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Evaluation of the Contribution of the Building Sector to PM2.5 Emissions in China:

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Executive Summary

In recent years, China has experienced severe air pollution with adverse health consequences as a result of pollutants emitted by activities related to its rapid economic development and urbanization. One pollutant of growing concern in China is PM2.5, inhalable fine particulate matter linked to serious respiratory diseases, lung cancer, cardiovascular problems, birth defects and premature death. PM2.5 is directly emitted as the non-combustible materials from point primary sources including combustion processes (e.g. diesel engines, coal boilers in power plants), but can also be formed through secondary sources through chemical reactions with gaseous pollutants or precursors such as SO_2 and NOx that are released into the atmosphere. Buildings directly generate PM2.5 emissions by burning coal for end-uses such as heating, and also indirectly generate pollutants by consuming electricity that is generated predominantly by coal-fired power plants. This study therefore focuses on primary PM2.5 emissions emitted directly as a result of coal combustion to generate heat and electricity for residential and commercial buildings.

In this study, we quantify the current and potential contribution of China's building sector to direct primary and indirect PM2.5 emissions and co-benefits of key pollution reduction strategies of energy efficiency, fuel switching and pollution control technologies on PM2.5 emissions reduction. We use a bottom-up end-use accounting model to model residential and commercial buildings' coal demand for heating and electricity demand in China's Northern and Transition climate zones from 2010 to 2030. The model is then used to characterize the current coal-based heating (e.g., district heating, combined heat and power generation, small-scale coal-fired boilers) and power generation technologies to estimate direct and indirect PM2.5 emissions. Model scenarios are developed to evaluate and compare the potential co-benefits of efficiency improvements, fuel switching and pollution control technologies in reducing building-related direct and indirect PM2.5 emissions. An alternative pathway of development in which district heating is introduced to China's Transition zone to meet growing demand for heat is also modeled to evaluate and quantify the potential impact on PM2.5 emissions.

We find that space heating contributed to more than half of the 1.55 Mt of total direct and indirect building-related PM2.5 emissions in 2010, with the majority of space heating PM2.5 emissions tracing

back to coal-based district heating in Northern China. Under the reference scenario of development in the building sectors, annual total direct PM2.5 will decrease from 964,000 tons in 2010 to 654,000 tons in 2030 due to assumed efficiency improvements in district heating, independent coal boilers and building shells. However, even with continuous efficiency improvements and gradual switching of heating fuels and electricity generation to non-coal based sources under the reference scenario, indirect PM2.5 emissions will not decline due to significant increase in commercial electricity demand but will flatten at nearly 600,000 tons annually between 2010 and 2030.

Comparing the Reference scenario results to a frozen counterfactual scenario further reveals that building energy efficiency improvements have the greatest co-benefit in reducing building-related PM 2.5 emissions, without increasing costs or other pollutants such as NO_X, SO_X and CO_2 emissions. More specifically, efficiency improvement in heating technologies (e.g., independent and district heating coal and gas boilers) and building shell can significantly decrease direct primary PM2.5 from heating, while electrical equipment efficiency improvements (e.g., appliances, HVAC, lighting) can play an equally important role in reducing indirect PM2.5 emissions. In addition, with continued policy support, a gradual switch from coal to natural gas for heating fuels and from coal-dominated electricity generation to increasing shares of non-fossil generation can also reduce indirect PM2.5 from the electricity consumed by buildings by 0.5 Mt annually by 2030. Beyond the reduction potential reflected in the Reference scenario, more aggressive reductions in building-related PM 2.5 will rely on further coal to gas fuel switching for heating fuels, with half or all coal-based heating fuels being replaced by natural gas. In reality, however, such aggressive fuel switching will likely face limits in natural gas supply and possibly increased secondary PM2.5 emissions if proper emissions control technologies are not implemented for natural gas boilers. In the absence of sufficient natural gas for aggressive fuel switching, accelerated efficiency improvements reaching the international best practice level and PM control technologies in large coal boilers can achieve similar magnitudes of savings. Lastly, increased demand for heating and introduction of district heating to the Transition Zone could add 5.1 Mt of additional cumulative direct primary PM2.5 from 2010 to 2030.

Based on these findings, relevant policy recommendations for addressing the rising contribution of buildings to total PM2.5 emissions include the following:

- Continue policy-driven energy efficiency improvements by implementing more stringent building codes, appliance and equipment standards and labeling programs, and incentives to effectively lower direct and indirect building-related PM2.5 emissions
- Accelerate the installation of PM control technologies in large coal boilers to help further reduce indirect PM2.5 emissions, a growing but often overlooked source of building-related PM2.5 emissions in China
- Evaluate the feasibility of increasing coal-to-gas fuel switching for heating to maximize direct PM2.5 reductions, while considering the growing demand but constrained supply for natural gas.
- Consider alternatives to coal-based district hearting for providing heating in the China's Transition zone as it can substantially increase building-related direct PM2.5 emissions

Because the scope of this study was limited to only primary direct PM2.5 emissions from coal combustion in boilers for generating heat and electricity, it did not account for secondary PM2.5 emissions. The potential for secondary PM2.5 formation from nitrates released by natural gas boilers in the absence of NO_X emissions controls was not considered in this study due to lack of data, and the fuel switching scenarios may overstate the PM2.5 benefits of switching from coal to natural gas. In light of these limitations, future areas of research could include more detailed analysis of direct primary PM2.5 from non-heating and electricity end-uses, secondary PM2.5 emissions, and the relative magnitude of building-related PM2.5 compared to PM2.5 emissions from other sectors.

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1. Introduction

In recent years, China has experienced severe air pollution with adverse health consequences as a result of pollutants emitted by activities related to its rapid economic development and urbanization. One example of an air pollutant of growing public concern is fine particulate matter (PM) such as particles smaller than 2.5 micrometers, PM2.5, which can be inhaled and have been linked to serious respiratory diseases, lung cancer, cardiovascular problems, birth defects and premature death.

The concern over PM2.5 levels is particularly great in Northern China, as recently exemplified by extremely high PM2.5 levels of greater than 500[1] micrograms per cubic meter in northern cities such as Beijing in early 2013 and the closure of all schools, airports and roads in the entire city of Harbin due to poor visibility poor and unprecedented PM2.5 levels of greater than 1000 micrograms per cubic meter in late October 2013. In Northern China, the contribution of coal burning to PM2.5 emissions is greater in the winter heating season, where the majority of heating fuel for centralized district heating boilers and smaller heat boilers is still coal. Coal burning is an important source of PM2.5 emissions, with estimates of it accounting for about one-fifth of total direct and indirect emissions in the winter in cities such as Beijing, along with other sources of vehicle exhaust, road dust, biomass burning and metal processing (Yu et al. 2013).

From an end-use perspective, the building sector is also an important source of PM emissions because it interacts closely with the urban environment by generating pollutants through its daily operation and end-uses (e.g., heating) and by connecting the indoor and outdoor environment. Buildings indirectly generate pollutants by consuming fossil fuel, with residential and commercial building energy demand driving fossil fuel combustion and its subsequent pollutants. In Northern China's winter season, for example, heating energy demand accounts for 16.6 kgce per m^2 with total annual consumption of 163 Mtce. Coal combustion emits pollutants such as particulates, SO2 and NOx and most of the small and medium-size coal-fired boilers do not have emission control measures installed. As a result, coal boilers can generate as much as four times the particulate matter, 100 times the SO_2 and 2.5 times the NOx emissions as natural gas boilers per unit of heat supplied (Wang 2010). In addition, buildings are also a

[1] In comparison, the World Health Organization recommended air quality guideline for 24-hour average is no greater than 25 micrograms per m3 and the U.S. daily average environmental standard is 35 micrograms per m3.

large user of electricity that is predominantly generated by coal-fired boilers in China. Thus, the energy services of residential and commercial buildings are responsible for contributing to China's PM2.5 emissions through both direct coal burning for heating and indirect coal burning to generate electricity.

This report quantifies the current and potential contribution of China's building sector to PM2.5 emissions and co-benefits of key emission reduction strategies of energy efficiency, fuel switching and pollution control technologies on PM2.5 emissions reduction. A bottom-up Long-range Energy Alternatives Planning (LEAP) accounting model is developed and used to quantify commercial and residential buildings' coal demand for heating and electricity generation in the cold and severe cold climate zones in Northern China and in the Hot Summer Cold Winter climate zone, also known as the Transition Zone between Northern and Southern China. The LEAP model is then used to characterize the current coal-based heating (e.g., district heating, combined heat and power generation, small-scale coal-fired boilers) and power generation technologies to estimate direct and indirect PM2.5 emissions for the building sector. Model scenarios are developed to evaluate and compare the potential co-benefits of efficiency improvements, fuel switching and pollution control technologies in reducing building-related direct and indirect PM2.5 emissions. An alternative pathway of development in which district heating is introduced to China's Transition zone to meet growing demand for heat is also modeled to evaluate and quantify the potential impact on PM2.5 emissions.

This report begins with a brief overview of the direct and indirect precursors to the formation of PM2.5 emissions and the concern over PM2.5 emissions from district heating. Next, the modeling methodology to quantify the direct PM2.5 emission from coal burning for heating and indirect PM2.5 emissions from the power sector for electricity attributed to buildings is introduced. The fourth section of the report analyzes the model results for building-related direct and indirect PM2.5 emissions for the Reference scenario of development. Then, the scenario analysis assumptions and model results of the key strategies to reduce building-related PM2.5 emissions – energy efficiency, fuel switching and post-combustion control technologies – are presented. Key findings and policy recommendations, as well as potential areas of future research are discussed in the last section.

2. Overview of PM2.5 Emissions Formation

As a more complex and relatively new pollutant of concern, the science and research on PM formation and sources is still new and ongoing. As with common air pollutants that are directly emitted such as SO2, NOx or greenhouse gases such as CO2, PM can also be directly emitted as the non-combustible materials from point primary sources including combustion processes (e.g. diesel engines, coal boilers in power plants). But unlike these common air pollutants, PM can also be formed through secondary sources through chemical reactions with gaseous pollutants or precursors such as SO2 and NOx that are released into the atmosphere. Previous studies have shown that secondary sources of PM2.5 could range from over 20% to over 60% of total PM2.5 measurements at a specific site as a result of temperature, humidity and solar radiation levels (He et al. 2002, Yu et al. 2013, and Yang et al. 2013). However, this study focuses only on primary PM2.5 emissions emitted directly by point-sources (i.e., coal boilers) because of the complex atmospheric air quality models that are needed to evaluate secondary PM formation.

Much of the work to date has focused on understanding the different sources and processes through which particulates of different sizes are formed, also known as source apportionment. Source apportionment methods that have been used to identify and understand the major sources of PM2.5 include positive matrix factorization, principal component analysis, and chemical mass balance. These methods all require first taking samples of aerosols at a particular location over a period of time to measure the elemental compositions of the PM samples. The three methods can then be used to analyze the specific trace elements that constitute a small portion of the PM2.5 mass, which can be considered elemental tracers or markers for specific sources. For example, Cl has been considered an elemental tracer for coal combustion in Beijing as confirmed by its markedly higher concentrations in the winter compared to other seasons (Yu et al. 2013). By using source apportionment, atmospheric scientists are able to quantify the relative contributions of different sources to a given PM sample for a particular location and time. The sources identified for daily 24-hour samples collected in Beijing Normal University for the year of 2010 by Yu et al. 2013 are shown in Figure 1 below.

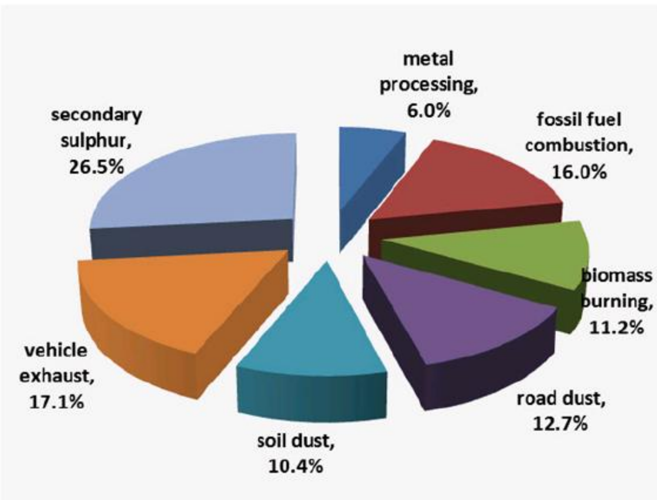


Figure 1. Beijing PM2.5 Sample Source Apportionment Results

Sources: Yu et al. 2013

While source apportionment studies can provide a comprehensive snapshot and comparison of the contributions of primary versus secondary sources of PM2.5 emissions, it does not help quantify the magnitude and scale of total PM2.5 emissions from a given source. For primary PM2.5 point sources, this can be done by conducting field measurements and data investigation to establish an emission factor database for atmospheric pollutants. In the U.S., the Environmental Protection Agency's AP-42 database provides emissions factors for different categories of coal-fired boilers depending on boiler type, coal quality, burner patterns, and emission control technologies. In China, the Ministry of Environmental Protection has published an emission factor database for the power sector, but only provided SO_2 and total PM emission factors. A recent study, Zhao et al. 2010, has also provided more detailed PM emission factors for three different types of coal-fired boilers in China's power sector based on samples taken from 8 coal-fired power plants. These specific PM emission factors can then be used in a bottom-up method to quantify the total PM emissions by multiplying the per unit emission factor (kilograms of particulate matter emitted per ton of coal burned) with the total amount of coal consumed. Zhao et. al. 2008 used this bottom-up method to estimate the total PM emissions of China's coal-fired power plants from 2000 to 2005 and to project the total PM emissions from 2010 to 2020.

As exemplified by the studies mentioned above, most of the recent PM-related work in China has focused either on source apportionment or on quantifying the PM emissions, including PM2.5, from coal-fired boilers in China's power sector. Presently, there has been very little work done to date to evaluate and quantify the PM2.5 emissions from coal burning to provide heat to buildings in Northern China. The lack of information and data on total PM2.5 emissions from coal burning for heating is problematic because unlike coal-fired boilers in the power sector, industrial boilers used for heating are much less likely to have PM control technologies or measures installed. Whereas the vast majority of coal-fired boilers for power generation have installed electrostatic precipitators, which help remove most of the larger particulates and most of the PM2.5, as well as more advanced fabric filters with higher removal efficiencies, very few industrial boilers have installed these control technologies due to high capital costs. As a result, uncontrolled PM emissions – and particularly PM2.5 emissions – from the coal-fired boilers used for heating in Northern China can be a large and potentially growing source of particulates associated with environmental degradation and severe human health risks.

In light of the information gap on quantifying PM2.5 emissions from coal combustion for heating in Northern China, this study uses a bottom-up energy end-use model to evaluate the contribution of the building sector to China's primary PM2.5 emissions, with a focus on heating in Northern China. The first scope of analysis focuses on quantifying the direct PM2.5 emissions from direct coal burning for heating buildings in Northern China, and the potential impacts from growing building heating demand in the Transition Zone. The second scope of analysis focuses on analyzing indirect PM2.5 emissions that occur in the power generation sector that is attributed to electricity use in the building sector. The impact of the co-benefits of building energy efficiency and fuel switching measures and technologies, as well as post-combustion treatment options, are also evaluated under these two scopes of analysis.

3. Modeling Methodology

In this study, a Long-range Energy Alternatives Planning (LEAP) model based on LBNL's China Energy End-Use Model was used to model the residential and commercial building sectors and their heating and electricity demand. Using the accounting framework provided by the LEAP software platform, this model captures diffusion of different end-use technologies and macroeconomic and sector-specific drivers of energy demand. For example, residential and commercial building floorspace is driven by urbanization, population growth and per capita demand for floorspace while energy demand is a function of energy demand intensities per square meter, technology and fuel shares. In addition to the building sectors, the LEAP model also models the power sector as an energy transformation module that is linked to the building energy demand modules. Determined by the total installed capacity, capacity factors and dispatch algorithms, the LEAP model dispatches sufficient electricity to meet the final energy requirements of the building energy demand modules.

Residential energy demand supports various household services and is shaped by a variety of factors, including location and climate. For China's residential building sector, urbanization and growth in household incomes drive energy consumption as urban households generally consume more commercial energy than rural households and rising household incomes correspond to increases in the size of housing units (and thus heating, cooling and lighting loads) and appliance and other equipment ownership. The model divides households into urban and rural locales and within these locales, end-uses are broken out into space heating, air conditioning, appliances, cooking and water heating, lighting and a residual "Others" category. Figure 2 shows the distribution of residential floorspace by region and

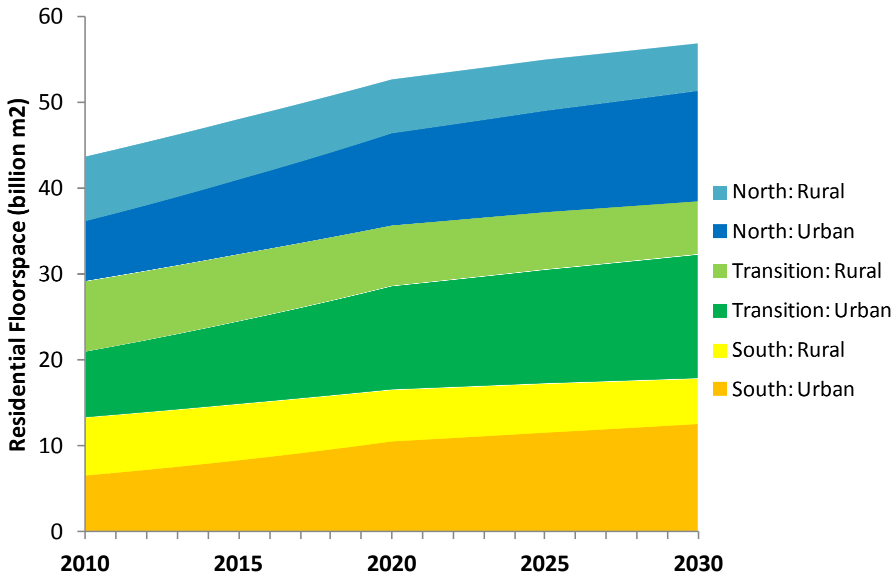


Figure 2. Residential Floorspace by Climate Zone and Urban-Rural Split

Figure 3 shows the overall model structure of the residential end-uses. In 2010, 33% of total residential space was located in the Northern Region, with a roughly even split between rural and urban households, and 35% was located in the Transition Zone, with slightly larger share in urban households than rural.

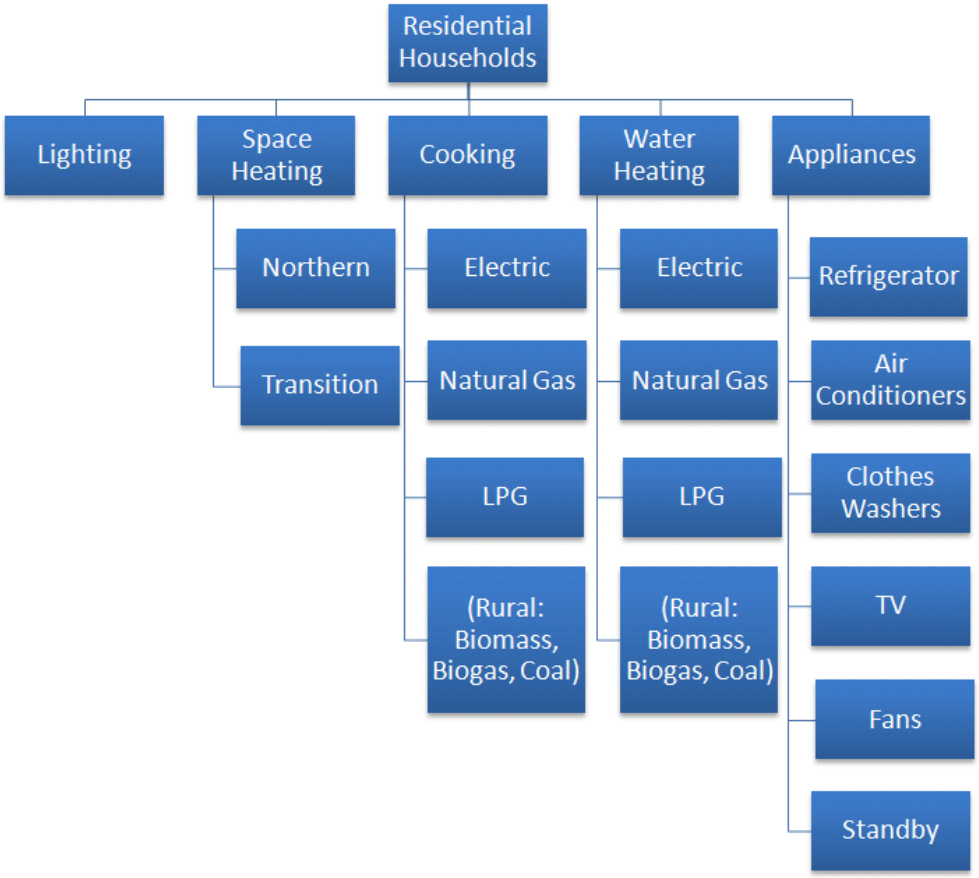


Figure 3. Model Structure for Residential Building Energy Demand

The residential building end-uses are further broken out by technologies; some appliances are broken out into classes by level of service, associated with by different levels of efficiency and technology types. Major appliances including air conditioners, refrigerators, clothes washers and televisions are modeled in more detail with stock turnover modeling, which includes information on initial stocks by vintage, energy efficiencies by vintage, efficiency degradation profiles, and lifetime or survival profiles. Space heating varies by geographic location, and is broken out into North, Transition and South zones based on China's climate zones (discussed further in section 3.1). For all end-uses, appropriate devices and fuels are assigned, with saturation (rates of penetration) and energy efficiencies based on historical statistical and survey data up to the base year and future values based on analysis of government plans, trends, and comparisons to other countries. Changes in energy demand in the model are in part a function of driver variables, e.g., GDP, population, household size and urbanization rate, which were determined exogenously and included in the model.

Commercial building energy consumption is driven by two key factors: building area (floor space) and end-use intensities such as heating, cooling, and lighting (MJ per m^2). In the model, commercial floor space is determined by the total number of service sector employees and the amount of built space per employee as commercial building construction in China is expected to be driven by the expansion of the services sector, as was the case for today's developed economies. 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, we estimate that the percentage of workers in the tertiary sector in the future and forecast the growth in floor space per employee based on regression derived from experience in Japan and the U.S.

Commercial building energy consumption varies by building type and its main functions, so the commercial building sector is broken out into the major building types of retail, office, school, hospital, hotel, and other buildings. Figure 4 shows the total projected floorspace of commercial buildings by building type in China. The key end-uses for each commercial subsector include space heating, space conditioning or cooling, water heating, lighting, and equipment.

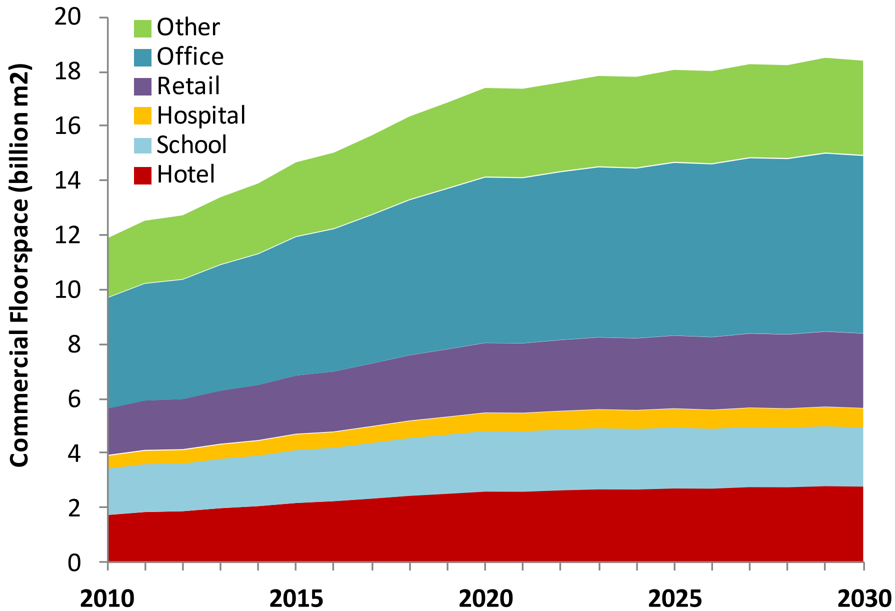


Figure 4. Commercial Floorspace by Building Type, 2010-2030

As with the residential sector, space heating in the commercial sector is also separated for Northern China and the Transition Zone, with the floorspace shares as shown in Figure 5. In Northern China, the space heating technology share and mix will be the same as the residential sector with 88% of heating provided by district heating technologies and only 12% provided by small, individual coal boilers.

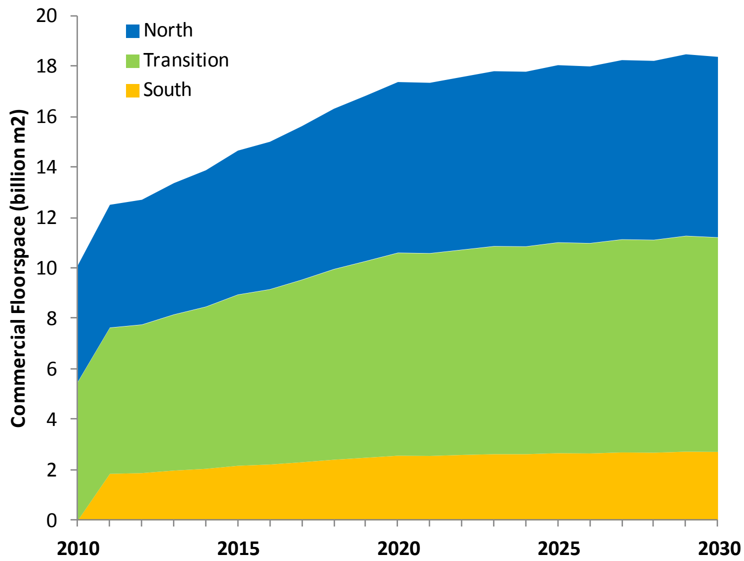


Figure 5. Commercial Floorspace by Climate Zone, 2010-2030

Figure 6 shows the overall model structure for commercial building energy demand.

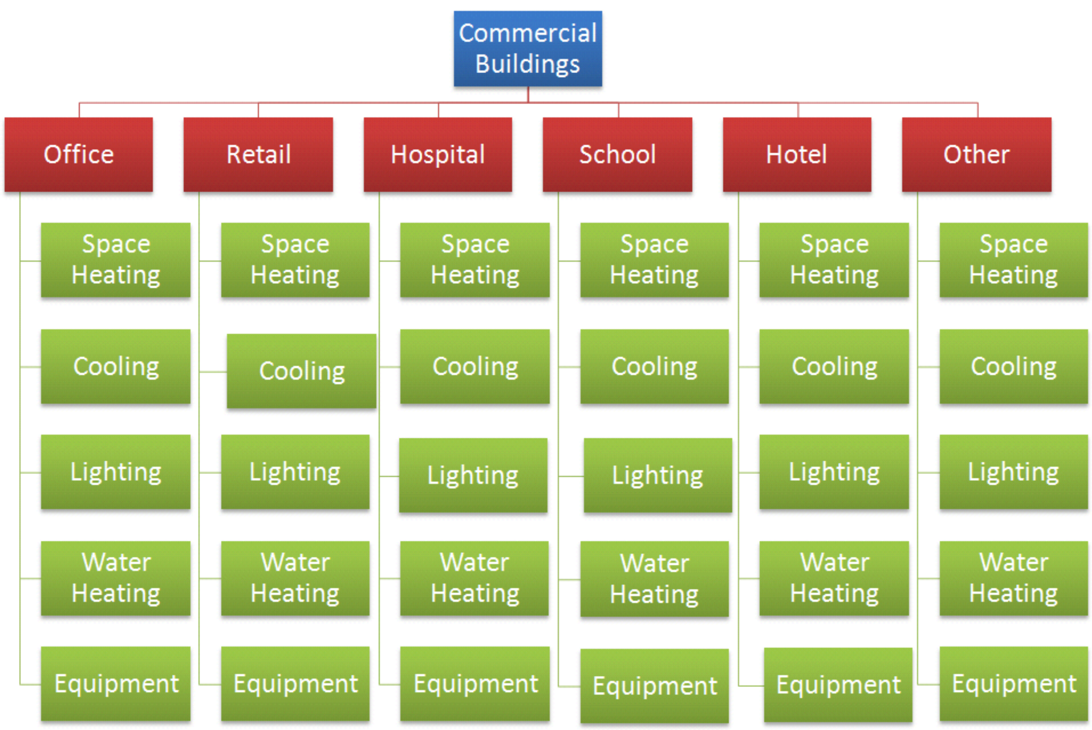


Figure 6. Model Structure for Commercial Building Energy Demand

Note: space heating under each building type is further separated into Northern China and Transition Zone.

In order to project the total building energy consumption by end-use and calculate the related primary PM2.5 emissions from building-related heating and electricity consumption, a reference scenario of a plausible energy demand outlook for China is developed. Unlike other business-as-usual scenarios, this reference scenario assumes that the Chinese economy will continue on a path of lowering its energy intensity with efficiency improvements consistent with moderate pace of "market-based" improvement in all sectors. This pace of efficiency improvement is aligned with what has been achieved in recent years as a result of energy policies and measures adopted under the 11th Five-Year Plan (FYP) and targets set under the 12th FYP. The efficiency improvements modeled under the reference scenario is represented by reductions in final energy intensities for specific technologies (e.g., annual kWh consumed per clothes washer) and where applicable, technology switching with growing market shares of more efficient technologies (e.g., switch from CFLs to LED for lightbulbs, and CRT to LED televisions). At the same time, the energy intensities assumed for each technology and end-use under the reference scenario do account for growing energy usage stemming from demand for more energy services such as lighting per m^2 and from increased equipment sizes such as larger refrigerators and televisions.

Table 1 presents a summary of the major assumptions for each building end-use type in the Reference Scenario. More detailed discussion of the assumed values and basis for each assumption can be found in other reports documenting the China Energy End-Use model, including Zhou et al. 2011 and Fridley et al. 2011.

Table 1. Summary of Building Energy Efficiency Assumptions under the Reference Scenario

Residential Buildings	
Heating Efficiency	Continuous efficiency improvement, with coal boilers improving from 63% in 2010 to 74% in 2030, gas boilers reaching 88% efficiency by 2030 and small efficiency improvements of 5% for electric heaters. District heating efficiency improves from 73% in 2010 to 80% in 2020 and 87% in 2030.
Building Shell Improvements: Heating	Continuous moderate efficiency improvement through 2030
Building Shell Improvements: Cooling	Continuous moderate efficiency improvement through 2030
Appliance (including Cooling) Efficiency	Continuous efficiency improvements and technology switching (e.g., incandescent to CFLs and LEDs) through 2030. Increased sizes and corresponding energy consumption of certain end-uses (refrigerators, TVs) taken into consideration.
Commercial Buildings	
Heating Efficiency	Continuous efficiency improvement, with coal boilers improving from 63% in 2010 to 74% in 2030, gas boilers reaching 88% efficiency by 2030 and small efficiency improvements of 5% for electric heaters. District heating efficiency improves from 73% in 2010 to 80% in 2020 and 87% in 2030. Continuous technology switching across all building types.
Cooling Efficiency	Continuous improvement (10-20% improvement per decade), reaching current International Best Practice by ~2030, and some technology switching across all building types.
Building Shell Improvements: Heating	50% improvement in fraction of new buildings growing by 1% per year
Building Shell Improvements: Cooling	25% improvement in fraction of new buildings growing by 1% per year
Lighting, Water Heating and Equipment Efficiency	18 % improvement by 2030, as a result of continuous technology switching and efficiency improvements. Increased energy use intensities (e.g., lighting per m2) taken into consideration.

3.1. Modeling Direct Primary PM2.5 from Coal Burning for Heating

In order to model the direct coal burning for heating for residential and commercial buildings, a more detailed and complex model structure was developed specifically for the space heating end-use. This structure is used to better characterize the different types of technologies used for personal and centralized district heating systems. The residential space heating model structure is shown in Figure 7.

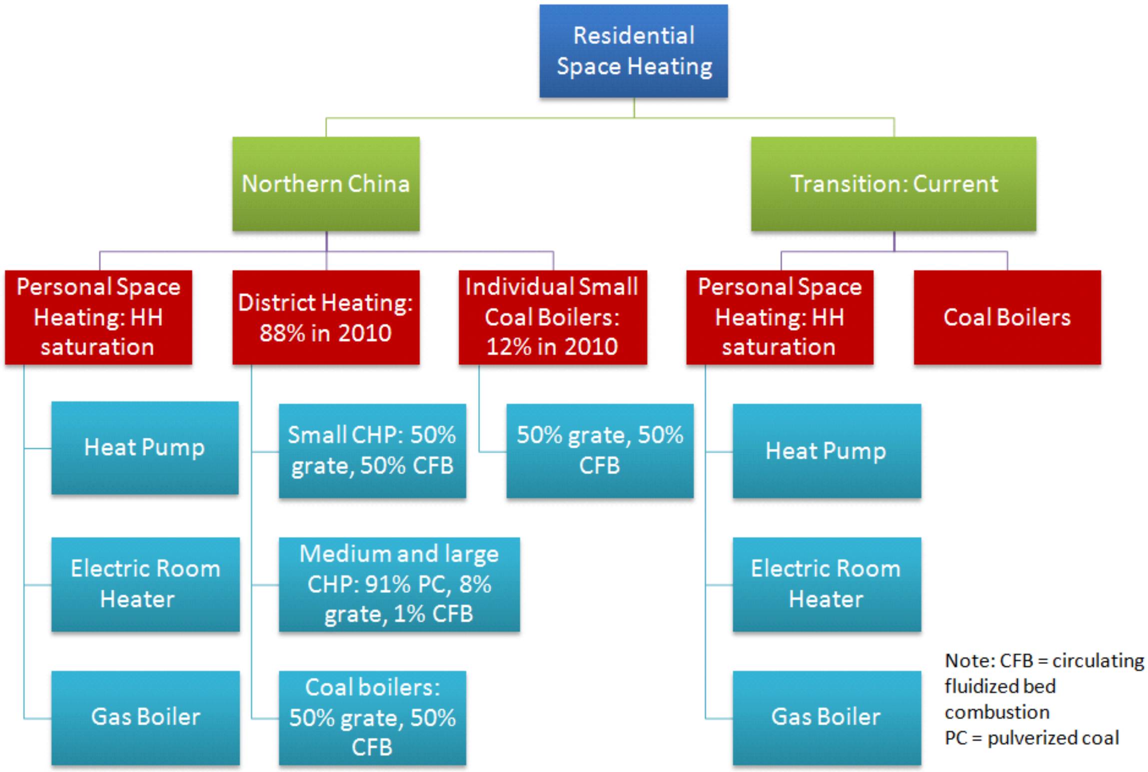


Figure 7. Model Structure for Residential Space Heating

For residential buildings in both Northern China and the Transition Zone, personal space heating is modeled using the same household ownership saturation function for the three main technologies of heat pump, electric room heater and gas boiler. In Northern China, coal-based heating is modeled as either large-scale, centralized district heating or individual small coal boilers that supply heat to individual buildings or small complexes. In 2010, the majority (88%) of heat supplied in Northern China District heating was provided by district heating with a very small share of 12% coming from individual small coal boilers. District heating is in turn modeled as three main groups of technologies: small combined heat and power (CHP) or cogeneration units, medium and large CHP or cogeneration units and large-scale industrial coal boilers that generate heat. Within each group of district heating technology, the technology shares for different boiler technologies (pulverized coal, grate and circulating fluidized bed) are assumed to remain constant at current levels as shown in Figure 7. The individual small coal boilers that also supply heat to residential buildings in Northern China are assumed to be made up of equal shares of grate boilers and circulating fluidized bed (CFB) boilers. In the transition zone, only coal boilers for heating are modeled as a separate heating technology outside of personal space heating equipment.

For commercial buildings, space heating in both Northern China and the Transition Zone is provided by five different technologies of coal boiler, gas boiler, heat pump, electric heater, and small cogeneration as shown in Figure 8. In Northern China only, some of the heat is also provided by district heating, which follows the same breakdown and technology shares as district heating in the residential sector. The space heating energy demand is expressed as final energy intensity per square meter, which varies by building type. The relative shares of the five (or six in Northern China) types of heating technologies used to meet the space heating energy intensity also varies by building type.

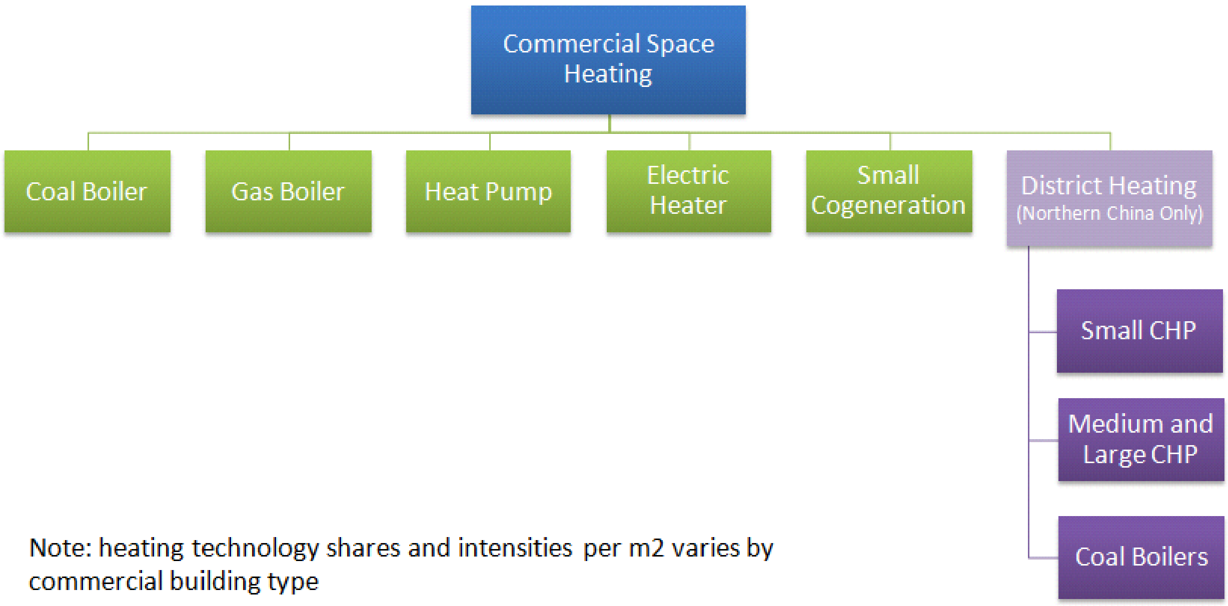


Figure 8. Model Structure for Commercial Space Heating

The total space heating energy demand by residential and commercial buildings under the reference scenario of continued efficiency improvements is shown below in Figure 9. Although heating demand from Northern China will continue to dominate total heating energy demand, demand from the transition zone – particularly from residential buildings – is also expected to increase over time. From 2010 to 2030, the transition zone's share of total heating energy demand will rise from only 6% to 17%.

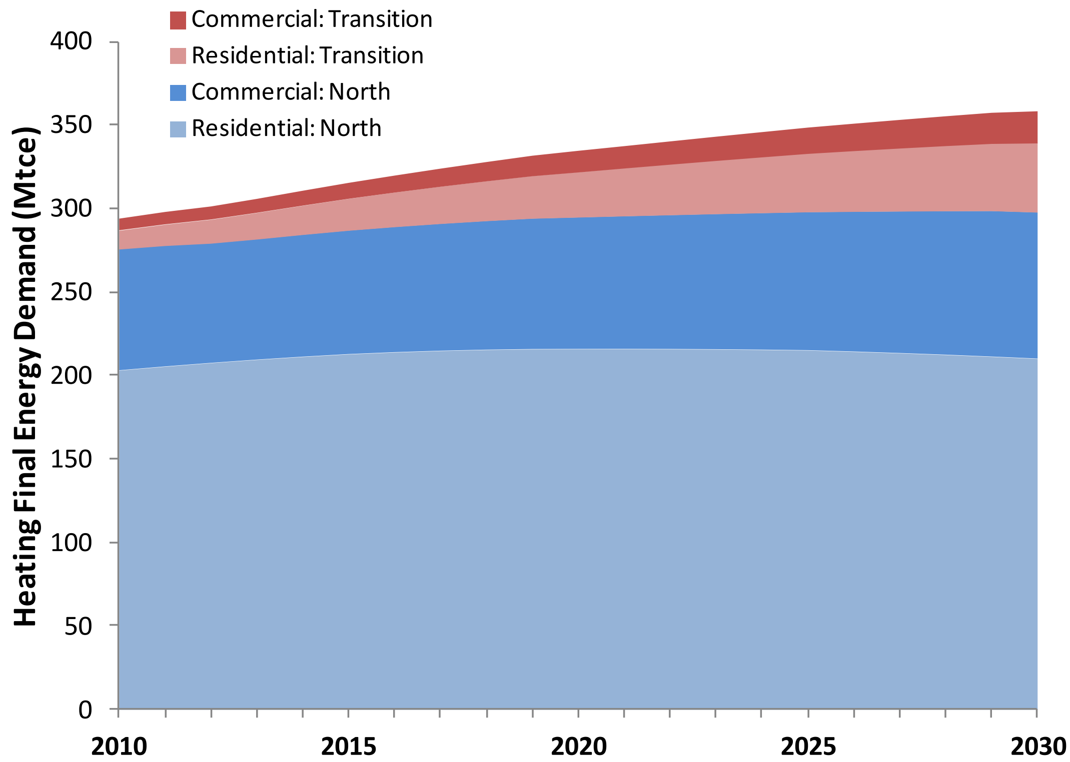


Figure 9. Total Heating Final Energy Demand by Region and Building Type

Figure 10 shows the total heating energy demand broken out by fuel type. As seen in the figure, coal is the primary fuel used to provide heating, accounting for 79% in 2010 and 50% in 2030. Although there is also a small and growing contribution from natural gas for heating, natural gas-fired boilers are relatively clean and emit negligible direct PM2.5 emissions. Thus, a direct primary emission factor of 0 is assumed for natural gas boilers and only coal consumption for heating is the only fuel source for direct primary PM2.5 emissions considered in this study.

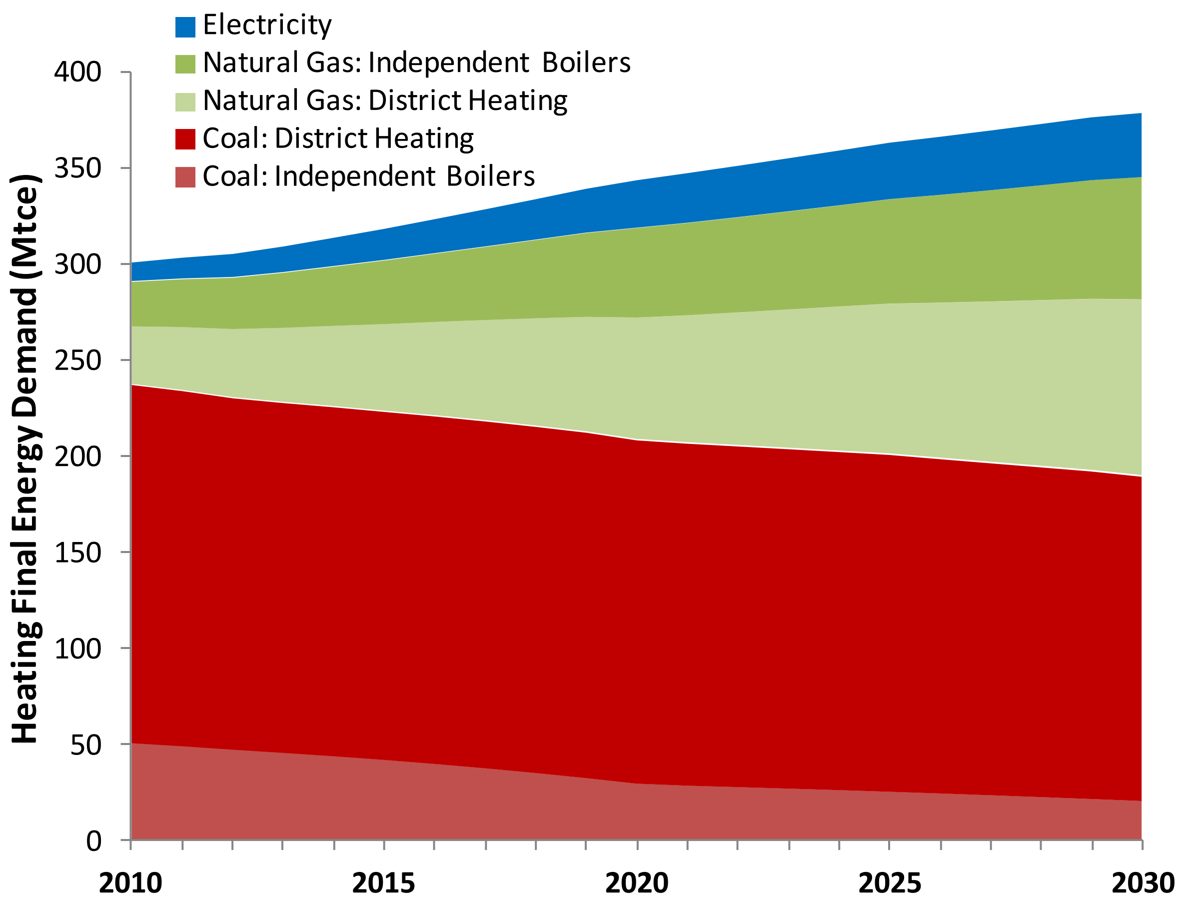


Figure 10. Heating Final Energy Demand for Reference Scenario, 2010-2030

Once the total heating energy demand and coal consumption for heating have been calculated, the emissions factors for different types of coal-fired boiler technologies are identified to calculate the total PM2.5 emissions. Because the PM emission factor is calculated as a function of the ash content of coal, an average ash content of 25% is assumed. The following emission factors shown in Table 2 were adapted from Lei et al. 2011 for four main categories of coal-fired boilers for heating.

Table 2. PM, PM10 and PM2.5 Emission Factors for Coal-fired Boilers for Heating

Unit: kg per ton of coal burned		PM	PM10	PM2.5
Large CHP Boilers	Pulverized coal	200	46	12
	Grate coal boilers	37.5	13.88	5.25
Small/Med CHP Boilers & Coal Boilers	Circulating fluidized bed	108	28.08	5.4
	Grate coal boilers	27	5.4	1.89

Source: Lei et al. 2011.

3.2. Modeling Indirect PM2.5 from Building Electricity Use

In order to quantify the indirect PM2.5 emissions from building electricity use, the power sector is modeled as an energy transformation module. The power generation module is used to model different power generation technologies including coal, natural gas, biomass, nuclear, wind, hydro, solar photovoltaic and concentrated solar thermal power generation. Coal generation is further differentiated into six main categories by size and efficiency, ranging from less than 100 MW generation units with average efficiency of 27% to greater than 1000 MW ultra-supercritical and IGCC generation units with average efficiency of 44%. For the smaller coal-fired boilers with less than 600 MW of capacity, the boiler technologies are further broken down into the three boiler types of pulverized coal (91%), grate (8%) and circulating fluidized bed (1%). All supercritical and ultra-supercritical coal boilers are assumed to use pulverized coal boilers. The installed capacity of the six categories of coal-fired generation is shown in Table 3.

For each technology type, the model includes parameters on total installed capacity, availability, and dispatch order. Following specified power sector module parameters, the model uses algorithms to calculate the amount and type of capacity required to be dispatched to meet the final electricity demand from the demand sectors of residential and commercial buildings, transport and industry. Specifically, the model uses an environmental dispatch order for generation, which favors non-fossil generation and reflects dispatch priority policies that are being considered in China. In the model, nuclear, wind, hydropower and other non-fossil generation are dispatched first, with coal generation dispatched last to meet all remaining electricity demand. The model also follows merit order dispatch for coal generation, where the largest and most efficient units are dispatched first to represent efficiency gains from structural shift to newer, larger-scale generation and mandated retirement of small, outdated generation units. China's announced targets for renewable generation and nuclear capacity expansion are used as the basis in setting the installed generation capacity.

It is important to note that the environmental dispatch algorithm adopted in our model assumes full implementation of the renewable energy prioritization dispatch introduced by the State Council in the 11th FYP period. Actual implementation of this dispatch order has only occurred in pilot regions thus far, and national-scale implementation still faces barriers that need to be addressed by additional policies and power sector reform. Nevertheless, we believe that environmental dispatch will be effectively implemented in the near-term given China's ambitious non-fossil energy targets of 15% by 2020 and newly announced target of 20% by 2030 in November 2014.

In terms of residential building electricity use, the major end-uses were shown in Figure 3 and include lighting, electric stoves for cooking, electric water heaters and the household appliances of refrigerators, air conditioners, clothes washers, televisions, fans, and standby power. In addition, electricity is also used for the personal space heating equipment of electric room heaters and heat pump. In the commercial building sector, electricity is also used for electric room heaters and heat pumps for space heating, cooling, lighting, water heating and equipment use. The energy intensities of each of these end-uses per square meters and their technology shares and efficiency levels are described in Zhou et al. 2011.

Figure 11 shows the total electricity consumption by major end-use for the residential and commercial buildings from 2010 to 2030. In the residential sector, the largest electricity end-users are appliances and other standby uses, followed by smaller shares from lighting and cooking. Similarly, in the commercial sector, lighting and equipment are also the two leading electricity end-uses, followed by cooling and space heating in the transition zone.

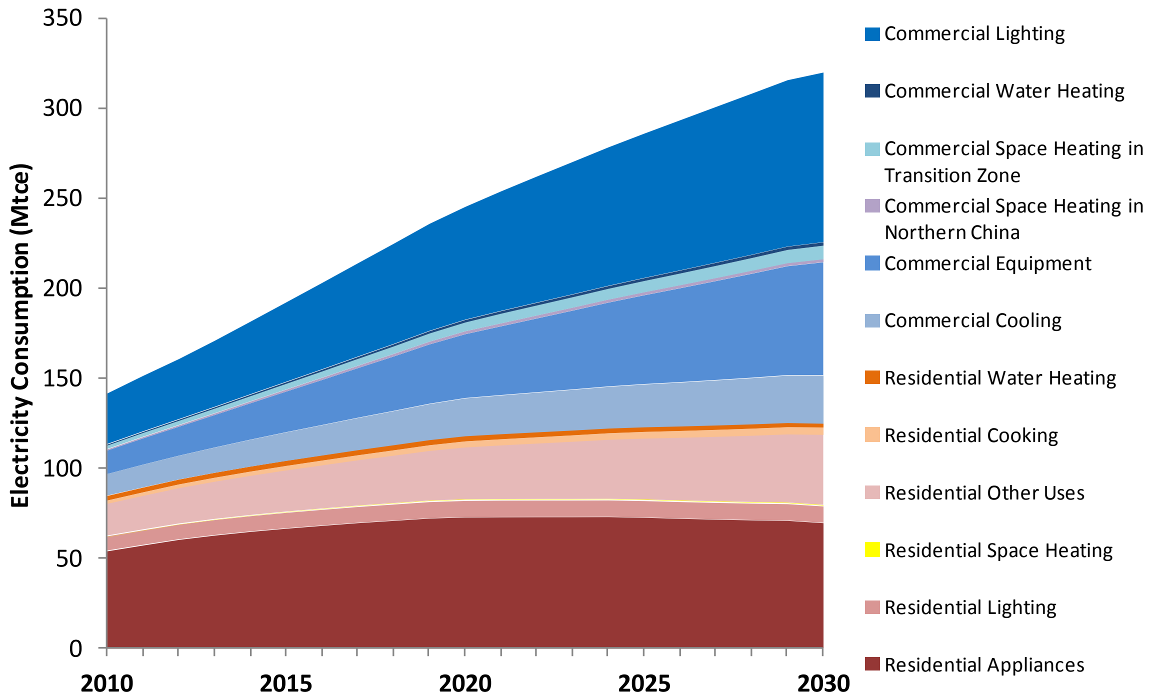


Figure 11. Electricity Consumption by Major Residential and Commercial End-Uses

Under the Reference scenario, fuel switching is assumed to occur in the power sector with growing share and generation shares for non-fossil electricity generation, followed by cleaner natural gas power generation. Coal generation is assumed to be dispatched last to meet the remaining electricity demand, with more efficient, larger-scale coal power plants (e.g., ultra supercritical) dispatched before smaller, inefficient units (e.g., subcritical). Table 3 shows the total installed capacity by electricity generation type and its share of total installed capacity for the selected years of 2010, 2020 and 2030.

Table 3. Reference Scenario Installed Electricity Generation Capacity by Fuel and Technology

	2010		2020		2030	
	GW	Share	GW	Share	GW	Share
Wind Power	22	2%	150	8%	300	13%

Solar PV	0.5	0%	17.8	1%	45.9	2%
Solar CSP	0.03	0%	2.2	0%	5.1	0%
Nuclear Power	16	1%	70	4%	130	6%
Hydropower	200	18%	300	17%	350	16%
Geothermal	0.11	0%	1	0%	2	0%
Biomass	5.5	0%	30	2%	40	2%
NG Fired CC	26.7	2%	65	4%	100	4%
Coal <100MW PC	145.9	13%	46.97	3%	0	0%
Coal <100MW Grate	12.8	1%	4.13	0%	0	0%
Coal <100MW CFB	1.6	0%	0.52	0%	0	0%
Coal 100 to 200MW PC	78.9	7%	46.97	3%	20.47	1%
Coal 100 to 200MW Grate	6.9	1%	4.13	0%	1.8	0%
Coal 100 to 200MW CFB	0.9	0%	0.52	0%	0.22	0%
Coal 200 to 300MW Subcritical PC	64.9	6%	83.21	5%	90.67	4%
Coal 200 to 300MW Subcritical Grate	64.9	6%	83.21	5%	90.67	4%
Coal 200 to 300MW Subcritical CFB	1.4	0%	1.85	0%	2.01	0%
Coal 300 to 600MW Subcritical PC	307	27%	278.73	16%	182.23	8%
Coal 300 to 600MW Subcritical Grate	27.28	2%	24.78	1%	16.2	1%
Coal 300 to 600MW CFB	6.82	1%	6.19	0%	4.05	0%
Coal 600 to 1000MW Supercritical PC	96.49	9%	361.32	20%	281.22	13%
Coal >1000P MW Ultra-Supercritical PC	48.34	4%	206.47	12%	562.44	25%

Note: Coal > 1000 MW is intended to represent both ultra-supercritical and IGCC units since both have similar process efficiencies.

As with heating, natural gas boilers are assumed to emit zero primary PM2.5 emissions and coal is the only fuel source for which indirect primary PM2.5 emissions are estimated in this study. The emission factors for coal-fired boilers for power generation were also adopted from Lei et al. 2011 and are the same as large boilers for CHP, as seen in Table 4.

Table 4. PM, PM10 and PM2.5 Emission Factors for Coal-fired Power Plants by Boiler Type

Unit: kg per ton of coal burned		**PM**	**PM10**	**PM2.5**
All Coal-fired Power Plants	Pulverized coal	200	46	12
	Grate coal boilers	37.5	13.88	5.25

Source: Lei et al. 2011.

With the decreasing share of coal-fired power plants, particularly smaller and inefficient units, and rising share of non-fossil electricity generation such as wind power, the average PM emission factors per kWh of electricity generated is expected to decrease over time. This in turn will affect the total indirect PM2.5 emissions for buildings, as discussed later in section 4.2.

4. PM2.5 Emissions Results for Reference Scenario

4.1. Direct Primary PM2.5 for Heating Buildings

4.1.1. Residential Buildings

The direct primary PM2.5 emissions from burning coal to heat residential buildings totals 561 thousand tons (kt) of PM2.5 in 2010, but is expected to decrease significantly over time through 2030 under our Reference scenario as a result of assumed continuous efficiency improvements in district heating and coal boilers as shown in Table 1.

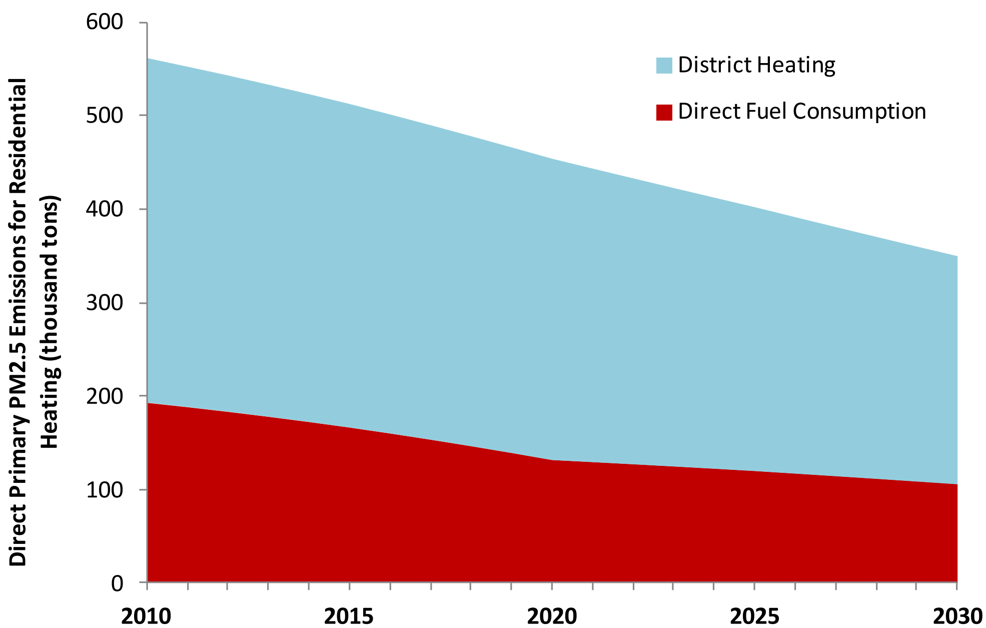


Figure 12. Direct PM2.5 Emissions for Residential Space Heating, 2010-2030

For example, district heating's efficiency is expected to increase from 73% in 2010 to 80% in 2020 and 87% in 2030, while coal boilers' efficiency increases from 62% in 2010 to 68% in 2020 to 74% in 2030. As a result, direct primary PM2.5 emissions from coal burning for district heating will decrease in absolute terms from 368 kt of PM2.5 in 2010 to 244 kt of PM2.5 in 2030. Primary PM2.5 emissions from direct coal consumption for heating totals 106 kt in 2030, or 45% lower than the 2010 levels. The 2010 and 2030 relative contributions of the two types of space heating to total direct residential PM2.5 emissions are shown in Figure 13.

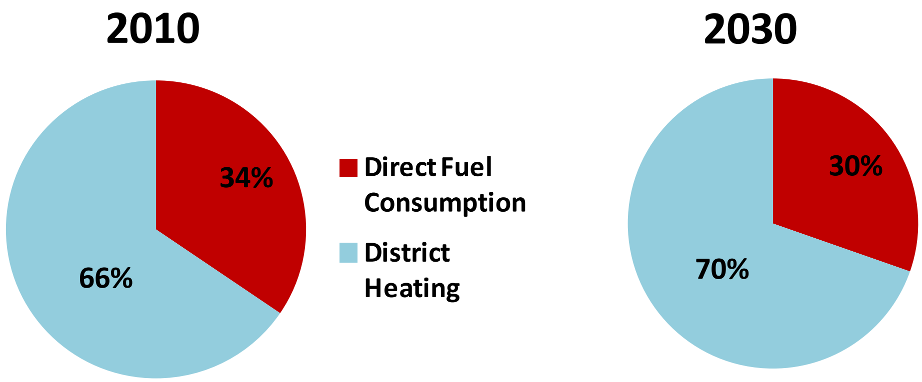


Figure 13. 2010 and 2030 Heating Technology Shares of Direct Residential PM2.5 Emissions

In terms of the contribution to PM2.5 emissions by heating region, the majority of direct primary PM2.5 emissions in the residential buildings sector will be from the Northern region as seen in Figure 14. The Transition zone accounts for less than 1% of total PM2.5 emissions in 2010 and 6% in 2030.

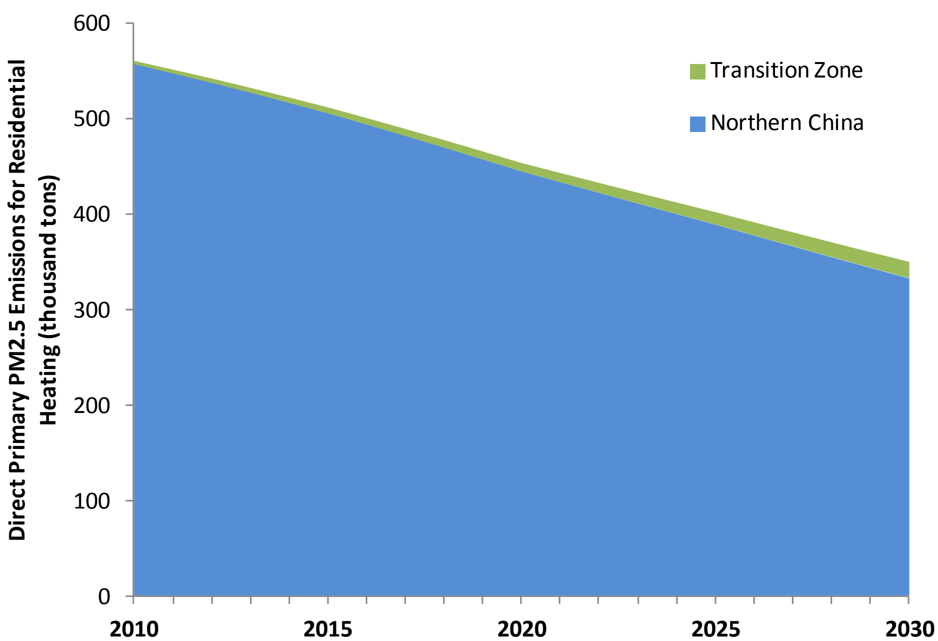


Figure 14. Direct Residential PM2.5 Emissions from Heating by Region

4.1.2. Commercial Buildings

As with residential buildings, district heating supplies the vast majority of heat for commercial buildings and thus emits the most direct primary PM2.5 emissions, followed by independent coal boilers and a very small share from electric heating devices. Over time, independent coal boilers for heating will be completed phased out and replaced by district heating, resulting in declining shares of PM2.5 emissions from independent coal boiler, as seen in Figure 15.

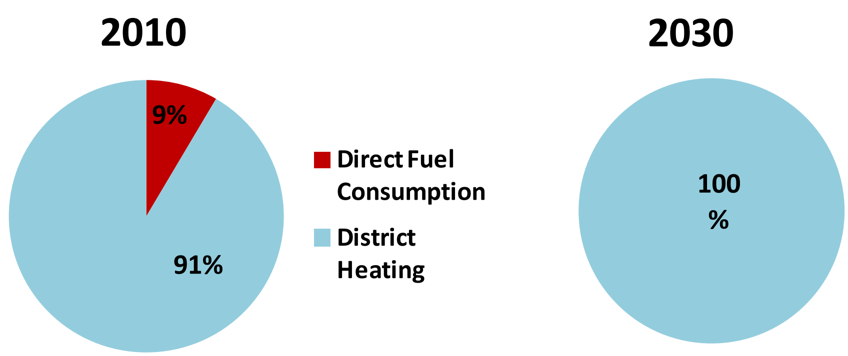


Figure 15. 2010 and 2030 Heating Technology Shares of Direct Commercial PM2.5 Emissions

Efficiency improvements in district heating and independent coal boilers over time also contribute to declining total direct primary PM2.5 emissions from heating commercial buildings. Figure 16 shows that the total primary PM2.5 emissions from coal burning for commercial heating will decline from 403 kt in 2010 to 301 kt in 2030

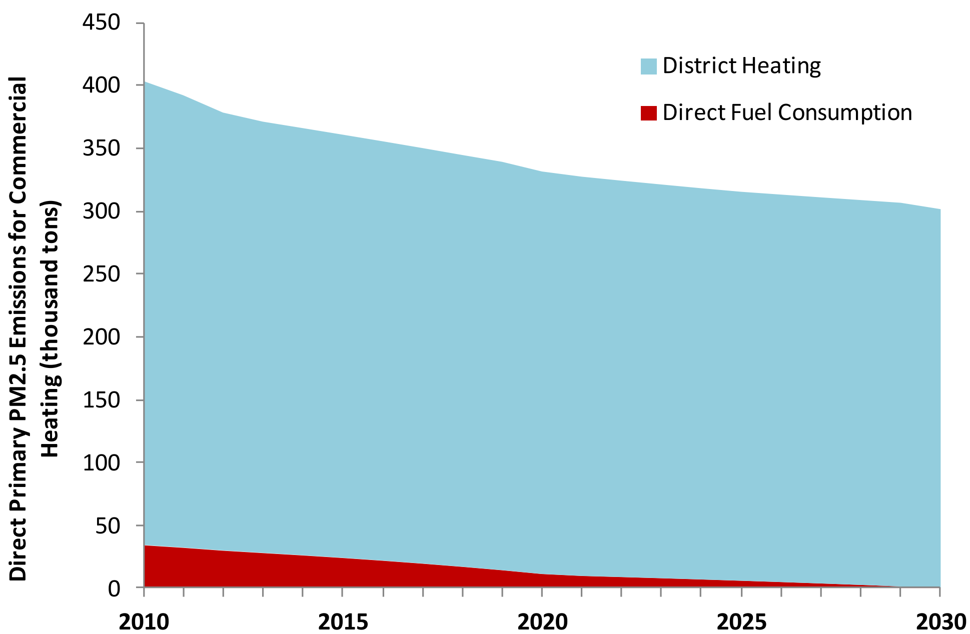


Figure 16. Direct PM2.5 Emissions for Commercial Space Heating, 2010-2030

Most of the PM2.5 emissions from heating commercial buildings is from Northern China as seen in Figure 17, with shares of over 95% of total PM2.5 from 2010 through 2030.

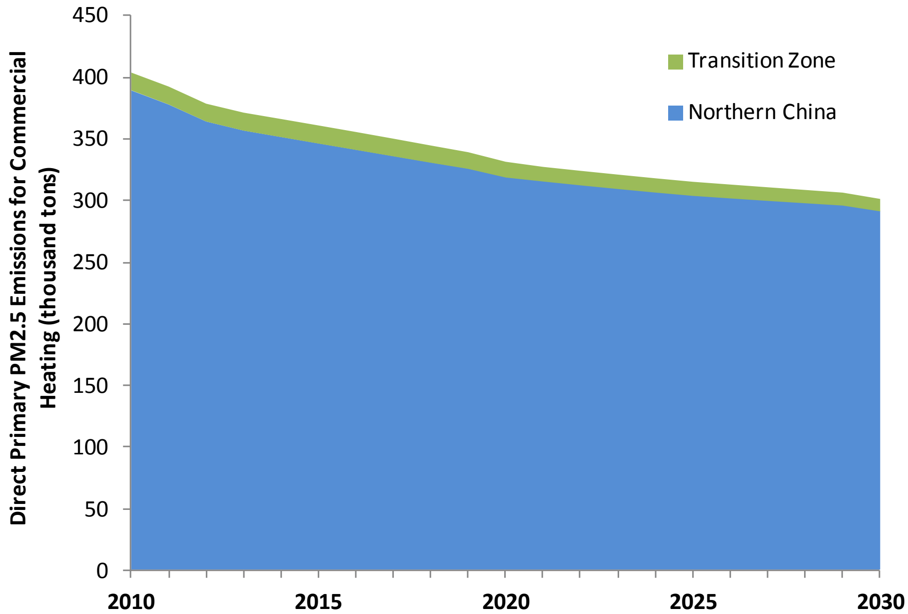


Figure 17. Direct PM2.5 Emissions for Commercial Space Heating by Region, 2010-2030

In terms of building type, Figure 18 shows that the largest share of direct PM2.5 emissions for space heating will be from heating office buildings, which has the largest share of commercial floorspace, followed by other commercial buildings, hotel and retail.

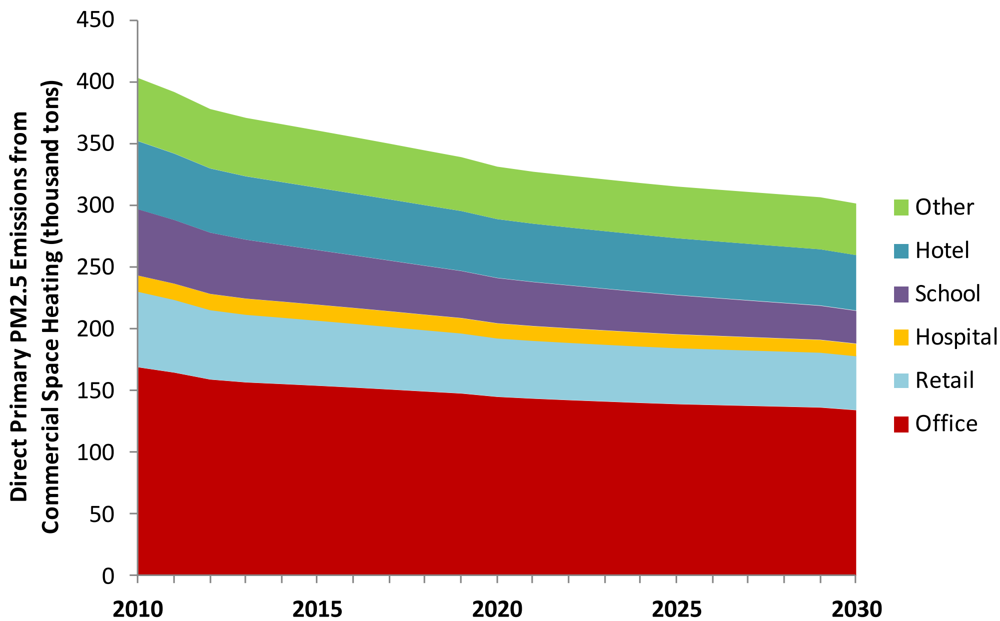


Figure 18. Direct Primary PM2.5 Emissions from Commercial Space Heating by Building Type

4.1.3. Total Building-related Direct PM2.5

In sum, residential and commercial buildings together contributed 965 kt of direct primary PM2.5 emissions in 2010. The vast majority of this building-related PM2.5 emissions from heating were emitted in Northern China, with a slightly larger share coming from residential than commercial buildings (Figure 19). By 2030, the total direct primary PM2.5 from heating residential and commercial buildings will decrease by one-third to 675 kt as a result of the continuous efficiency improvements and fuel switching. Northern China will still account for 99% of the total direct PM2.5, but with an almost even split between commercial and residential buildings.

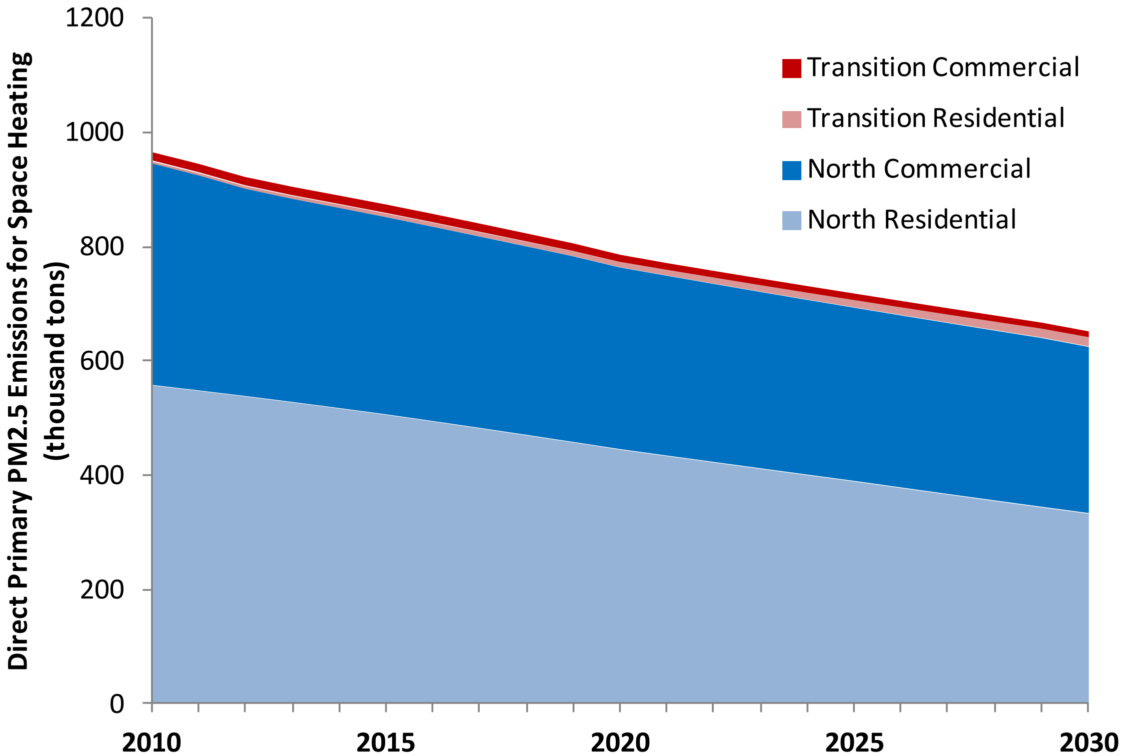


Figure 19. Direct Primary PM2.5 Emissions for Heating by Building Type and Region

4.2. Indirect PM2.5 from Building Electricity Use

The indirect PM2.5 emissions from building-related electricity use for residential and commercial buildings are shown in Figure 20. From 2010 to 2030, indirect PM2.5 emissions will remain relatively constant between 570kt to 580 kt PM2.5 per year, despite rapid growth in total building electricity consumption over time as seen in Figure 11. This is the result of the fuel and coal technology switching assumed to occur for the entire power sector under the Reference scenario and the subsequent decreasing average PM2.5 emission factor per kWh of electricity generated from 2010 to 2030.

Unlike direct PM2.5 emissions, indirect PM2.5 also remains flat as a result of increased usage and rapidly rising electricity demand for end-uses in commercial buildings (as seen in Figure 11) offsetting electricity savings from improved efficiency in lighting and electrical equipment. The relative share of indirect PM2.5 from commercial buildings will steadily increase, from 37% in 2010 to 48% in 2020 and 56% in 2030. Despite moderate efficiency improvements in electricity end-uses, commercial buildings' electricity demand for end-uses including lighting and equipment use grows rapidly. This results in increasing indirect PM2.5 emissions from the commercial building sector. This is different from the residential sector, where appliance ownership is expected to reach saturation in the near future and small increases in usage are largely offset by efficiency improvements, resulting in a plateauing of residential electricity consumption after 2020 and decreasing indirect PM2.5 emissions. However, the share of indirect PM2.5 from electricity consumed for residential electric heating is expected to double over time from 9% of total residential indirect PM2.5 in 2010 to 18% in 2030.

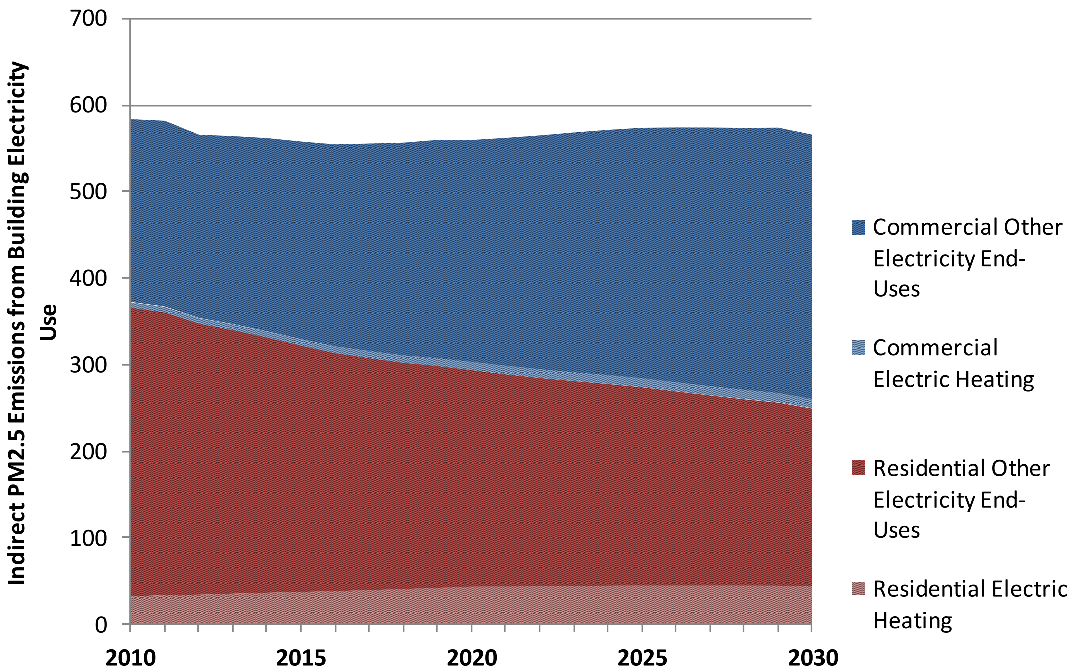


Figure 20. Indirect PM2.5 Emissions from Residential and Commercial Electricity Use

4.3. Total Building-related PM2.5 Emissions

Total building-related PM2.5 emissions are the sum of direct PM2.5 from heating and indirect PM2.5 from the buildings' share of electricity consumption. Indirect PM2.5 emissions can be further divided into building electricity consumption for heating and building electricity consumption for other end-uses (e.g., appliances and commercial equipment, lighting, etc.)

Figure 21 shows the relative shares of direct and indirect PM2.5 by building source for the base year of 2010. In 2010, total building-related PM2.5 was 1.55 Mt of PM2.5, with 62% as direct PM2.5 from heating and 38% as indirect PM2.5 from building electricity use. The 38% share from building-related indirect PM2.5 can be further broken down into 2.5% share for electricity used for heating and 35.5% share for electricity used to power other equipment and lighting end-uses. Residential heating alone contributed more than one-third of total building-related PM2.5 emissions in 2010, with another one-fourth of total building-related PM2.5 coming from commercial heating.

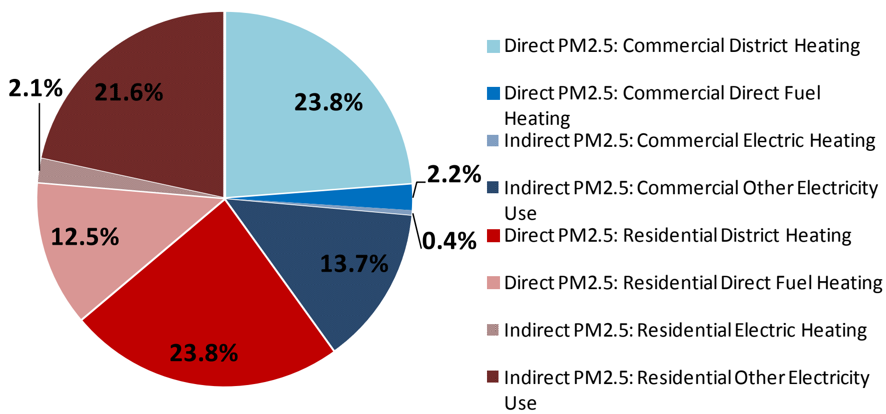


Figure 21. 2010 Total Building-related PM2.5 by Source

Over time, however, the relative shares of indirect PM2.5 are expected to rise, as seen in Figure 22. By 2030, indirect PM2.5 from residential and commercial buildings will contribute 20% and 26%, respectively, of the 0.91 Mt total building-related PM2.5. The vast majority of this will be from electricity consumed for non-heating end-uses, as the share of PM2.5 from electric heating reaches only 5% for residential and commercial buildings combined by 2030. The growth in indirect PM2.5 emissions from commercial buildings is the fastest, driven again by the rising demand for non-heating electricity end-uses across building types.

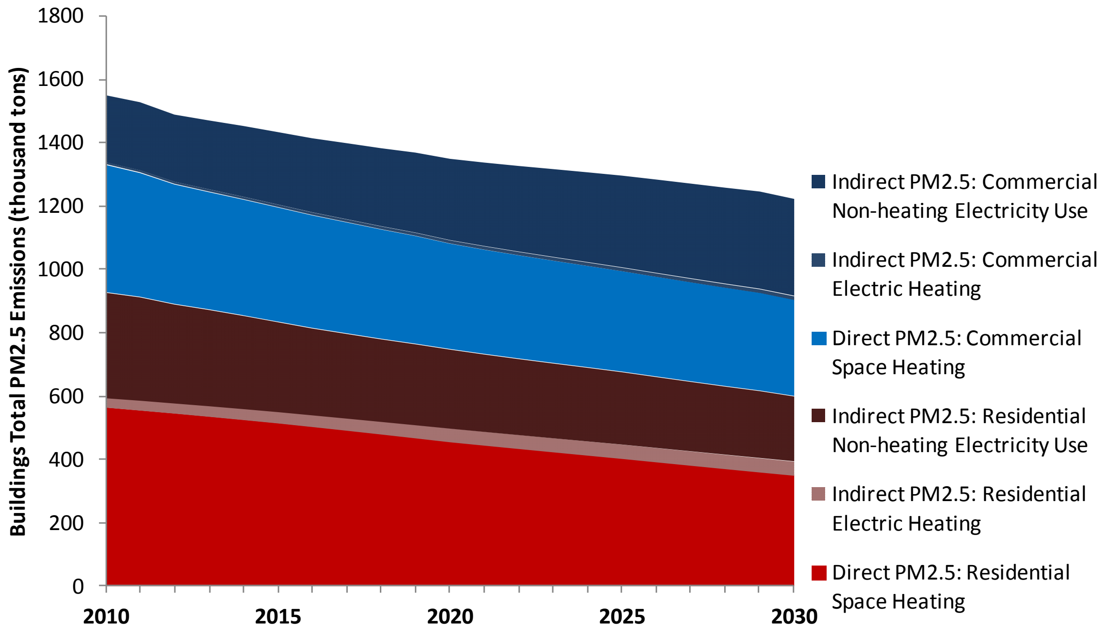


Figure 22. Direct and Indirect PM2.5 by Building Type, 2010 to 2030

5. Strategies for Reducing Building-related PM2.5 Emissions and Potential Impacts

In addition to the district heating in the Transition Zone scenario, four other scenarios were developed to evaluate the potential impact of different strategies to reduce building-related PM2.5 emissions. These strategies include continuously improving the efficiency of building shell and end-uses, promoting fuel switching for heating technologies, and installing PM emission control technologies to coal boilers in the power sector.

5.1. Building Energy Efficiency Improvements

Continuously improving the energy efficiency of heating, cooling and equipment technologies provide benefits in reduced energy consumption and energy-related CO2 emissions, and can also provide co-benefits in reducing both direct PM2.5 emissions from heating and indirect PM2.5 emissions from electricity use. We use three scenarios to evaluate the potential PM2.5 emissions reduction impact of different paces of improving building energy efficiency: a frozen efficiency scenario, the reference scenario of continuous efficiency improvement and an accelerated efficiency improvement scenario.

5.1.1. Continuous and Accelerated Efficiency Improvement Scenarios

In our model, continuous building efficiency improvements are embodied in the reference scenario because unlike typical business-as-usual scenarios, our reference scenario represent a likely path of development for China's building sector assuming that recently implemented efficiency policies and measures will continue at the same pace through 2030. In order to evaluate the potential PM2.5

reductions for this continuous pace of efficiency improvement represented by the Reference scenario, a counterfactual frozen efficiency scenario was developed. This frozen efficiency scenario assumes that without further policy action, the efficiency levels of heating, cooling and all other building end-uses will remain frozen at the 2010 level for both residential and commercial buildings. It also assumes that there will be no heating or cooling efficiency improvements in the residential and commercial building shells.

In addition to the Reference scenario of continued efficiency improvement, another scenario was developed to evaluate the PM2.5 reduction co-benefits of more aggressive efficiency improvements across all building end-uses. The more aggressive pace of efficiency improvement include greater efficiency improvements during the same timeframe, including possibly reaching the current international best practice level of efficiency earlier than under the reference scenario. A summary of the key differences in efficiency assumptions between these three scenarios of efficiency improvements is shown in Table 5. This Accelerated Efficiency Improvement scenario is compared to the Reference scenario to show the additional co-benefits in PM2.5 reduction that could be achieved through more aggressive and earlier implementation of efficiency measures.

Table 5. Continuous and Accelerated Efficiency Improvement Scenario Assumptions

	Frozen Efficiency Scenario	**Reference Scenario with Continuous Efficiency Improvement**	**Accelerated Efficiency Improvement Scenario**
Residential Buildings			
Appliance Efficiency	Efficiency is frozen at 2010 base year level through 2030.	Moderate Efficiency Improvement (1/3 improvement relative to Accelerated Efficiency)	Moderate Improvement of new equipment in 2010 – near Best Practice by 2020
Building Shell Improvements: Heating	Efficiency is frozen at 2010 base year level through 2030.	Moderate Efficiency Improvement (1/3 improvement relative to Accelerated Efficiency)	50% improvement in new buildings by 2010 – 75% improvement in new buildings by 2020.
Building Shell Improvements: Cooling	Efficiency is frozen at 2010 base year level through 2030.	Moderate Efficiency Improvement (1/3 improvement relative to Accelerated Efficiency)	25% improvement in new buildings by 2010 – 37.5% improvement in new buildings by 2020.
Commercial Buildings			
Heating Efficiency	Efficiency is frozen at 2010 base year level through 2030.	Moderate Efficiency Improvement by 2020	Current International Best Practice by 2020

Cooling Efficiency	Efficiency is frozen at 2010 base year level through 2030.	Current International Best Practice after 2020	Current International Best Practice by 2020
Building Shell Improvements: Heating	Efficiency is frozen at 2010 base year level through 2030.	50% improvement in fraction of new buildings growing by 1% per year	50% improvement in all new buildings by 2010, 75% improvement in all new buildings by 2025
Building Shell Improvements: Cooling	Efficiency is frozen at 2010 base year level through 2030.	25% improvement in fraction of new buildings growing by 1% per year	25% improvement in all new buildings by 2010, 37.5% improvement in all new buildings by 2025
Lighting and Equipment Efficiency	Efficiency is frozen at 2010 base year level through 2030.	18 % improvement by 2030	48 % improvement by 2030

As seen in the table, the Accelerated Efficiency Improvement scenario includes more aggressive improvements and thus energy savings in both heating and electricity consumption for cooling, lighting and equipment. As a result of less heating fuel use and electricity use relative to the Reference scenario, the Accelerated Efficiency Improvement scenario will have lowered building-related direct PM2.5 emissions for heating and indirect building-related PM2.5 emissions from electricity savings.

5.1.2. Impact of Continuous Improvement under Reference Scenario

5.1.2.1. Direct PM2.5 Emissions

The notable decline in direct primary PM2.5 emissions from heating buildings – despite increasing demand for heating - can be attributed directly to the continuous efficiency improvements assumed to take place between 2010 and 2030 (see Table 1). Without these continuous efficiency improvements, such as under the counterfactual frozen efficiency scenario, total direct primary PM2.5 emissions from heating buildings will continue to rise and reach nearly 1.1 Mt by 2030 (Figure 23).

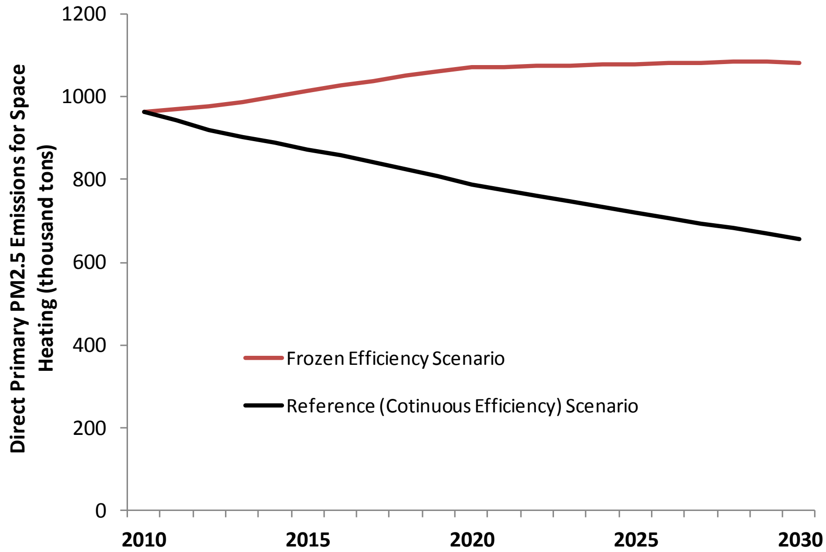


Figure 23. Direct Primary PM2.5 for Heating for Frozen and Reference Efficiency Scenarios

Most of the direct PM2.5 emission reductions are from Northern residential buildings, followed by Northern commercial buildings, since these are the largest heating users. Key efficiency improvement measures that contributed to this reduction include improving district heating efficiency from 73% to 87% by 2030 for both residential and commercial buildings, improving coal boilers' efficiency for heating from 63% to 74% by 2030 and improving heating efficiency of both residential and commercial building shells. From 2011 to 2030, the annual reduction in direct PM2.5 emissions as a result of continuous efficiency improvements under the reference scenario will grow from 16 kt in 2011 to 168 kt in 2030 (Figure 24).

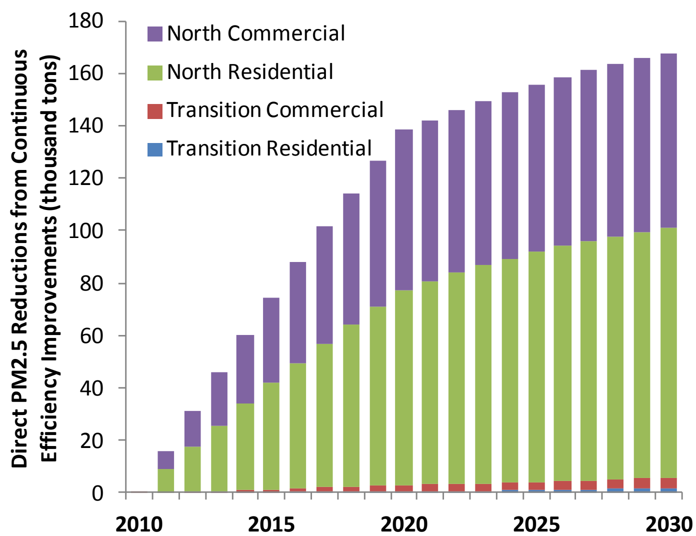


Figure 24. Direct Primary PM2.5 Reduction under Reference (Continuous Efficiency) Scenario

5.1.2.2. Indirect PM2.5 Emissions

Continuous efficiency improvements modeled under the Reference scenario also have significant impact on reducing the total building-related indirect PM2.5 emissions. The implicit savings as a result of electrical equipment efficiency improvements can be seen by comparing the total indirect PM2.5 emissions of the reference scenario to the frozen efficiency scenario in Figure 25. Without continuous improvements in building end-uses of residential appliances and commercial equipment, lighting, and HVAC equipment that all consuming electricity, building-related indirect PM2.5 emissions will grow at an annual rate of 3% to 1.06 Mt by 2030.

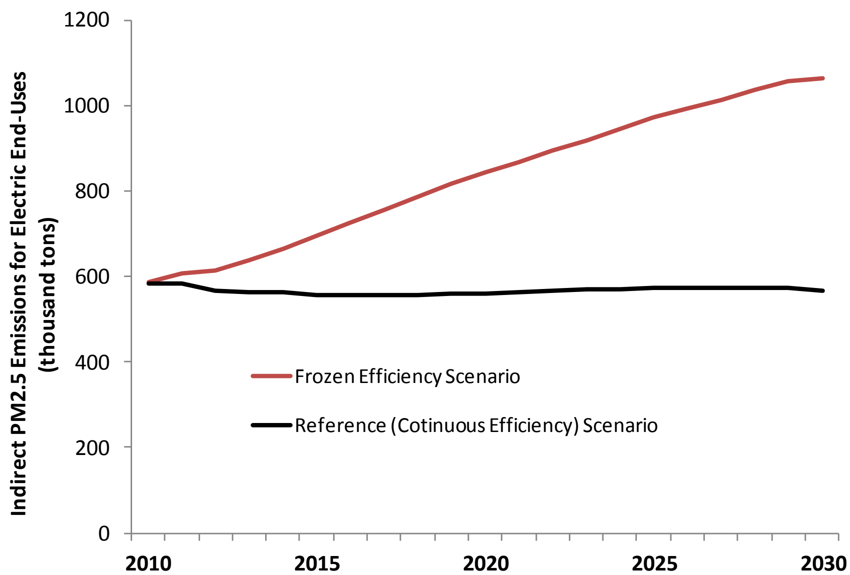


Figure 25. Indirect PM2.5 Emissions for Frozen and Reference Efficiency Scenarios

In other words, the continuous efficiency improvements represented by the Reference scenario will result in 250 kt of annual PM2.5 reductions by 2030, or cumulative reductions of 2.26 Mt from 2010 to 2030 (Figure 26). Most of this reduction will be achieved through commercial buildings, where demand for electricity services continues to grow rapidly. This magnitude of indirect PM2.5 reductions is similar in scale to direct PM2.5 reductions and suggests that efficiency improvements can play an important role in reducing both direct and indirect PM2.5 emissions.

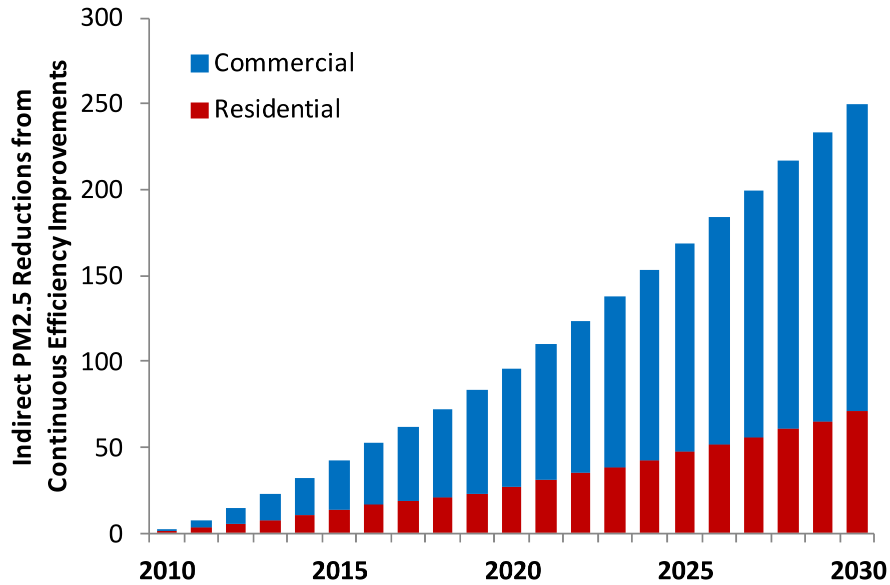


Figure 26. Annual Reductions in Indirect PM2.5 from Continuous Efficiency Improvements

5.1.3. Impact of Accelerated Efficiency Improvement

Figure 27 shows the total direct and indirect PM2.5 results for the accelerated efficiency improvement scenario, compared to the reference scenario. Because the reference scenario already incorporated assumptions about continuous efficiency improvements for all building end-uses and captured significant PM2.5 reductions as a result of these improvements, there is a smaller – albeit growing - incremental PM2.5 reduction from efficiency gains under the accelerated efficiency scenario. By 2030, the accelerated efficiency scenario will result in 6% savings in total direct and indirect building-related PM2.5, with annual emissions of 1.143 Mt PM2.5 instead of 1.218 Mt PM2.5 under the reference scenario.

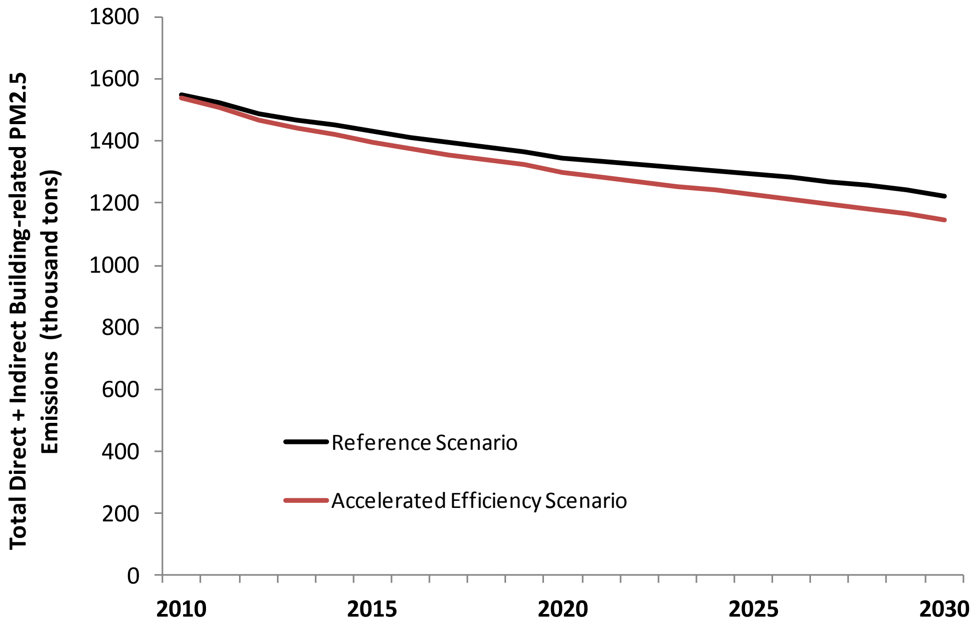


Figure 27. Total Building-related PM2.5 for Accelerated Efficiency Scenario

Figure 28 shows that the annual incremental PM2.5 reductions from accelerated efficiency improvement, compared to the reference scenario of continuous efficiency improvement, will increase from 11 kt in 2010 to 76 kt in 2030. The vast majority of this reduction will be in indirect PM2.5, with less than 3% of the total reduction coming from direct PM2.5 for space heating because space heating technologies are already very efficiency under the reference scenario. The largest reduction is in residential indirect PM2.5 (shown by the red shaded portion in Figure 28) because most of the additional efficiency gains under the accelerated efficiency improvement scenario are in residential electricity end-uses such as appliances and lighting. This is followed by reductions in commercial indirect PM2.5 (shown by the blue shaded portion) resulting from additional efficiency improvements in commercial HVAC, lighting and equipment.

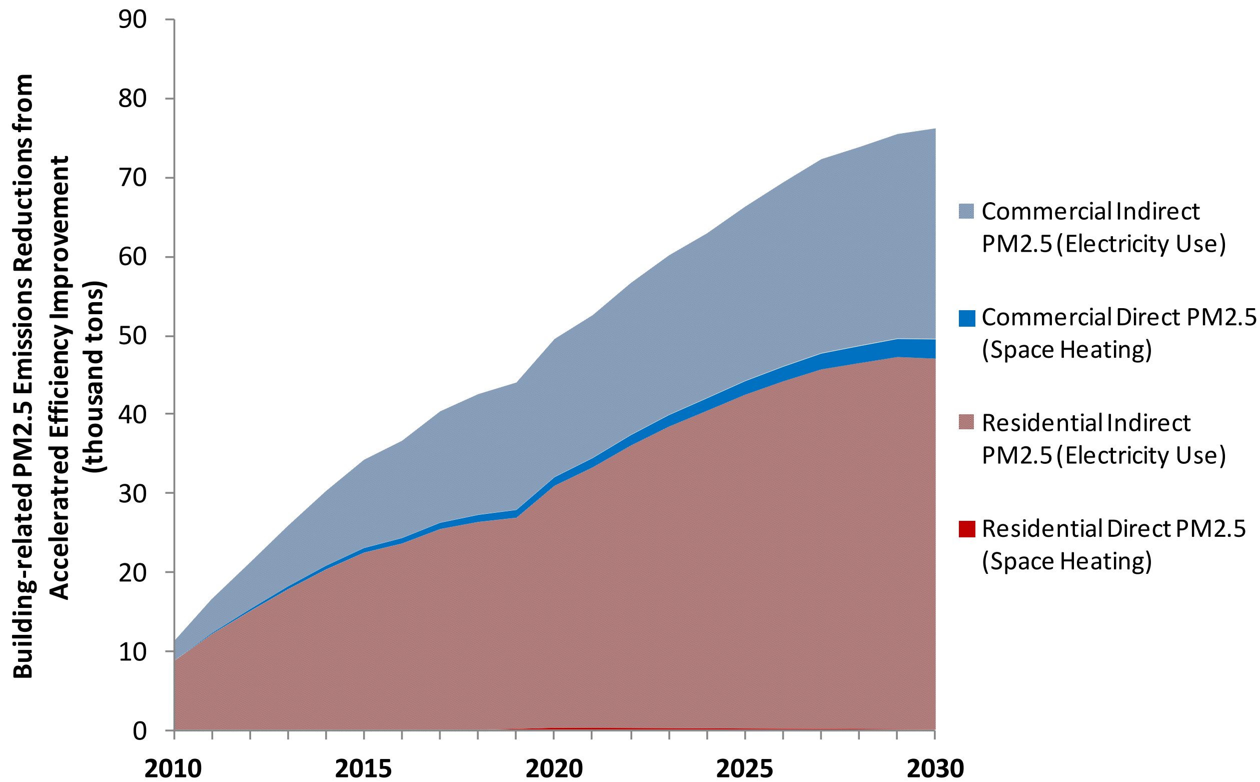


Figure 28. Building-related PM2.5 Reductions from Accelerated Efficiency Improvement by Source

5.2. Heating Fuel Switching Scenarios

In China, coal is the dominant fuel for both centralized (i.e. district heating) heating and individual boilers for heating. For example, all small combined heat and power (CHP) units and independent industrial boilers for heating used coal, while 92% of large and medium CHP units and 83% of boilers for district heating are also coal-based. Coal combustion in turn emits primary PM2.5 emissions. Natural gas boilers, on the other hand, are generally considered cleaner and contribute to less primary PM2.5 emissions and are assumed to emit zero primary PM2.5 in this study.[2] Thus, promoting more aggressive switch from coal-fired boilers for heating to natural gas boilers for heating can help reduce primary PM2.5 emissions.

5.2.1. Scenario assumptions

As previously discussed, our Reference scenario already includes assumptions of gradual fuel switching for heating fuels based on recent trends and policies promoting increased use of natural gas for space heating. Specifically, the Reference scenario assumes that the natural gas share of large and medium co-

[2] However, improper operating conditions (e.g., poor air-fuel mixing) and non-optimal combustion chamber temperatures in natural gas boilers may result in the release of smoke, carbon monoxide, small amounts of unburned hydrocarbons and NO_X emissions.

generation units will increase from 8% in 2010 to 17% in 2030 and replace coal-fired units under the reference scenario. For other individual boilers for district heating, natural gas will also replace increasing shares of coal-fired boilers with natural gas share rising from 17% in 2010 to 40% in 2030 under the reference scenario. In order to evaluate the PM2.5 emissions reductions that result from the assumed gradual fuel switching under the Reference scenario, a counterfactual frozen fuel switching scenario was developed. This counterfactual frozen fuel switching scenario assumes that the heating fuel shares and power generation fuel shares remain frozen at the 2010 base year level through 2030 in the absence of continued policy to promote fuel switching.

In addition to the reference scenario, much more aggressive fuel switching can be pursued as a strategy to reduce both coal consumption and primary PM2.5 emissions. Two additional scenarios are developed to evaluate the maximum technical potential impact of two very aggressive paths of fuel switching from coal to natural gas on direct, primary PM2.5 emissions from heating. The50% fuel switching scenario assumes that 50% of direct coal burning for heating and CHP for heat generation will be switched to natural gas by 2030, with fuel switching occurring at a continuous pace from 2013 until 50% fuel switching is achieved by 2030. The second scenario, the accelerated or 100% fuel switching scenario, assumes that 100% of coal use for CHP and individual boilers will be replaced by natural gas by 2030, with fuel switching also beginning in 2013 and continuing at a pace to reach 100% natural gas by 2030. As maximum technically feasible scenarios, these two fuel switching scenarios do not consider future constraints in the natural gas supply or costs and are intended to show the upper bounds of potential PM2.5 reduction from fuel switching.

The changes in fuel shares for the four main types of heating technologies under these four different fuel switching scenarios are shown in Table 6.

Table 6. Heating Fuel Shares for Fuel Switching Scenarios

	2010	**2020**			**2030**		
	All Scenarios	***Reference***	***50% Fuel Switch***	***100% Fuel Switch***	***Reference***	***50% Fuel Switch***	***100% Fuel Switch***
Large & Medium CHP Units							
Coal	92%	88%	76%	62%	83%	50%	0%
Natural Gas	8%	12%	24%	38%	17%	50%	100%
Small CHP Units							
Coal	100%	100%	81%	62%	100%	50%	0%
Natural Gas	0%	0%	19%	38%	0%	50%	100%
Individual boilers for District Heating							
Coal	83%	70%	57%	44%	60%	30%	0%

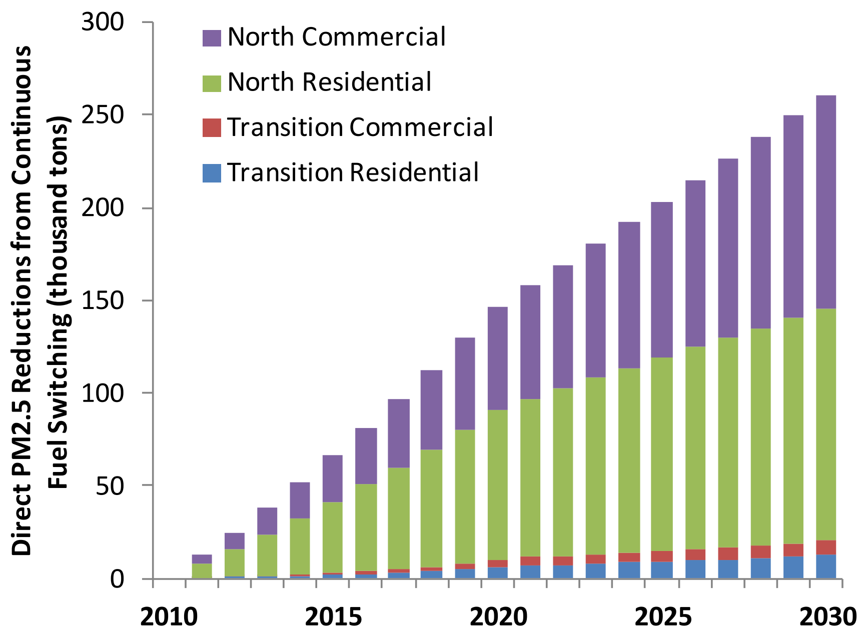
Natural Gas	17%	30%	43%	56%	40%	70%	100%
Independent industrial boilers							
Coal	100%	100%	81%	62%	100%	50%	0%
Natural Gas	0%	0%	19%	38%	0%	50%	100%

Note: The natural gas share of individual boilers for district heating will exceed 50% under the 50% fuel switching scenario because of higher starting point of 17% share of natural gas in 2010.

5.2.2. Impact of Gradual Fuel Switching under Reference Scenario

5.2.2.1. Direct PM2.5 Emissions

In addition to direct PM2.5 emissions reductions from continuous efficiency improvements, there are additional reductions from the continuous switching in the heating fuel mix assumed to occur under the Reference scenario. As a result of this fuel switching, direct PM2.5 emissions reductions from residential and commercial buildings will increase from 12 kt per year in 2011 to 260 kt per year in 2030. As with reductions from continuous efficiency improvements, most of this reduction will be seen in Northern commercial and residential buildings where most of the heat is consumed.



5.2.2.2. Indirect PM2.5 Emissions

Compared to the frozen fuel shares scenario, the fuel switching modeled under the Reference scenario also reduces indirect PM2.5 from the building sector. There are two main factors for this reduction in indirect PM2.5 emissions. First, there is fuel switching from electricity to natural gas use for commercial cooling because of the expected growing penetration of centralized air conditioning by natural gas replacing small shares of electricity-based room and centralized air conditioning. This in turn reduces the total electricity consumption and related indirect PM2.5 emissions from commercial cooling when compared with the frozen fuel switching scenario. Second, as discussed in section 3.2, the Reference power sector is assumed to shift away from coal-fired units, particularly inefficient smaller coal-fired units that emit greater PM2.5 per kWh generated, to clean non-fossil generation over time. This fuel switch in power generation essentially reduces the total coal input to the power sector and decreases the average PM2.5 emission factor for electricity generation from 0.004 kg PM2.5 per kilogram of coal equivalent (kgce) of electricity generated in 2010 to 0.002 kg PM2.5 per kgce electricity generated in 2030. These two factors result in the growing annual reductions in indirect PM2.5 from continuous fuel switching shown in Figure 29.

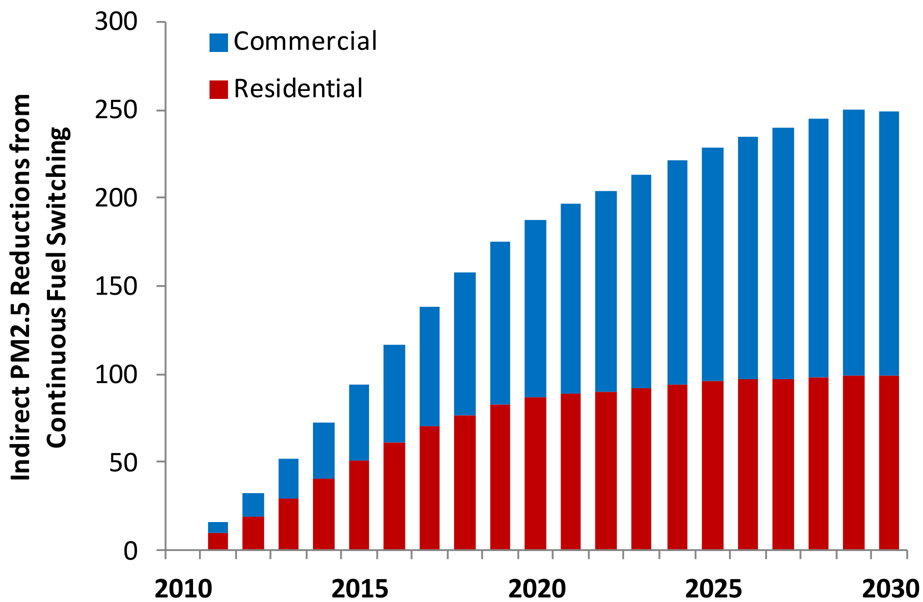


Figure 29. Annual Reductions in Indirect PM2.5 from Continuous Fuel Switching

5.2.3. Impact of Aggressive Fuel Switching

Figure 30 shows that 50% and 100% reductions in the building direct primary PM2.5 emissions for space heating are possible under the two maximum technical potential scenarios. By 2030, the direct primary PM2.5 for space heating will decrease from 655 kt under the Reference scenario to 326 kt tons if 50% coal-to-gas heating fuel switching is achieved and to 0 kt if 100% fuel switching is achieved. Cumulatively from 2010 to 2030, this translates into direct primary PM2.5 reductions of 3.11 Mt under the 50% fuel switching scenario, and 6.16 Mt under the 100% fuel switching scenario.

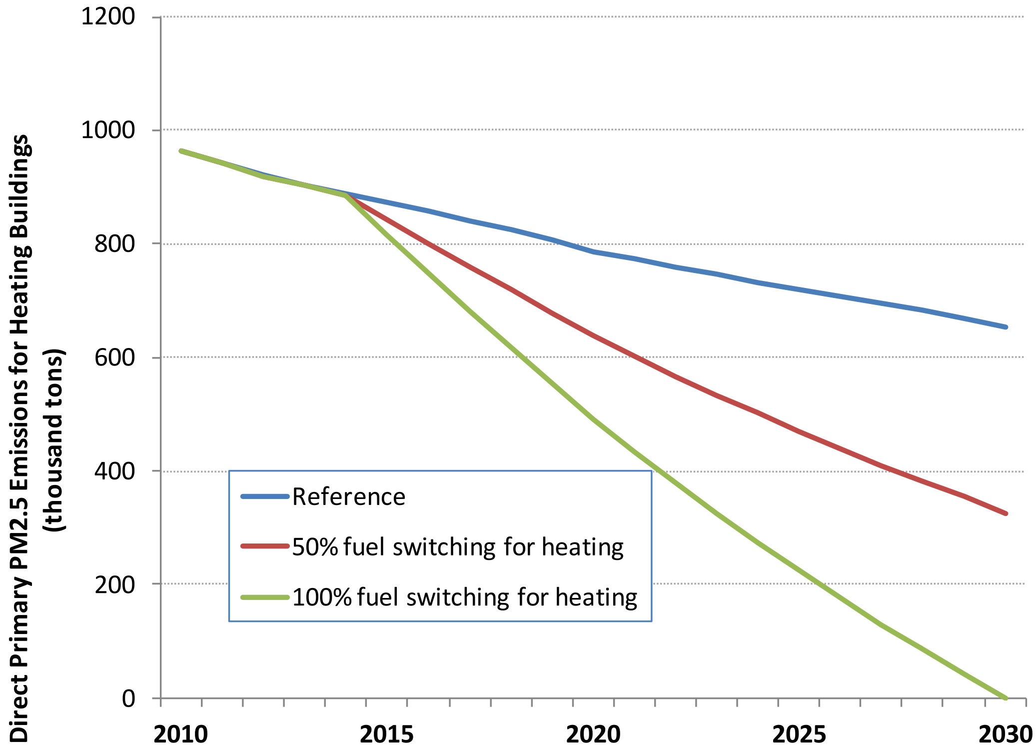


Figure 30. Direct Primary PM2.5 for Heating for 50% and 100% Fuel Switching Scenarios

In addition to the significant reductions in direct primary PM2.5 with aggressive fuel switching, there are also smaller reductions in indirect PM2.5 as a result of the fuel switching. Figure 31 shows the reductions in indirect PM2.5 (green shaded portion) from building electricity use and direct PM2.5 (red portion) from space heating under the 50% fuel switching scenario. In 2030, the annual reductions of indirect PM2.5 will reach 62 kt, compared to reductions of 328 kt of direct PM2.5. From 2010 to 2030, cumulative reductions of direct and indirect PM2.5 will total 3.6 Mt as a result of switching 50% of coal to natural gas for heating by 2030.

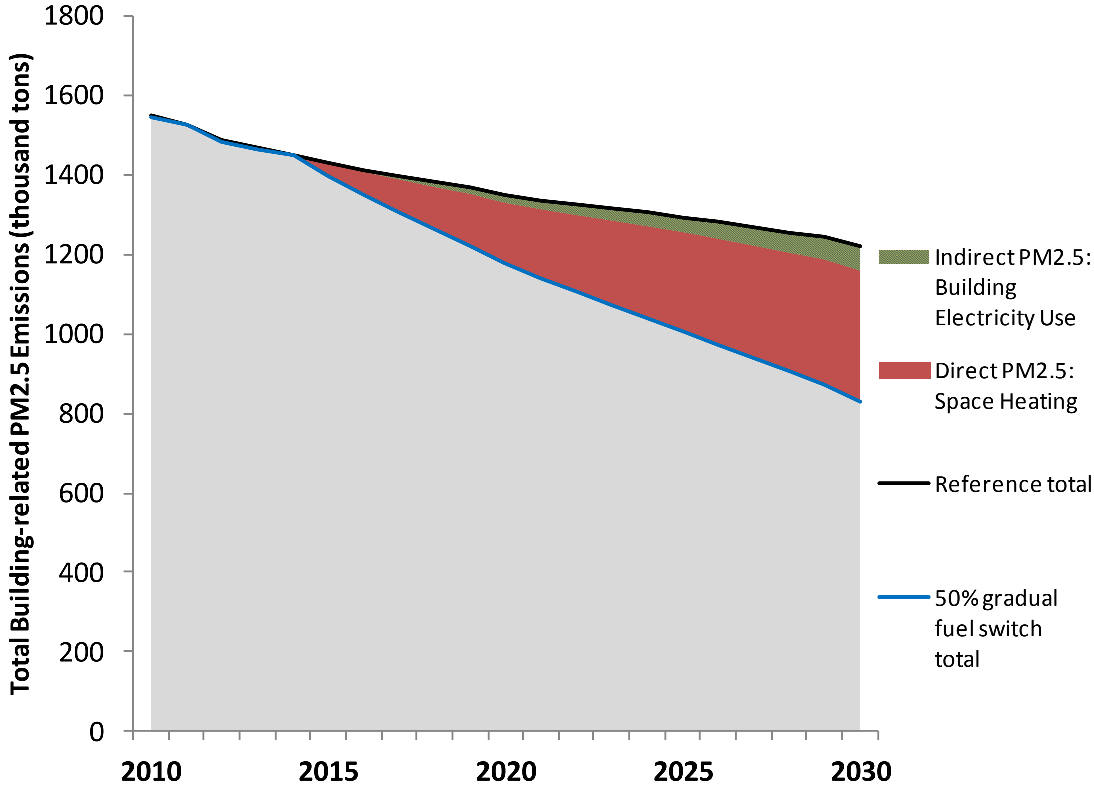


Figure 31. Direct and Indirect PM2.5 Emissions Reductions from 50% Fuel Switching

Similarly, Figure 32 shows that larger reductions in both direct and indirect PM2.5 are possible if 100% of heating fuels is switched from coal to natural gas by 2030. The 100% fuel switch of heating fuels from coal to natural gas will eliminate nearly 67% of the total annual building-related PM2.5 emissions expected in 2030 under the Reference scenario. Under the 100% fuel switching scenario, indirect PM2.5 reductions will reach 124 kt per year by 2030 while direct PM2.5 reductions will reach 654 kt per year by 2030. This translates into cumulative reductions of 7.1 Mt of direct and indirect PM2.5 from 2010 to 2030 as a result of the 100% fuel switching.

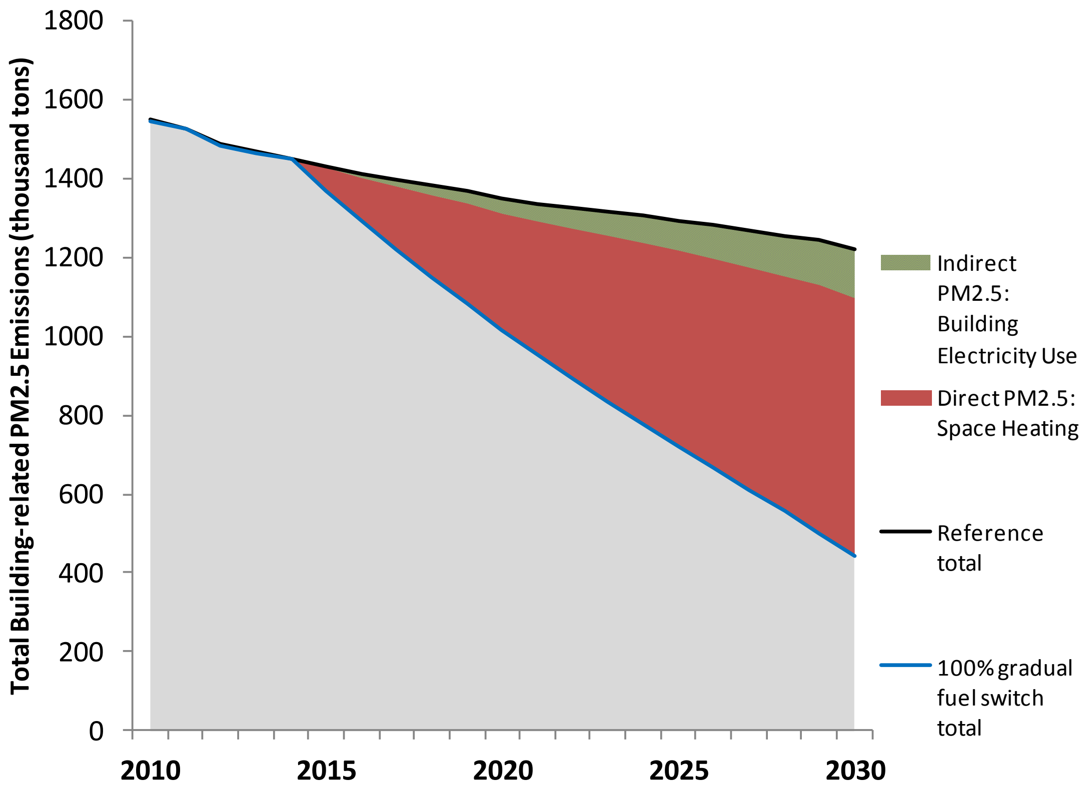


Figure 32. Direct and Indirect PM2.5 Emissions Reductions from 100% Fuel Switching

5.3. Post-combustion Emissions Control Technologies for Power Sector

The installation of emissions control technologies, especially the control technologies designed to capture PM, can help remove significant amounts of PM, PM10 and PM2.5 emissions. While some emissions control technologies such as cyclone separators and wet scrubbers are intended to remove SOx and NOx emissions, they can also be effective in removing some PM, especially PM with larger particle sizes. The major emissions control technologies include the following four types:

1. **Cyclone separators:** These are mechanical collectors that use centrifugal forces to separate and remove particles. Cyclone separators can help reduce PM emissions from coal combustion, and are often used as a pre-collector upstream, but are relatively ineffective at removing particles smaller than PM10.
2. **Wet Scrubbers:** Wet scrubbers are installed to capture PM emissions as well as to control SO2 emissions in coal-fired boilers. In wet scrubbers, lime or limestone slurry is used to react with SO_2 in the flue gas within larger absorber vessel to capture SO_2, and partial PM removal is achieved as a co-benefit.
3. **Electrostatic Precipitator (ESP):** Electrostatic precipitators are PM control technologies that use electrical charge to separate and collect particles in the flue gas stream by charging the fly ash particles. They consist of a series of parallel vertical plates through which the flue gas is directed.

Zhao et al. 2008 reported removal efficiencies of 87% to 99.2% for different sizes of pulverized coal boilers, and a follow-up study (Zhao et al. 2010) also identified removal efficiencies of 90.9% to 97.9% for smaller coal-fired power plants. In the U.S., ESP technology has been installed in more than 70% of existing coal-fired power plants to remove PM (Staudt 2011) and 95% of Chinese coal-fired power plants have installed electrostatic precipitators in 2010 (Li 2013).

4. **Baghouse or Fabric Filter:** Baghouse or fabric filters are the latest and most effective technologies for controlling PM in coal-fired boilers. These fabric filters collect dry PM as flue gas passes through the filter made of woven or felted material in the shape of a bag or envelope. These filters can be installed downstream in coal-fired power plants that already have ESP installed, and are extremely effective (>99% removal rates) in capturing even the smallest PM particles. In the U.S., 35% of coal-fired power plants have installed fabric filters and installation is also increasing amongst Chinese coal-fired power plants, rising from 5% in 2010 to 10% in 2012 (Li 2013).

Table 7 compares the PM removal efficiencies for these four control technologies in China for different sizes of PM particles.

Table 7. Comparison of PM Removal Efficiencies by Control Technology

	Fabric Filters	Electrostatic Precipitator	Wet Scrubbers	Cyclone Separators
PM	99.9%	99%	99%	90%
PM10	99.5%	98%	90%	70%
PM2.5	99%	93%	50%	10%

Source: Zhao et al. 2008

5.3.1. Scenario assumptions

A post-combustion emissions control scenario is developed to examine the impacts in PM2.5 emissions reduction from continued deployment of the two most effective PM control technologies, ESP and fabric filters. In this scenario, installation of PM control technologies is only considered for coal-fired boilers in the power sector and not for heating applications due to the prohibitively high capital costs for smaller boilers.

Under this scenario, installation of end-of-pipe filter bags combined with ESP is assumed to rise gradually from its current Chinese share of 10% to the current U.S. level of 35% by 2030. At the same time, the share of ESP installations only is assumed to decline from the 2012 share of 95% to 65% due to rising installations of filter bags. Table 8 shows the shares of ESP only and filter bags with ESP in China's coal-fired power plants under the reference and emission control scenario.

Table 8. PM Control Technology Penetration Shares in Chinese Coal-fired Power Plants

	2010	2020		2030	
	All Scenarios	***Reference***	***Power Gen PM Control***	***Reference***	***Power Gen PM Control***
Electrostatic Precipitators Only	95%	87%	80%	80%	65%
Filter Bags	5%	13%	20%	20%	35%

5.3.2. Impact of Accelerated Installation of PM Control Technologies

The installation of PM control technologies in the power sector will reduce the indirect PM2.5 emissions of all electricity generated, including the share that is consumed by buildings, but will not affect direct PM2.5 emissions from space heating. The total indirect PM2.5 emissions from building electricity consumption for the reference and power generation PM control scenarios are shown in Figure 33. Total building-related indirect PM2.5 will decrease from 584 kt in 2010 to 465 kt in 2030 as a result of the installation of PM control technologies. As shown by the shaded green and red portions in Figure 33, the reduction in indirect PM2.5 resulting from the installation of PM control technologies is almost evenly divided between residential and commercial buildings, with a slightly larger share of total reductions coming from the commercial sector. In 2030, the annual reductions for residential and commercial sectors total 45 kt and 57 kt of indirect PM2.5, respectively, under the power generation PM control scenario. This suggests that rapidly deploying PM control technologies in the power sector can reduce building-related indirect PM2.5 emissions by 893 kt cumulatively from 2010 to 2030. The incremental reductions in PM2.5 from more rapidly deploying PM control technologies (compared to the Reference scenario) appear relatively small for two reasons. First, for both scenarios, we assume that coal-fired power plants are increasingly phased out of the power sector in favor of rapidly growing renewable and non-fossil generation capacities that are also prioritized in generation dispatch. Second, because continued installation of pollution control technologies at rates consistent with recent deployment is incorporated into our Reference scenario, the incremental acceleration in pollution control deployment is not as large, with only 15 percentage point higher share of filter bags by 2030.

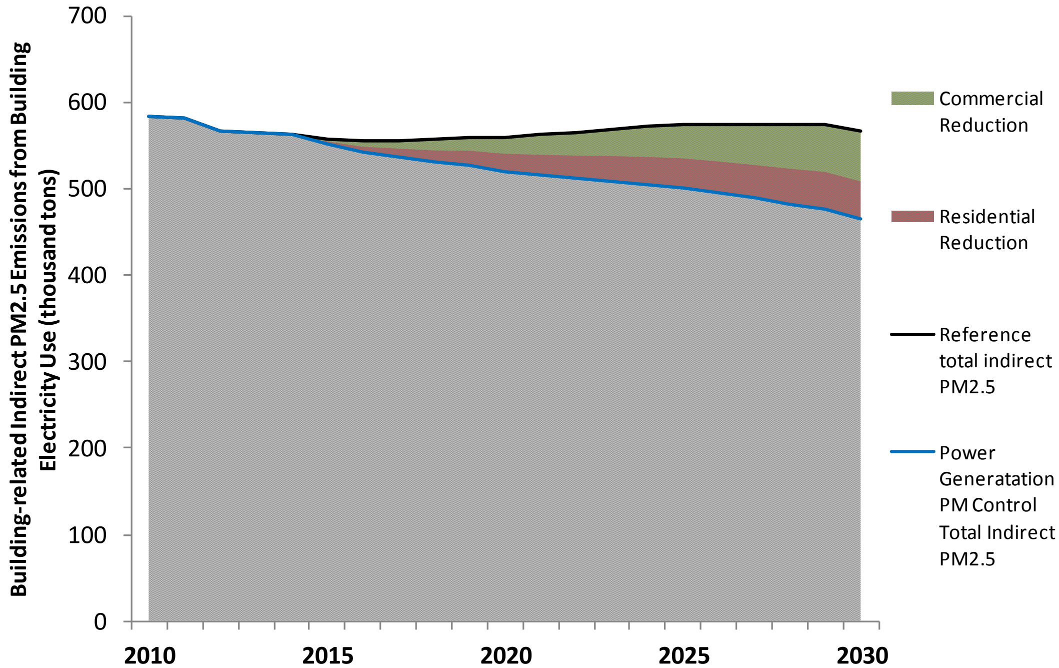


Figure 33. Indirect PM2.5 from Building Electricity Use for Power Generation PM Control Scenario

5.4. Scenario Comparisons

5.4.1. Comparison of total building-related PM2.5 for key strategies

As seen in the scenario results for the three key strategies for reducing building-related PM2.5 emissions, each strategy has different PM2.5 reduction potentials as well as different effects on the future trajectory of building-related PM2.5 emissions. Figure 34 compares the total building-related direct and indirect PM2.5 emissions for the key reduction strategies of improving efficiency, switching heating and electricity generation fuels and installing PM control technologies on coal-fired power plants. Whereas total building-related PM2.5 emissions will steadily increase from 2010 to 2030 under the frozen efficiency and frozen fuel shares scenario, promoting heating and electricity fuel switching will help flatten total PM2.5 emissions even if there is no efficiency improvement. However, implementing continuous efficiency improvements along with gradual fuel switching will help lower annual building-related PM2.5 emissions, as evidenced by the declining PM2.5 emissions trajectory of the Reference scenario. Accelerated efficiency improvement and installing PM control technologies in the power sector are two strategies to further reduce PM2.5 emissions from the Reference scenario; both can achieve small incremental reductions in building-related PM2.5 emissions.

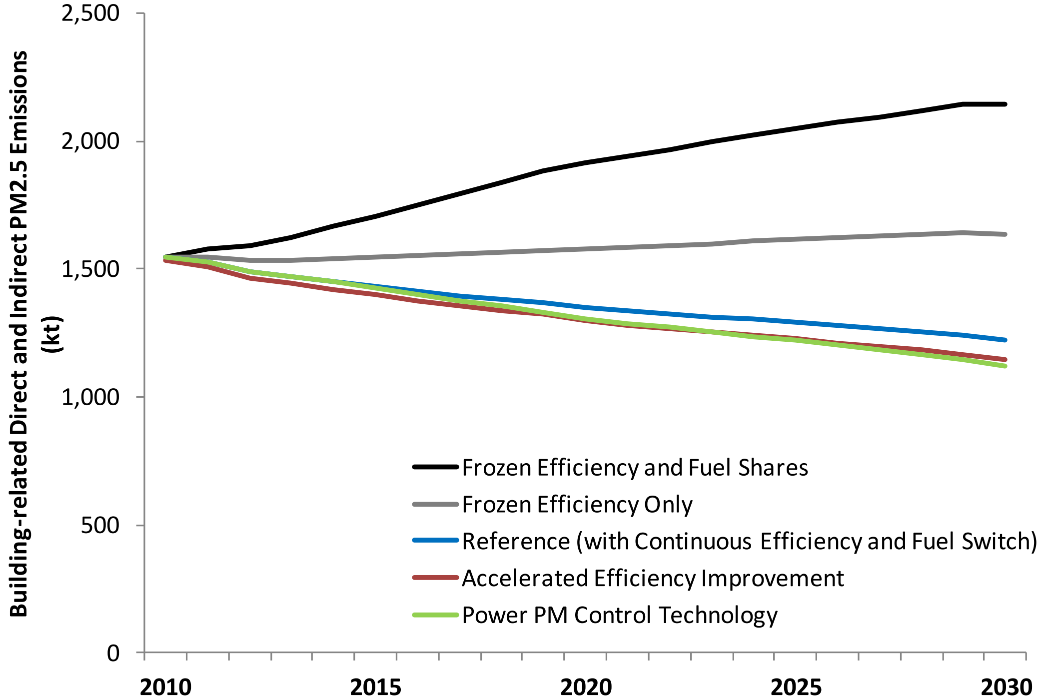


Figure 34. Total Building-related Direct and Indirect PM2.5 Emissions for Key Reduction Strategies

Figure 35 shows the contribution of building energy efficiency improvements and heating and electricity fuel switching in reducing building-related PM2.5 emissions under the Reference scenario, relative to the frozen counterfactual scenarios. As seen in the figure, both fuel switching and energy efficiency improvements have similar magnitudes of PM2.5 emissions reduction potential, although fuel switching has slightly greater reduction potential by 2030.

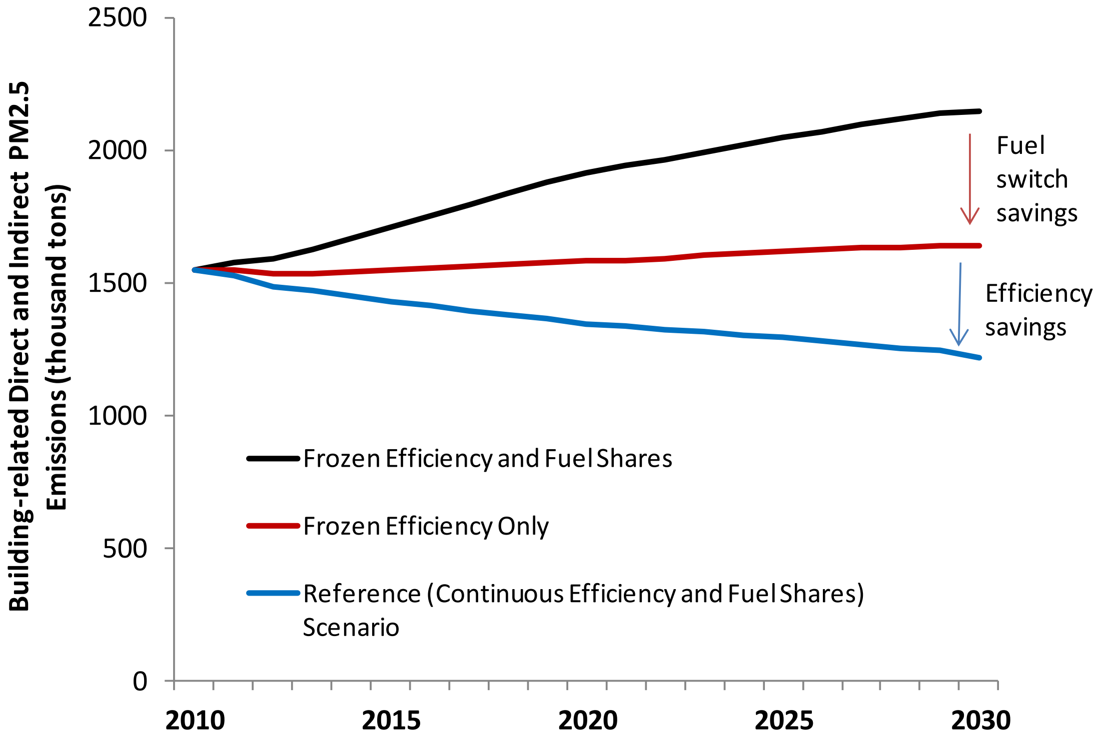


Figure 35. Comparison of Building-related Direct and Indirect PM2.5 Emissions for Frozen and Reference Scenarios

The reductions potential for efficiency improvement and fuel switching modeled in the Reference Scenario are further broken down into annual direct and indirect PM2.5 emissions reduction in Figure 36. Efficiency improvements in heating technologies result in slightly larger cumulative reductions in direct PM2.5 emissions, with 2.36 Mt saved from 2010 to 2030, compared to the 2.26 Mt of indirect emissions saved as a result of electrical equipment efficiency improvements. By 2030, however, the annual reduction in indirect PM2.5 emissions is greater than in direct PM2.5 emissions. For fuel switching, the emissions reduction potential in indirect PM2.5 is slightly greater than that of direct PM2.5 emissions. This suggests that switching fuels for electricity generation and prioritizing larger coal-fired generation can significantly reduce building-related PM2.5 emissions, in addition to the common strategy of switching heating fuels from coal to natural gas. Cumulatively from 2010 to 2030, fuel switching will reduce 2.85 Mt of direct PM2.5 emissions and 3.32 Mt of indirect PM2.5 emissions.

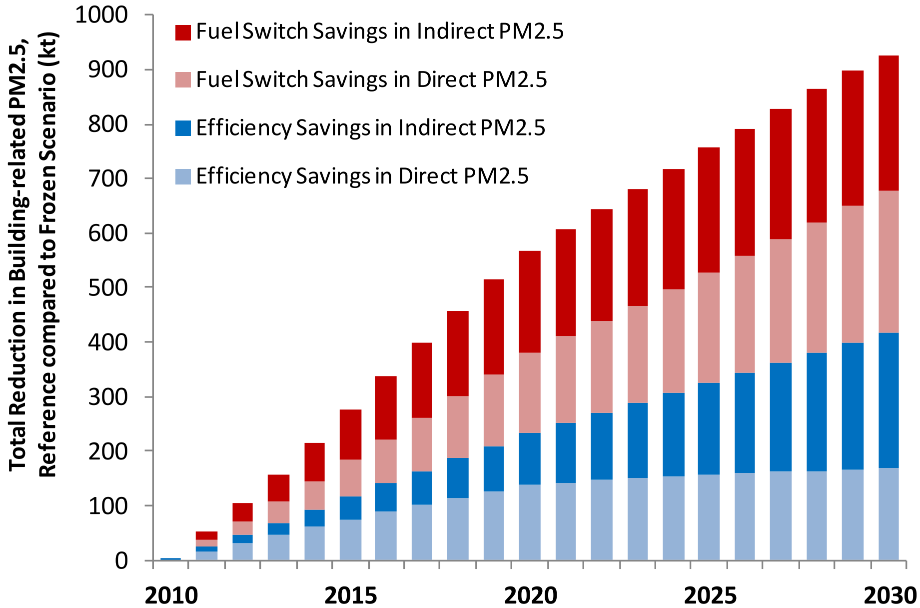


Figure 36. Building-related PM2.5 Reduction Potential for Reference Scenario by Source

5.4.2. Comparison of annual reductions for key strategies

Figure 37 compares the relative contribution of the three PM2.5 reduction strategies to annual reductions of direct and indirect PM2.5 emissions from the building sector for selected years of 2015, 2020, 2025 and 2030. This shows that for all strategies, there is a greater annual reduction potential in indirect PM2.5 emissions from building electricity consumption, which is often overlooked because it is not directly accounted for in the building sector. It also reiterates the significant annual reduction potential of energy efficiency and fuel switching.

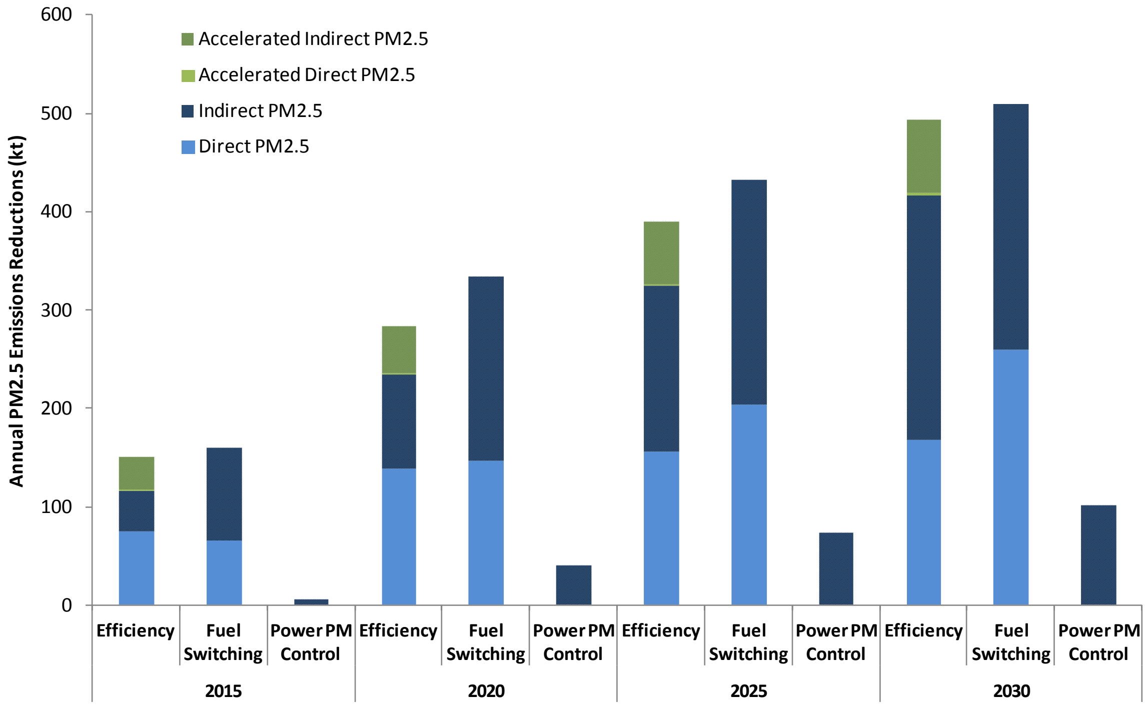


Figure 37. Comparison of Annual Building-related PM2.5 Emissions Reduction for Key Strategies for Selected Years

These same findings are highlighted in Figure 38, which compares the 2030 reduction potential of each individual strategy in a waterfall chart. By 2030, the largest reduction in total building-related PM2.5 emissions will be in electrical equipment efficiency, followed by heating and other electricity generation fuel switching and heating efficiency improvements. Installing PM control technologies in the power sector can further reduce indirect PM2.5 emissions, but the scale of reduction is much smaller compared to energy efficiency and fuel switching improvements.

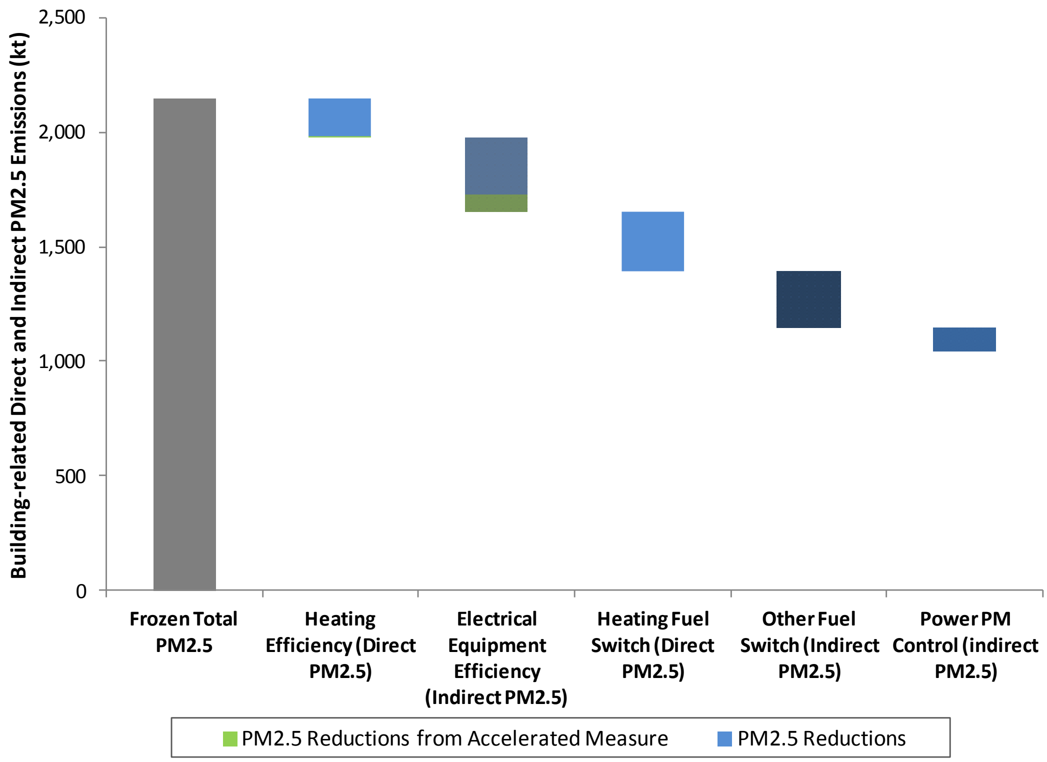


Figure 38. Waterfall of 2030 Building-related PM2.5 Emissions Reduction Potential by Strategy

Although the PM2.5 emissions reduction potential for individual strategies are independent and not directly additive, the waterfall chart shows that a significant portion of the total building-related PM2.5 emissions under the frozen scenario can be reduced through these key strategies. If all of the strategies were implemented, it is conceivable that the total building-related PM2.5 emissions could be much lower, possibly by 50% or more, than the frozen scenario total.

6. Scenario Analysis: District Heating in Transition Zone

In addition to the Reference scenario, another scenario was developed to evaluate an alternative pathway of heating development in China and the subsequent PM2.5 emissions impact. This specific scenario evaluates the possible increase in heating demand in the Transition Zone as a result of rising incomes and demand for thermal comfort, and the PM2.5 consequences of potentially introducing predominantly coal-based district heating to the Transition Zone.

The specific modeling assumptions and results for this alternative pathway of development for the building sector are presented below.

6.1. Scenario Assumptions

In China, district heating is currently only provided in the Northern cold and severe cold climate zones and heating demand in the Transition zone with hot summer and cold winter climate is provided solely by personal heating devices. In the near future, as household income and demand for greater thermal comfort continues to rise, demand for heating is expected to become more important in the Transition zone. In our model for all scenarios, we assume that the energy demand for heating per m^2 of floorspace in the Transition Zone will more than double for residential households and triple for commercial buildings. This is very different from the situation in Northern China, where heat is already over-supplied in the residential sector due to unmetered district heating. Introducing the district heating currently utilized in Northern China to the Transition zone is a feasible option for expanding the provision of heat to buildings in the Transition Zone.

A specific scenario is developed to model the potential application of district heating in the Transition zone and its impacts on heating-related direct PM2.5 emissions for buildings, assuming that centralized district heating will also become the major source of heating in the area. More specifically, the Transition zone is assumed to achieve the same shares of district heating and heating by coal-fired boilers as Northern China under this scenario. In other words, both the residential and commercial heating technology share and mix in the Transition Zone will be the same as shown in the Northern China residential example in Figure 7. This is a likely conservative assumption since the older district heating infrastructure in Northern China is heavily coal-dominated and responsible for significant amount of PM2.5 emissions, and if new district heating infrastructure were introduced in the Transition Zone, it could include greater share of cleaner natural gas-fired boilers. However, the roll-out of natural gas boilers for district heating in the Transition Zone realistically would also be limited by China's growing deficit in domestic natural gas supply, with one-third of natural gas demand currently being met by imports. Thus, for this scenario analysis, we took the simplifying assumption of assuming the new district heating boilers in the Transition Zone would follow that of Northern China.

6.2. Impact of District Heating in the Transition Zone

The modeling results show that if district heating was adopted in the Transition zone with the same saturation and shares as Northern China, then the annual total direct primary PM2.5 will increase by 200 kt to 300 kt per year between 2010 and 2030 when compared to the Reference scenario. Figure 39 shows that the annual direct PM2.5 under the district heating in transition zone scenario will reach 990 kt by 2030, or nearly 50% higher than the 654 kt annual total for 2030 under the reference scenario.

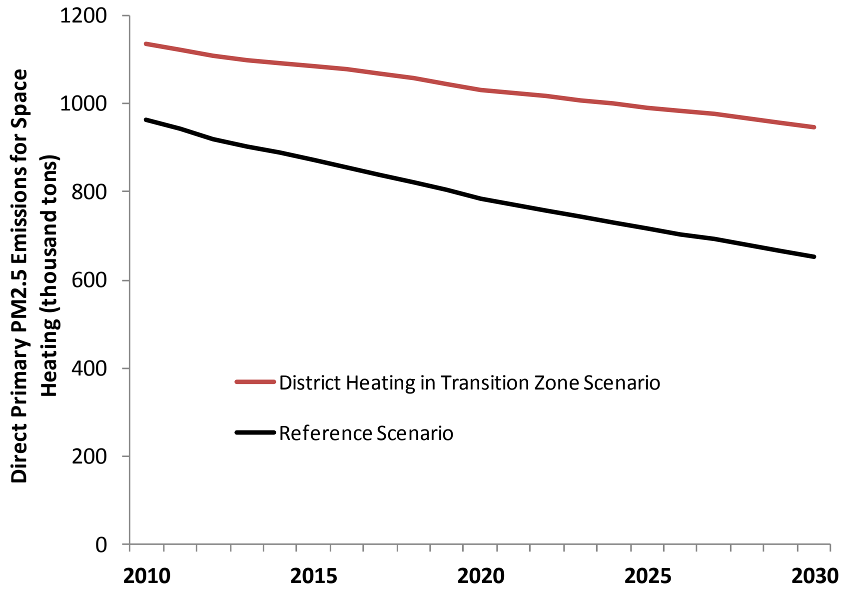


Figure 39. Direct Primary PM2.5 for District Heating in Transition Zone and Reference Scenarios

Figure 40 shows that the additional direct primary PM2.5 from district heating in the Transition zone will be evenly split between the residential and commercial sectors, with slightly larger share of 53% coming from the commercial sector by 2030. Cumulatively, the annual increase in PM2.5 from district heating in the transition zone will total 5.1 Mt of PM2.5 from 2010 to 2030. This significant increase in PM2.5 from district heating in the Transition Zone can be traced to the high shares of coal-fired district heating boilers replacing independent gas boilers, heat pump air conditioners and electric heater that were previously providing heat in this area.

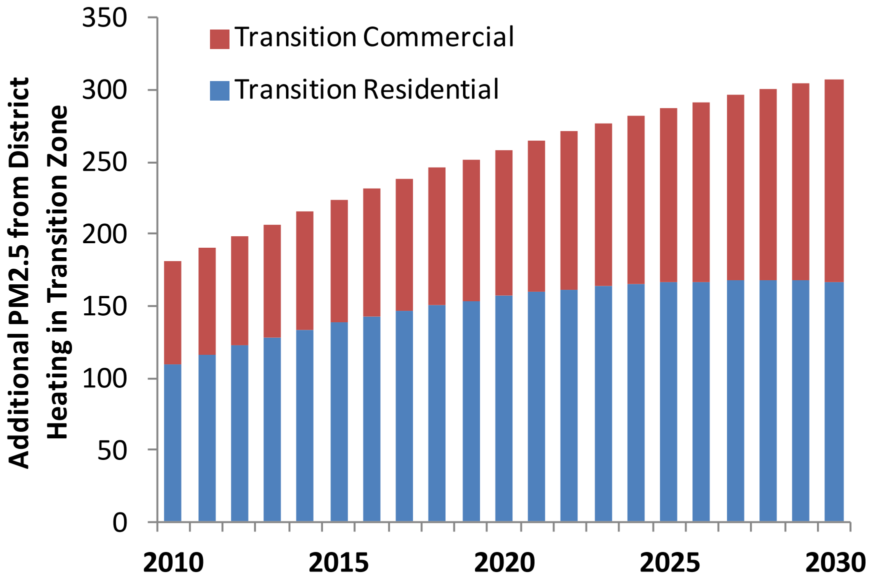


Figure 40. Additional Direct Primary PM2.5 from District Heating in Transition Zone

Because the introduction of district heating to the Transition Zone will only affect coal consumption for heating and no changes to electricity end-uses or the power sector are expected, there is no additional impact on indirect PM2.5 emissions. Under the district heating in Transition zone scenario, the annual total building-related direct and indirect emissions will reach 1.49 Mt by 2030, compared to the 1.22 Mt annual total in 2030 under the Reference scenario.

7. Conclusions

In the past few years, rising PM2.5 emissions have caught the Chinese public and policymakers' attention with unprecedented levels of measured PM2.5 concentrations and growing environmental and public health concerns. Buildings are expected to become an increasingly large source of PM2.5 emissions as they consume fossil fuel direct to provide heat and indirectly by consuming electricity generated by coal-dominated power sector. There is a need to focus on uncontrolled direct primary PM2.5 emissions from coal-fired boilers used to provide heat, particularly in Northern China, but also on the less obvious indirect PM2.5 emissions from the electricity consumption that is attributable to buildings.

In this study, we used a bottom-up model to characterize heating and electricity end-use demand for residential and commercial buildings in China's Northern and Transition climate zones and the fuels and technologies used to meet that demand from 2010 to 2030. We find that space heating contributed to more than half of the 1.55 Mt of total direct and indirect building-related PM2.5 emissions in 2010, with the majority of space heating PM2.5 emissions tracing back to coal-based district heating in Northern China. Under the reference scenario of development in the building sectors, total direct PM2.5 will decrease due to assumed efficiency improvements in district heating and independent coal boilers as well as heating shell improvements over time. However, even with continuous efficiency improvements and gradual switching of heating fuels and electricity generation to non-coal based sources under the reference scenario, indirect PM2.5 emissions will not decline due to rapid growth in commercial electricity demand but will only be flattened between 2010 and 2030. By 2030, total direct and indirect PM2.5 emissions would reach 1.22 Mt under the Reference scenario.

Comparing the Reference scenario results to a frozen counterfactual scenario further reveals that building energy efficiency improvement have the greatest co-benefit in reducing building-related PM 2.5 emissions, without increasing costs or other pollutants such as NO_X, SO_X and CO_2 emissions. More specifically, efficiency improvement in heating technologies (e.g., independent and district heating coal and gas boilers) and building shells can significantly decrease direct primary PM2.5 from heating, while electrical equipment efficiency improvements (e.g., appliances, HVAC, lighting) can play an equally important role in reducing indirect PM2.5 emissions. In addition, with continued policy support, a gradual switch from coal to natural gas for heating fuels and from coal-dominated to non-fossil electricity generation can also significantly reduce indirect PM2.5 from the electricity consumed by buildings. Beyond the reduction potential reflected in the Reference scenario, more aggressive reductions in building-related PM 2.5 will rely on further coal to gas switching for heating fuels, with half or all coal-based heating fuels being replaced by natural gas. In reality, however, such aggressive fuel switching will likely face limits in natural gas supply and possibly increased secondary PM2.5 emissions if proper emissions control technologies are not implemented for natural gas boilers. In the absence of sufficient natural gas for aggressive fuel switching, accelerated efficiency improvements reaching the international best practice level and PM control technologies in large coal boilers can achieve similar magnitudes of savings. Lastly, increased demand for heating and introduction of district heating to the Transition Zone could add 5.1 Mt of additional cumulative PM2.5 from 2010 to 2030.

Based on these findings, some relevant policy recommendations for addressing the rising contribution of buildings to total PM2.5 emissions can be made. Continuing policy-driven energy efficiency improvements through the implementation of more stringent building codes, appliance and equipment standards and labeling programs, and incentives can effectively lower direct and indirect building-related PM2.5 emissions. Accelerating the installation of PM control technologies in large coal boilers can help further reduce indirect PM2.5 emissions, a growing but often overlooked source of building-related PM2.5 emissions in China. The feasibility of increasing coal-to-gas fuel switching for heating can be evaluated to maximize direct PM2.5 reductions, but needs to take into consideration the growing demand but constrained supply for natural gas. Lastly, alternatives to introducing coal-based district heating to meet growing heat demand from China's Transition zone should be considered as it can substantially increase building-related direct PM2.5 emissions and exacerbate existing air quality problems.

The scope of this study was limited to only primary PM2.5 emissions from coal combustion in boilers for heating and for generating electricity. It does not take into account the secondary sources of PM emissions, which can be significant in terms of the total atmospheric PM levels. The potential for secondary PM2.5 formation from nitrates released by natural gas boilers in the absence of NO_X emissions controls was not considered in this study due to lack of data, and the fuel switching scenarios may overstate the PM2.5 benefits of switching from coal to natural gas. In light of these limitations, future research could focus on characterization of the building sector's contribution to secondary PM2.5 emissions with a more rigorous analysis using data on natural gas boilers and capabilities for modeling secondary PM formation. In addition, more detailed analysis of direct primary PM2.5 emissions from other building end-uses such as cooking and biomass burning for rural heating would strengthen the analysis of building-related PM2.5 emissions. Given the importance of renewables and non-fossil in displacing coal used in the power sector, more sensitivity analysis of the impact of dispatch orders on PM2.5 emissions in the power sector and subsequent impact on buildings' indirect PM2.5 emissions would also be of value. Lastly, additional research and modeling to contextualize the relative magnitude of building-related PM2.5 in estimates of total national PM2.5 could provide valuable insights.

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References

Fridley D., Zheng N., Zhou N., Ke J., Hasabiegi A. and W. Morrow. 2011. "China's Energy and Emissions Paths to 2030." LBNL-4866E. Berkeley, CA: Lawrence Berkeley National Laboratory.

He K., Zhang Q., Ma Y., Yang F., Cadle S., Chan T., Mulawa P., Chan C., and X. Yao. 2002. "Source apportionment of PM2.5 in Beijing." *Fuel Chemistry Divisions Preprints* 47 (2): 678-679.

Lei Y., Zhang Q., He K. and D.G. Streets. 2011. "Primary anthropogenic aerosol emission trends in China, 1990-2005." Atmospheric Chemistry and Physics 11: 931-954.

Li, P. 2013, "Current Status of Pollutant Control for Power Plants in China." 23 May 2013. http://www.worldcoal.org/bin/pdf/original_pdf_file/current_status_of_pollutant_control_for_coal-fired_power_plants_in_china(23_05_2013).pdf.

Staudt, J. 2011. "Control Technologies to Reduce Conventional and Hazardous Air Pollutants from Coal-fired Power Plants." Report prepared for Northeast States for Coordinated Air Use Management. http://www.nescaum.org/documents/coal-control-technology-nescaum-report-20110330.pdf/

Wang J. 2010. "Comparative Analysis of Coal-fired and Natural Gas-fired Boilers for Heating (in Chinese). *District Heating* 3: 57-60.

Yang L., Cheng S., Wang X., Nie W., Xu P., Gao X., Yuan C and W. Wang. 2013. "Source identification and health impact of PM2.5 in a heavy polluted urban atmosphere in China." *Atmospheric Environment* 75: 265-269.

Yu L., Wang G., Zhang R., Zhang L., Song Y., Wu B., Li X., An K. and J. Chu. 2013. "Characterization and source apportionment of PM2.5 in an urban environment in Beijing." *Aerosol and Air Quality Research* 13: 574-583

Zhao Y., Wang S., Duan L., Lei Y., P. Cao, and J. Hao. 2008. "Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction." *Atmospheric Environment* 42: 8442-8452.

Zhao Y., Wang S., Nielsen C., Li X. and J. Hao. 2010. "Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants." *Atmospheric Environment* 44: 1515-1523.

Zhou N., Fridley, D., McNeil, M., Zheng, N., Ke, J., and M. Levine. 2011. "China's Energy and Carbon Emissions Outlook to 2050." LBNL-4472E. Lawrence Berkeley National Laboratory Report.