although economically attractive, especially for large scale furnaces. Scrap preheating will reduce power consumption by 70 kWh/t (8.6 kgce/t) liquid steel.

The “best practice” DRI-scrap-fed EAF consumes 100% scrap. It consumes 409 kWh/t (50.3 kgce/t) liquid steel for the EAF and 65 kWh/t (8 kgce/t) liquid steel for gas cleaning and ladle refining, as well as 0.15 GJ/t (5.1 kgce/t) liquid steel of natural gas and 8 kg/t liquid steel of carbon. Installing a scrap preheater would reduce power use in the EAF by 70 kWh/t (8.6 kgce/t), reducing total electricity use to 404 kWh/t (49.6 kgce/t) liquid steel.

A-3.1.3. Casting

Continuous casting values are based on the International Iron and Steel Institute’s EcoTech plant which includes “all those proven energy saving technologies that are economically attractive” (IISI 1998) and the thin slab/near net shape casting values are based on Worrell et al. (2004). Casting can be either continuous casting or thin slab/near net shape casting. Best practice continuous casting uses 0.06 GJ/t (2.0 kgce/t) steel of final energy (IISI 1998). Energy is only used to dry and preheat the ladles, heat the tundish, and for motors to drive the casting equipment. Thin slab/near net shape casting is a more advanced casting technique which reduces the need for hot rolling because products are initially cast closer to their final shape using a simplified rolling strand positioned behind the caster’s reheating tunnel furnace, eliminating the need for a separate hot rolling mill. Final energy used for casting and rolling using thin slab casting is 0.20 GJ/t (6.9 kgce/t) steel.

A-3.1.4. Rolling and Finishing

Hot Rolling

Rolling of the cast steel begins in the hot rolling mill where the steel is heated and passed through heavy roller sections to reduce the thickness. Best practice values for hot rolling are 1.55 GJ/t (53.0 kgce/t), 1.75 GJ/t (59.6 kgce/t), and 1.98 GJ/t (67.5 kgce/t) of steel of final energy for rolling strip, bars, and wire, respectively (IISI 1998). Electricity consumption for the best practice hot strip mill is based on hot strip mill 2 at Corus, IJmuiden, Netherlands (Worrell 1994). The best practice values assume 100% cold charging, a walking beam furnace with furnace controls and energy efficient burners, and efficient motors. Hot charging and premium efficiency motors may further reduce the rolling mill energy use.

Cold Rolling

The hot rolled sheets may be further reduced in thickness by cold rolling. The coils are first treated in a pickling line followed by treatment in a tandem mill. The best practice final energy intensity for cold rolling is 0.09 GJ/t (3.0 kgce/t) steam, fuel use of 0.053 GJ/t (1.8 kgce/t) and electricity use of 87 kWh/t (10.7 kgce/t) cold rolled sheet (IISI 1998), equivalent to 0.47 GJ/t (13.7 kgce/t) cold sheet.

Finishing

Finishing is the final production step, and may include different processes such as annealing and surface treatment. The best practice final energy intensity for batch annealing is steam use of 0.173 GJ/t, fuel use of 0.9 GJ/t and 35 kWh/t of electricity, equivalent to 1.2 GJ/t (41.0 kgce/t). Best practice energy use for continuous annealing is assumed to be equal to fuel use of 0.73 GJ/t, steam use of 0.26 GJ/t, and electricity use of 35 kWh/t, equivalent to final energy use of 1.1 GJ/t (or 38.1 kgce/t). Continuous annealing is considered the state-of-the-art technology, and therefore assumed to be best practice technology.

Table A-3.1.1 Cross-Cutting Energy-Efficiency Measures for the Iron and Steel Industry

Energy Management Programs and Systems	
Strategic Energy Management Programs	Assessments
Energy teams	
Energy and Process Control Systems	
Monitoring	Modeling
Optimization	
Steam Systems	
Boiler Energy-efficiency Measures	
Demand matching	Boiler feed water
Boiler allocation control	Optimization of boiler blowdown rate
Flue shut-off dampers	Reduction of flue gas quantities
Maintenance	Reduction of excess air
Insulation improvement	Flue gas monitoring
Removal of soot and scale	Installation of turbulators
Preheating the water supply with heat from flue gas	Recovery of heat from boiler blowdown
Recovery of condensate	
Combined Heat and Power (CHP)	
Steam injected gas turbine	High-temperature CHP
Steam expansion turbine	Combined Cycle
Natural gas expansion turbine	
Steam Distribution System Energy-efficiency Measures	
Shutting off excess distribution lines	Checking and monitoring steam traps
Proper pipe sizing	Thermostatic steam traps
Insulation related measures	Shutting of steam traps
Reduction of distribution pipe leaks	Vapor recompression to recover low pressure waste steam
Recovery of flash steam	Replacement of pressure-reducing valves by backpressure turbogenerators
Motor Systems	
Motor management plan	Proper motor sizing
Maintenance	Adjustable-speed drives (ADSs)
Energy–efficient motors	Power factor correction
Rewinding of motors	Minimizing voltage unbalances
Pump Systems	
Operation and maintenance	Adjustable speed drives (ASDs)
Monitoring	Avoiding throttling valves
Controls	Proper pipe sizing
Reduction of demand	Replacement of belt drives
More efficient pumps	Precision castings, surface coatings or polishing
Proper pump sizing	Improvement of sealing
Multiple pumps for varying loads	Curtailing leakage through clearance reduction
Impeller trimming (or shaving sheaves)	Dry vacuum pumps

Fan Systems	
Minimizing flow	Proper fan sizing
Minimizing pressure	Adjustable speed drives (ASDs)
Control density	High efficiency belts (cog belts)
Fan efficiency	
Compressed Air Systems	
Reduction of demand	Maximizing allowable pressure dew point
Maintenance	Optimizing compressor(s) to match load
Monitoring	Controls
Reduction of leaks (in pipes and equipment)	Proper sizing of storage capacity
Electronic condensate drain traps (ECDTs)	Proper pipe sizing
Air quality	Heat recovery
Reduction of the inlet air temperature	Adjustable speed drives (ASDs)

Source: Worrell et al., forthcoming

Table A-3.1.2 Process-Specific Energy-Efficiency Measures for the Iron and Steel Industry

Iron Ore and Ferrous Reverts Preparation (Sintering)	
Heat recovery from sintering and sinter cooler	Use of waste fuel in sinter plant
Reduction of air leakage	Improve charging method
Increasing bed depth	Improve ignition oven efficiency
Emission Optimized Sintering (EOS®)	Other measures
Coke Making	
Coal moisture control	Coke dry quenching (CDQ)
Programmed heating	Coke oven gas (COG)
Variable speed drive coke oven gas compressors	Next generation coke making technology
Single Chamber System (SCS)	
Iron Making – Blast Furnace	
Injection of pulverized coal	Recovery of blast furnace gas
Injection of natural gas	Top gas recycling
Injection of oil	Improved blast furnace control
Injection of plastic waste	Slag heat recovery
Injection of coke oven gas and basic oxygen furnace gas	Preheating of fuel for hot stove
Charging carbon composite agglomerates (CCB)	Improvement of combustion in hot stove
Top-pressure recovery turbines (TRT)	Improved hot stove control
Steelmaking – BOF	
Recovery of BOF gas and sensible heat	Improvement of process monitoring and control
Variable speed drive on ventilation fans	Programmed and efficient ladle heating
Ladle preheating	
Steelmaking – EAF	
Increasing power	Refractories using engineering particles
Adjustable speed drives (ASDs)	Direct current (DC) arc furnace
Oxy-fuel burners/lancing	Scrap preheating

Post-combustion of flue gases	Waste injection
Improving process control	Airtight operation
Foamy slag practices	Bottom stirring/gas injection
Casting and Refining	
Integration of casting and rolling	Tundish heating
Ladle preheating	
Shaping	
Use efficient drive units	Installation of lubrication system
Gate Communicated Turn-Off (GCT) inverters	
Hot Rolling	
Recuperative or regenerative burners	Integration of casting and rolling
Flameless burners	Proper reheating temperature
Controlling oxygen levels and variable speed drives on combustion air fans	Process control in hot strip mill
Avoiding overload of reheat furnaces	Heat recovery to the product
Insulation of reheat furnaces	Waste heat recovery from cooling water
Hot charging	
Cold Rolling	
Continuous annealing	Inter-electrode insulation in electrolytic pickling line
Reducing losses on annealing line	Automated monitoring and targeting systems
Reduced steam use in the acid pickling line	

Source: Worrell et al. (2010).

A-3.2. SO_2 Control Technologies

SO_2 emissions from steel production are mostly from combustion of sulfur compounds in the sinter feed (coke breeze and iron ores). Additional SO_2 emissions are from the induration process (drying, heating, and cooling) in pelletization, and coke oven firing. SO_2 emissions from steel production can be mitigated by minimizing the sulfur content in the raw materials (especially the sinter feed) and coal, sinter waste gas recycling, sinter flue gas desulfurization, and use of other selected mitigation technologies such as fabric filters, dry-gas off-gas cleaning, fine wet scrubbers, and regenerative activated carbon (RAC) (IFC 2007; EC 2009).

In this study, two SO_2 mitigation scenarios were developed. The first scenario focuses on full implementation of one of the mitigation technologies available for steel production: wet desulfurization. The second scenario assumes full implementation of sinter waste gas recycling. These two techniques are explained in more detail below.

A-3.2.1. Sinter Waste Gas Recycling

Sinter waste gas recycling can be achieved in four different ways: recycling part of the waste gas from the whole sinter strand back to the entire surface of the sinter strand, recycling parts of the waste gas to other parts of the sinter strand, recycling of waste gas from the end sinter strand combined with heat exchange, and recycling of waste gas from part of the end sinter strand and use of waste gas from the sinter cooler. Each of these techniques is explained below.

Recycling part of the waste gas from the whole sinter strand back to the entire surface of the sinter strand

For this option, which is also called emission optimized sintering (EOS), part of the mixed collected waste gas from the whole sinter strand is recycled back to the entire surface of the sinter strand. Approximately 40 to 45% of the sinter waste gas can be recycled resulting in a decreased gas flow to the atmosphere of 45 to 50% (EC 2011).

In a case study reported in the Netherlands using this technique, coke breeze consumption was reduced by 10% to 15% and the strand productivity remained unchanged. It is reported in EC (2011) that:

> The sinter quality, defined as reduction disintegration, is constant, the FeO in the sinter increases by 1.5%, reducibility increases, cold strength decreases slightly, and the mean diameter remains approximately 17 mm. The use of the sinter produced in the blast furnace did not show any adverse effects...

This technique ultimately results in capital and operational cost savings because the waste gas flow and associated emissions of dust and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) are reduced. Thus, abatement equipment is used to treat reduced volumes of waste gases before they are released to the atmosphere.

For the Dutch case study, coke breeze consumption was reduced from 60 kg/t sinter to 48 kg/t sinter. This led to a decrease in SO_2 emissions of 15-20% for high basicity sinter. Extra suction fans with installed electric capacity of 200 to 400 kW were installed which increased energy consumption 3MJ/t to 8 MJ/t sinter (te Lindert and van der Panne 1997).

This option can be used in both new and existing plants, although additional investment costs are lower when installed in new facilities (EC 2011). The following costs and savings were reported for the Dutch case study plant (EC 2011):

> The investment required to implement this technique at the Dutch sinter plant at Corus, Ijmuiden, the Netherlands with a total conventional waste gas flow of approximately 1.2 million Nm^3/h from three sinter strands, was EUR 17 million. Operational costs were decreased compared to conventional sintering due to reduced input of coke breeze. Operational savings are estimated at EUR 2.5 million/yr. This figure is based on a reduced consumption of coke breeze by 6 kg/t sinter, at a price of EUR 100/t coke breeze and sinter production of 4.2 Mt/yr.

Recycling part of the waste gas to other parts of the sinter strand

For this option, up to 25% of the waste gas is selectively recycled in both new and existing plants “based on local suction of the sintering waste gas under the strand and its local recycling above the sinter bed,” which is what distinguishes this from the EOS process (EC 2009). It is reported that with this process, the recycled waste gas oxygen concentration remains high (19%), the moisture level is low (3.6%), the RDI remains constant, the Shatter Index increases by 0.5%, and there is a solid fuel savings of 6% (EC 2009).

The advantages of this option are that the unused oxygen in the waste gas can be recirculated and the waste gas in different sections can be treated separately, significantly reducing investment and operational costs compared to conventional sintering. Investment costs for the gas recycling system were 8 to 10 million Euro in 1997 excluding the $deNO_X$, $deSO_X$ and other abatement equipment. In addition, coke consumption is reduced up to 6% and there are also reductions in operational costs (EC 2009).

Environmental benefits of this option include a 28% decrease in the released waste gas, a 56% decrease in dust emissions, a 63% decrease in the SO_2 discharge (including the end-of-pipe desulphurization of gas arising from zone 3) and a 3% decrease in NOx emissions (EC 2009).

Recycling of waste gas from the end sinter strand combined with heat exchange

For this option, exhaust gases from the second half of the sinter strand are collected and then recirculated to the entire sinter strand. During the recirculation, dust is filtered out of the waste gases, dioxins and furans are partially destroyed, and sulphur oxides and chlorine compounds are adsorbed. Consumption of solid fuel is reduced by 5-7 kg solid fuel/t sinter because the CO in the recirculated gases provides heat. SO_2 emissions reduction is 27-35%. This process can be implemented in new and existing sinter plants. Capital investment costs for this option are 14 million Euro (EC 2011).

Recycling of waste gas from part of the end sinter strand and use of waste gas from the sinter cooler

For this option, waste gases from wind boxes toward the discharge end of the sinter strand or from the cooler are selectively recirculated using the Eposint process. This option can be used in both new and existing plants. Fuel consumption is decreased by 2 to 5 kg coke/t sinter, coke consumption is decreased, the CO is used as fuel, and there is a reduction of 40% in off-gas volume. SO_2 emissions reduction is 25 – 30%. Emissions of NOx and dioxins are reduced as they are decomposed in the sinter bed. The sinter layer absorbs or filters SOx. While 15 million Euro investment costs are needed for a suction area of 250 m^2, there are operational energy savings and reduced costs for fine wet scrubber or fabric filters with adsorbing agents for waste gas cleaning because of the reduced gas volume (EC 2011).

A-3.2.2. Wet desulphurization

Wet desulphurization involves absorbing SO_2 in a spray tower with a calcium (Ca or magnesium (Mg) solution after the waste gases have been cooled. The resulting gypsum or magnesium sulphate slurry is then removed. Reaction agents include steel slag, slaked lime, calcium chloride and slaked lime, slaked lime and chalk, or magnesium hydroxide. Wet desulphurization can also be achieved with fine scrubber systems (EC 2009). Approximately 85% - 90% of the SO_2 emissions can be reduced using wet desulphurization, although efficiencies of 95 – 99 % have been reported. Costs for this technology, however, are higher than for sinter waste gas recycling. Capital costs of 50-80 million Euro and operations costs of 0.5 to 1.1 Euro per t sinter are reported (EC 2011).

A-3.2.3. Summary Data for SO_2 Abatement Measures/Techniques for the Steel Industry

Table A-3.2 provides summary information on the two SO_2 abatement techniques discussed above for the iron and steel industry.

Table A-3.2 Summary Data for SO_2 Abatement Measures for the Iron and Steel Industry

Technology	SO_2 Emission Reduction	Costs	References
Sinter Waste Gas Recycling	25% - 63%	Capital: 8 - 17 million Euro O&M: 2.5 million Euro/year	EC 2009
Wet Desulfurization	90%	Capital: 50 - 80 million Euro O&M: 0.5 – 1.1 Euro/t sinter	EC 2011

A-3.3. CO_2 Control Technologies

CO_2 emissions from steel manufacturing are the result of combustion of fossil fuels and from production of electricity use to power motors and other electrical equipment in iron and steel-making facilities. Fuel-related CO_2 emissions are dependent upon the type of fuel burned (e.g. coal, coke, fuel oil, natural gas, petroleum coke, alternative fuels).

The CO_2 emissions abatement technologies and measures evaluated in this report include increased energy efficiency to reduce the use of fossil fuels, increased use of thin slab/near net shape casting, reduced use of coal and increased use of natural gas, and an accelerated shift to electric arc furnace steel production.

A-3.3.1. Increased Energy Efficiency

Improved thermal efficiency reduces the use of fossil fuels for iron and steel production, in turn reducing energy-related emissions of CO_2. Improved electricity efficiency reduces fossil fuels required for production of off-site electricity at power plants. Sometimes, fossil fuels are used to produce electricity on-site, either alone or in combination with on-site waste heat. In either case, energy-related CO_2 emissions are also reduced.

International best practice values for energy intensity of steel production were provided in Section A-3.1 above. Additional information on the energy savings, CO_2 emissions reduction, and costs of a number of energy-efficiency technologies and measures is provided in Table A-3.3.1 and A-3.3.2 below.

Table A-3.3.1 Energy Savings, Costs, and Carbon Dioxide Emissions Reductions for Energy-Efficiency Technologies and Measures Applied to Integrated Steel Production.

Option	Fuel Savings (GJ/tonne crude steel)	Electricity Savings (GJ/tonne crude steel)	Primary Energy Savings (GJ/tonne crude steel)	Annual Operating Costs (US$/tonne crude steel)	Retrofit Capital Cost (US$/tonne crude steel)	Carbon Dioxide Emissions Reduction (kgC/t)
Iron Ore Preparation (Sintering)						
Sinter plant heat recovery	0.12	0.00	0.12	0.00	0.66	3.41
Reduction of air leakage	0.00	0.00	0.01	0.00	0.02	0.12
Increasing bed depth	0.02	0.00	0.02	0.00	0.00	0.59
Improved process control	0.01	0.00	0.01	0.00	0.03	0.30
Use of waste fuels in sinter plant	0.04	0.00	0.04	0.00	0.04	1.16
Coke Making						
Coal moisture control	0.09	0.00	0.09	0.00	14.69	0.55
Programmed heating	0.05	0.00	0.05	0.00	0.07	0.31
Variable speed drive coke oven gas compressors	0.00	0.00	0.00	0.00	0.09	0.01
Coke dry quenching	0.37	0.00	0.37	0.15	20.99	2.25
Iron Making - Blast Furnace						
Pulverized coal injection to 130 kg/thm	0.69	0.00	0.69	-1.78	6.24	11.42
Pulverized coal injection to 225 kg/thm	0.51	0.00	0.51	-0.89	4.64	8.45
Injection of natural gas to 140 kg/thm	0.80	0.00	0.80	-1.78	4.46	13.35
Top pressure recovery turbines (wet type)	0.00	0.10	0.30	0.00	17.84	4.29
Recovery of blast furnace gas	0.06	0.00	0.06	0.00	0.27	0.98
Hot blast stove automation	0.33	0.00	0.33	0.00	0.27	5.49
Recuperator hot blast stove	0.07	0.00	0.07	0.00	1.25	1.19
Improved blast furnace control systems	0.36	0.00	0.36	0.00	0.32	5.93
Smelting reduction processes*	3.2	0.00	3.2	-6.3	-120	52.7
Steelmaking – Basic Oxygen Furnace						
BOF gas + sensible heat recovery	0.92	0.00	0.92	0.00	22.00	12.55
Variable speed drive on ventilation fans	0.00	0.00	0.01	0.00	0.20	0.14
Integrated Casting						
Adopt continuous casting	0.24	0.08	0.49	-5.35	11.95	36.06
Efficient ladle preheating	0.02	0.00	0.02	0.00	0.05	0.27
Thin slab casting	3.13	0.57	4.89	-31.33	134.25	177.60
Strip casting*	-	-	0.22	-	180	-
Integrated Hot Rolling						
Hot charging	0.52	0.00	0.52	-1.15	13.09	7.18
Process control in hot strip mill	0.26	0.00	0.26	0.00	0.61	3.59
Recuperative burners	0.61	0.00	0.61	0.00	2.18	8.38
Insulation of furnaces	0.14	0.00	0.14	0.00	8.73	1.91
Controlling oxygen levels and VSDs on combustion air fans	0.29	0.00	0.29	0.00	0.44	3.95
Energy-efficient drives (rolling mill)	0.00	0.01	0.03	0.00	0.17	0.39
Waste heat recovery (cooling water)	0.03	0.00	0.03	0.06	0.70	0.46
Low NOx Oxy-Fuel Burners	0.77	-0.02	0.7	0.36	2.5	9.8
Integrated Cold Rolling and Finishing						
Heat recovery on the annealing line	0.17	0.01	0.19	0.00	1.55	2.73
Reduced steam use (pickling line)	0.11	0.00	0.11	0.00	1.61	1.55
Automated monitoring and targeting system	0.00	0.12	0.38	0.00	0.63	5.51
General						
Preventative maintenance	0.43	0.02	0.49	0.02	0.01	9.74
Energy monitoring and management system	0.11	0.01	0.14	0.00	0.15	2.60
Cogeneration	0.03	0.35	1.1	0.00	14.52	22.39
Variable speed drive: flue gas control, pumps, fans	0.00	0.02	0.06	0.00	1.30	0.40

Note: Primary energy is calculated based on the conversion factor for electricity to primary energy in the U.S. Also, CO_2 emission reductions are based on the U.S. CO_2 emissions factors for fuel and electricity.

Table A-3.3.2 Energy Savings, Costs, and Carbon Dioxide Emissions Reductions for Energy-Efficiency Technologies and Measures Applied to Secondary Steel Production.

Option	Fuel Savings (GJ/tonne crude steel)	Electricity Savings (GJ/tonne crude steel)	Primary Energy Savings (GJ/tonne crude steel)	Annual Operating Costs (US$/tonne crude steel)	Retrofit Capital Cost (US$/tonne crude steel)	Carbon Dioxide Emissions Reductions (kgC/t)
Steelmaking Electric Arc Furnace						
Improved process control (neural network)	0.00	0.11	0.33	-1.00	0.95	4.81
Flue gas Monitoring and Control	0.00	0.05	0.17	0.00	2.00	2.40
Transformer efficiency - UHP transformers	0.00	0.06	0.19	0.00	2.75	2.72
Bottom Stirring / Stirring gas injection	0.00	0.07	0.22	-2.00	0.60	3.20
Foamy Slag Practice	0.00	0.07	0.20	-1.80	10.00	2.88
Oxy-fuel burners	0.00	0.14	0.44	-4.00	4.80	6.41
Eccentric Bottom Tapping (EBT) on existing furnace	0.00	0.05	0.17	0.00	3.20	2.40
DC-Arc furnace	0.00	0.32	1.00	-2.50	3.90	14.42
Scrap preheating – Tunnel furnace (CONSTEEL)	0.00	0.22	0.66	-1.90	5.00	9.61
Scrap preheating, post combustion - Shaft furnace (FUCHS)	-0.70	0.43	0.63	-4.00	6.00	9.62
Twin Shell DC w/ scrap preheating	0.00	0.07	0.21	-1.10	6.00	3.04
IHI process*	-	-	1.9	-	-	-
Contiarc process*	-0.03	0.77	2.33	-10	-	34.8
Comelt process*	-0.25	0.44	1.11	-8 to -10	3.90	16.9
Secondary Casting						
Efficient ladle preheating	0.02	0.00	0.02	0.00	0.05	0.27
Thin slab casting	2.86	0.57	4.62	-31.33	134.29	64.68
Strip casting*	-	-	0.22	-	180	-
Secondary Hot Rolling						
Process control in hot strip mill	0.26	0.00	0.26	0.00	0.61	3.59
Recuperative burners	0.61	0.00	0.61	0.00	2.18	8.38
Insulation of furnaces	0.14	0.00	0.14	0.00	8.73	1.92
Controlling oxygen levels and VSDs on combustion air fans	0.29	0.00	0.29	0.00	0.44	3.95
Energy-efficient drives in the rolling mill	0.00	0.01	0.03	0.00	0.17	0.39
Waste heat recovery from cooling water	0.03	0.00	0.03	0.06	0.70	0.46
Low NOx Oxy-Fuel Burners	0.77	-0.02	0.7	0.36	2.5	9.8
General Technologies						
Preventative maintenance	0.09	0.05	0.24	0.02	0.01	4.09
Energy monitoring & management system	0.02	0.01	0.06	0.00	0.15	1.02

Note: Primary energy is calculated based on the conversion factor for electricity to primary energy in the U.S. Also, CO_2 emission reductions are based on the U.S. CO_2 emissions factors for fuel and electricity.

A-3.3.2. Increased Use of Thin Slab/ Near Net Shape Casting[25]

Thin slab casting is a new technology integrating casting and hot rolling in one process, thereby reducing the need to reheat the steel before rolling it. Pioneered in the U.S. by Nucor at the Crawfordsville and Hickmann plants, various plants are operating, under construction, or ordered worldwide. Originally designed for small scale process-lines, the first integrated plants constructed or announced the construction of thin slab casters (Germany, Netherlands, Spain) with capacities up to 1.5 Mt/year. Currently, four suppliers supply this technology.

Near net shape casting/strip casting is the most recent development in metal shaping. Currently, metals are cast in ingots or slabs. The ingots and slabs need to be reheated after casting to roll them in the final shape. Near net shape/strip casting integrates the casting and hot rolling of steel into one process step, thereby reducing the need to reheat the steel before rolling it. Strip casting directly casts a strip of 1 to 10 mm. Starting in 1975, around 11 clusters of steel producers, technology suppliers, and research groups developing near net shape/strip casting emerged in Europe, Japan, Australia, United States and Canada. Since then, three commercial technologies have emerged. All three technologies are based on the same principle as proposed by Bessemer. The steel is cast between two water-cooled casting rolls. This results in very rapid cooling and high production speeds. The major advantage of strip casting is the large reduction in capital costs, due to the high productivity and integration of several production steps. The technology was first applied to stainless steel, and two plants have demonstrated strip casting of carbon steel.

A-3.3.3. Reduced Use of Coal and Increased Use of Natural Gas

The share of different fuels used in the iron and steel industry is also an important variable that should be considered. The fuel shares will influence the energy intensity of the iron and steel industry, as well as the related carbon dioxide emissions. Figures A-3.3.1and A-3.3.2 show the shares of different fuels used (both as fuel and nonfuel) in the U.S. and Chinese iron and steel industries. As can be seen, there are significant differences in the types of fuel used in this industry in the two countries. For example, in the U.S. natural gas accounts for 34.5% of final energy use, while only accounting for 0.45% in China.

In addition to the share of fuels used directly in the iron and steel industry, the share of fuels used for power generation in each country is also an important factor, especially if the CO_2 emissions of the industry in two countries are compared. This becomes even more important because of the significant difference in the share of EAF steel production in various countries. For instance, since the share of EAF steel production in the U.S. is higher than that of in China, the share of electricity use in total energy use is also higher compared to that of the Chinese iron and steel industry. In this case, the fuel share for the power generation in the country and as the result the emission factor of the grid (kg CO_2/kWh) plays an important role in CO_2 emissions of the iron and steel industry in the two countries.

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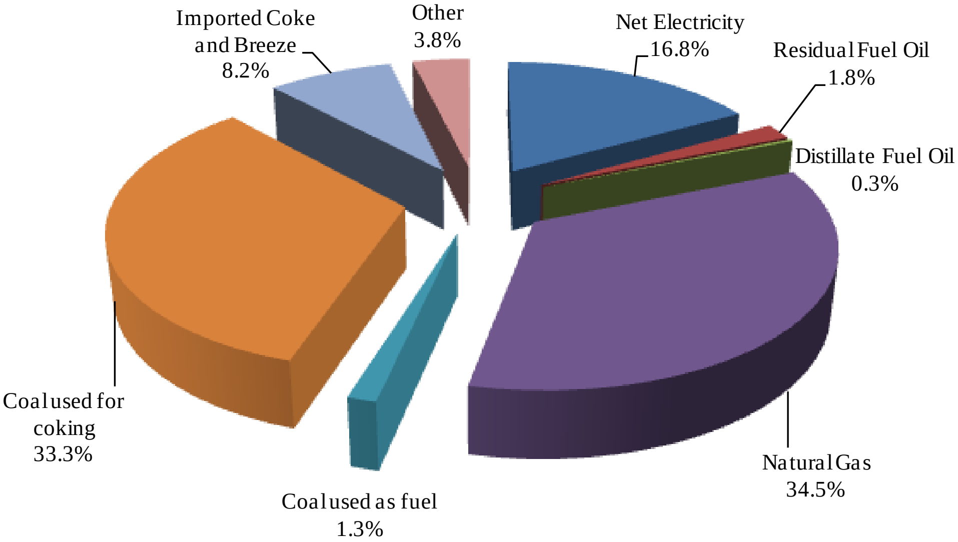
[25] Excerpted from Worrell et al. (2010).

Figure A-3.3.1 Total Energy Use (Fuel and Nonfuel) in the U.S. Iron and Steel Industry, 2006

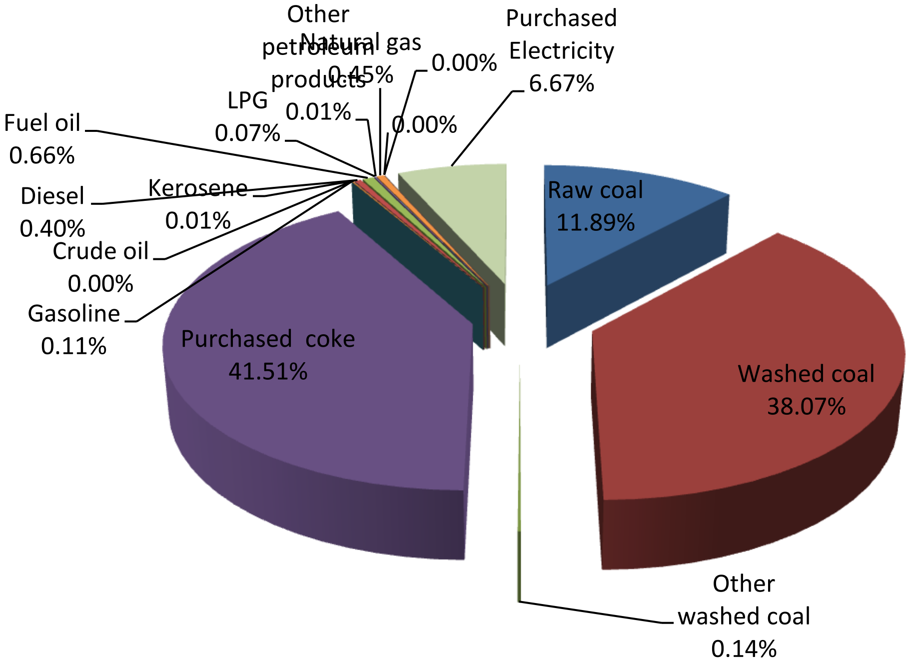


Source: U.S. DOE/EIA, 2010.

Notes:

1. These are fuel inputs to the U.S. iron and steel industry. Fuel conversion (e.g. from coal to coke) within the industry is not included.
2. Electricity is in final energy and is not converted to primary energy.

Figure A-3.3.2 China 2006 Primary Energy Use (Fuel and Non-fuel) of Iron and Steel Industry

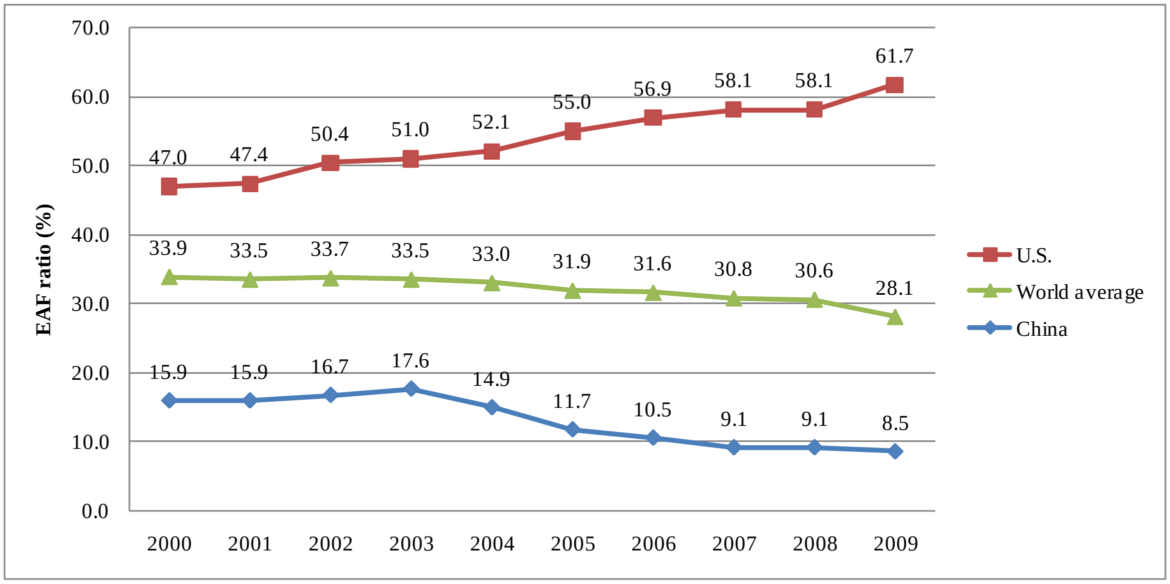


Source: China Iron and Steel Research Institute (CISRI) calculations based on NBS 2010c.

A-3.3.4. Accelerated Shift to Electric Arc Furnace Steel Production

The structure of the steel manufacturing sector is one of the key variables that affects the energy intensity and CO_2 emissions of the steel industry. Electric arc furnace (EAF) steel production uses significantly less energy for the production of one tonne of steel. In 2006, the share of EAF steel production in total steel production was 10.5% in China and 56.9% in the U.S. The world average EAF production in 2006 was 31.6% (see Figure A-3.3.3). An accelerated shift to EAF steel production will reduce the energy use and CO_2 emissions per unit of steel production.

Figure A-3.3.3 Share of EAF in Total Steel Production in China and the U.S. and World Average Values



Source: worldsteel 2009

Appendix B. Sulfur Content in Chinese Coal

In China's coal reserves, coal with less than 1% of sulfur content ("low-sulfur coal") accounts for 17% of the total, and coal with more than 3% of sulfur content ("high-sulfur coal") accounts for 25% of the total. But coal that has 1% to 3% of sulfur content ("medium-sulfur coal") represents 58% of all. The majority of coal in China has more than 2% of sulfur content. Table B-1 below shows the average sulfur contents of each type of coal.

Table B-1 Average Sulfur Content of Different Types of Coal in China

Type	Dry Basis Sulfur Content S_Q^g (%)		
	Average	Min	Max
Lignite coal	1.11	0.15	5.20
Long flame coal	0.74	0.13	2.33
Non-caking coal	0.89	0.12	2.51
Weakly caking coal	1.20	0.08	5.81
Gas coal	0.78	0.10	10.24
Fat coal	2.33	0.11	8.56
Coking coal	1.41	0.99	6.38
Lean coal	1.82	0.15	7.22
Meagre coal	1.94	0.12	9.58
Anthracite coal	1.58	0.04	8.53
Total	1.21	0.04	10.24

Table B-1 shows the average sulfur contents in different types of coal have significant differences. The trend is that the lower coal rank it has; the lower sulfur content it gets. For instance, long-flame coal, non-caking coal and gas coal all have less than 1% of sulfur content averagely. Fat coal that has strong caking property has the highest sulfur content, averagely about 2.33%.