Quantifying PM2.5 Emissions from China's Building Sector and Co-benefits of Energy Efficiency

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ABSTRACT

In recent years, China has experienced severe air pollution with adverse health consequences, as exemplified by recent reports of extremely high PM2.5 levels in northern cities such as Beijing. PM2.5 sample measurements have identified coal burning as a significant primary pollutant source in China, especially when coal is used as a major heating fuel in the winter. As urbanization and household income rises and demand for thermal comfort increases, the growth in coal use by the building sector, particularly for winter heating, will make buildings an increasingly significant source of PM2.5 emissions. In addition, building electricity consumption's contribution to indirect PM2.5 emissions generated by coal-fired boilers in the power sector is also often overlooked.

This paper quantifies the current and potential contribution of China's building sector to PM2.5 emissions and co-benefits of energy efficiency, fuel switching and pollution control technologies on PM2.5 emissions reduction. A bottom-up accounting model is developed and used to quantify commercial and residential buildings' coal demand for heating and electricity generation. The model then characterizes 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 PM2.5 emissions. The results underscore the important impact of energy efficiency on not only energy savings and CO_2 emissions reduction, but also on improved air quality in terms of lowered PM2.5 emissions.

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). PM2.5 can be inhaled and have been linked to serious respiratory diseases, lung cancer, cardiovascular problems, birth defects, and premature death (Lei et al. 2011). PM is directly emitted as the non-combustible materials from point primary sources, including combustion processes in diesel engines and coal boilers for generating heat or electricity. In addition, PM can also be formed through secondary sources through chemical reactions with gaseous pollutants or precursors such as SO_2 and NOx that have been released into the atmosphere. 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 needed to evaluate secondary PM formation.

From an end-use perspective, the building sector is an important source of PM emissions and indirectly generates pollutants by consuming fossil fuel. This is especially true in China, where coal is the dominant fuel for heating and electricity generation. In the cold and severe cold climate zones[1] of Northern China, annual heating energy demand totals 163 million tonnes of coal equivalent (Mtce[2]) with coal providing the majority of heating fuel for centralized district heating boilers and smaller independent heat boilers. Coal combustion emits pollutants such as particulates, SO_2, and NOx and most of the small[3] and medium-size coal-fired boilers have not installed emission control measures (Lei et al. 2011). 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 the second largest user of electricity, 80% of which is generated by coal-fired boilers in China. In recognition of buildings' growing share of total energy consumption and related emissions, China recently adopted revised mandatory building energy codes and established building energy efficiency and green buildings labeling programs, national and local targets and subsidies for energy efficiency retrofits.

Because the science and research on the formation and sources of PM is still new and ongoing, there are very few available references on PM2.5 emissions from burning coal to provide heat and electricity for Chinese buildings. The lack of information and data on total PM2.5 emissions from coal burning for heating is especially 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. As a result, uncontrolled PM emissions – and particularly PM2.5 emissions – from the coal-fired boilers used for heating in Northern China is a large and potentially growing source of particulates associated with environmental degradation and severe human health risks.

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 from a national perspective. We first analyze the direct PM2.5 emissions from burning coal to heat buildings in Northern China. We then evaluate the indirect PM2.5 emissions from coal-fired power generation, which are attributable to electricity use in the buildings sector. Lastly, we evaluate and compare the co-benefits of building energy efficiency and fuel switching measures and technologies, as well as post-combustion treatment options on reducing building-related direct and indirect PM2.5 emissions.

Modeling Methodology

To quantify China's building-related PM2.5 emission from heating and electricity consumption, a Long-range Energy Alternatives Planning (LEAP) model based on LBNL's China 2050 (Demand and Resource Energy Analysis Model) DREAM 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

[1] China has five main climate zones: the cold and severe cold zones in Northern China, the hot summer warm winter and temperate zones in Southern China, and the hot summer cold winter "Transition Zone" between Northern and Southern China. Centralized district heating is provided during the winter season in Northern China, while individual heating devices (e.g., electric heaters, heat pumps) are used to provide heating in the other regions.
[2] Mtce is the standard unit for energy in China. 1 Mtce is equal to 29.3 million GJ.
[3] In 2010, approximately12% of the residential heat supply in Northern China was provided by small, independent coal boilers.

diffusion of different end-use technologies and macroeconomic and sector-specific drivers of energy demand. 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. Rising household incomes also 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, appliances, cooking, water heating, and lighting. Commercial building energy consumption is driven by building area (floor space) and end-use intensities such as heating, cooling, and lighting (MJ per m^2), and varies by building type and its main functions, with the major building types of retail, office, school, hospital, hotel, and other buildings modeled. The key end-uses for each commercial subsector include space heating, space cooling, water heating, lighting, and equipment. For all end-uses, appropriate devices and fuels are assigned, with saturation/penetration rates and energy efficiencies based on historical statistical and survey data up to the 2010 base year and future values based on analysis of government plans, trends, and comparisons to other countries.

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 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) for development and targets set under the 12th FYP. The efficiency improvements modeled under the reference scenario are 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 light bulbs, 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. Detailed descriptions of model drivers and key assumptions for all end-uses and detailed analysis of the reference scenario energy outlook are not provided here but are documented in a previous report on the China Energy End-Use Model, Fridley et al. 2011.

Modeling Direct Primary PM2.5 from Coal Burning for Heating

For both residential and commercial buildings, space heating varies by geographic location and is divided into North, Transition and South zones based on climate. 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, for example, 88% of heat supplied in Northern China was provided by district heating with a very small share of 12% coming from individual small coal boilers. District heating is 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. Each group of district heating technologies are also characterized by the relative shares of pulverized coal, grate and circulating fluidized bed boilers, while individual small coal boilers are assumed to be evenly divided between 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. Details on the technology shares and assumed emission factors are documented in Khanna et al. 2014.

Figure 1 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 coal-fired boilers are considered to be the only source of direct primary PM2.5 emissions from heating. In terms of heating energy demand by building type and region, heating demand from Northern China and residential buildings dominates the total, but demand from the transition zone 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%.

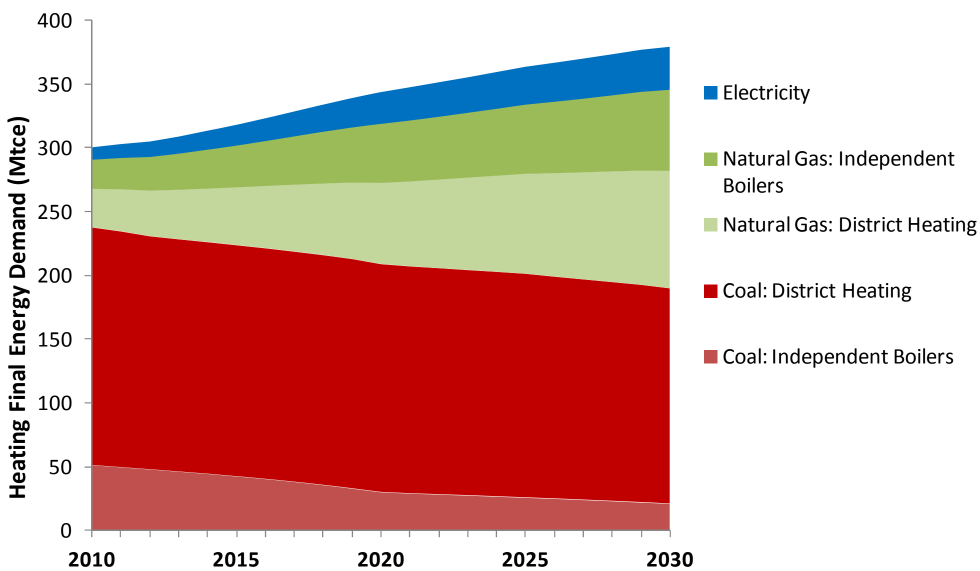

Figure 1. Chinese buildings heating final energy demand by fuel.

To calculate the PM2.5 emissions from coal consumed for heating, the emissions factors for different types of coal-fired boiler technologies are adapted from Lei et al. 2011 for large CHP boilers (12 kg PM2.5/ton coal burned for pulverized coal boilers, 5.25 kg PM2.5/ton for grate coal boilers) and other small and medium boilers (1.89 kg PM2.5/ton coal for circulating fluidized bed boilers and 5.4 kg PM2.5/ton coal for grate coal boilers).

Modeling Indirect PM2.5 from Building Electricity Use

In order to quantify the indirect PM2.5 emissions from building electricity use, we use our model's power generation module 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 generation units with average efficiency of 44%. For each technology type, the model includes parameters on total installed capacity, availability, and dispatch order. China's announced targets for renewable generation and nuclear capacity expansion are used as the basis in setting the installed generation capacity. Based on specified power sector module parameters, the model uses an environmental dispatch order for dispatching generation to meet the calculated total electricity demand given the 2007 State Council dispatch rule prioritizing prioritize wind, solar, hydropower and nuclear before fossil fuel generation and ongoing pilot implementation of the rule. Nuclear, wind, hydropower and other non-fossil generation are dispatched first as the cleaner resources, with coal generation dispatched last to meet all remaining electricity demand. The model also dispatches the largest and most efficient coal-fired units first to represent efficiency gains from mandated retirement of small, outdated generation units and shift to cleaner, larger-scale units.

The major residential electric end-uses modeled include lighting, electric stoves for cooking, electric water heaters and the major 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. Commercial building electric end-uses include 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 meter, their technology shares and efficiency levels are described in Zhou et al. 2011. Figure 2 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.

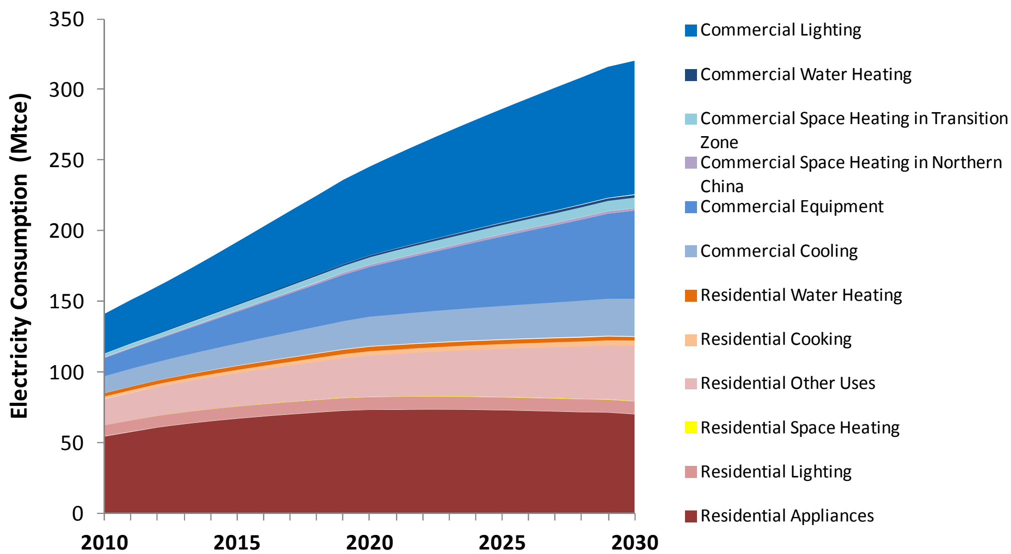

Figure 2. Electricity consumption by major residential and commercial end-uses.

Under the reference scenario, fuel switching is assumed to occur in the power sector with growing shares of non-fossil as well as cleaner natural gas power generation. Coal is the only fuel source for which indirect primary PM2.5 emissions are estimated in the power sector, with coal-fired generation assumed to have the same PM2.5 emission factors as large boilers for CHP.

Scenario Analysis for Strategies to Reduce PM2.5 Emissions

In addition to the reference scenario, three sets of alternative reduction strategy scenarios were developed to evaluate the potential impact of different strategies to reduce PM2.5 emissions: continuously improving the building shell and end-use efficiency, fuel switching for heating technologies, and installing improved PM emission control technologies in coal boilers in the power sector. Table 1 details the key underlying assumptions and differences between the baseline and reduction strategy scenario(s). Because the reference scenario represents a likely path of development for China's building sector and already incorporated assumptions about policy-driven continuous improvements in building efficiency and heating fuel switch, a frozen counterfactual baseline was used to evaluate these two strategies.

Table 1. Key assumptions of PM2.5 reduction strategy scenarios

Reduction Strategy	**Baseline Scenario**	**Reduction Strategy Scenario(s)**	
Building Energy Efficiency Improvement	**Frozen Efficiency Scenario:** building energy efficiency levels and end-use intensities are frozen at 2010 levels	**Reference Scenario of continuous efficiency improvement:** • continued efficiency improvements in appliances and equipment at recent pace • 50% and 25% improvement in building shell for heating and cooling, respectively; • 18% improvement in commercial lighting by 2030 • district heating coal boiler efficiency improves from 73% to 87% by 2030 • efficiency for individual coal boilers for heating improves from 63% to 74% by 2030 • current international practice for commercial cooling by 2030	**Accelerated Efficiency Improvement Scenario:** • accelerated efficiency improvements in appliances and equipment • 75% and 38% improvement in building shell for heating and cooling • 48% improvement in commercial lighting by 2030 • same improvements as Reference Scenario in heating coal boiler efficiency • current international best practice for commercial cooling by 2020
Fuel Switching	**Frozen Fuel Switching Scenario:** natural gas heating fuel shares frozen at 2010 levels: 8% for large/medium CHP boilers, 17% for individual boilers	**Reference Scenario of continuous fuel switching:** evaluate a feasible pace of continuous fuel switching with doubling of 2010 natural gas shares by 2030	
PM Emissions Control Technologies for Power Sector	**Reference Scenario:** fabric filter installation doubles from 10% in 2010 to 20% in 2030	**PM Emissions Controls Scenario:** accelerated penetration of fabric filters installed in coal-fired boilers for power sector from 10% in 2010 to 35% in 2030. Control technologies not considered for heat boilers due to prohibitively high costs.	

Note: More details on these assumptions can be found in the full upcoming report on which this paper is based, Khanna et al. 2014

Building-related PM2.5 Emissions under Reference Scenario

Direct Primary PM2.5 Emissions for Heating

Residential and commercial buildings together contributed 965 thousand metric tons (kt) of direct primary PM2.5 emissions in 2010. Figure 3 shows that the vast majority of building-related PM2.5 emissions from heating were emitted in Northern China, with a slightly larger share coming from residential than commercial buildings. Direct primary PM2.5 emissions for heating both residential and commercial buildings can decrease over time due to continuous efficiency improvements and heating fuel switch assumed to occur under the reference scenario as a result of continuation of current and planned efficiency policies. For residential buildings, 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. Residential primary PM2.5 emissions from direct coal consumption for heating totals 106 kt in 2030, or 45% lower than the 2010 levels. For commercial buildings, independent coal boilers for heating will be completely phased out and replaced by district heating, resulting in declining shares of PM2.5 emissions from independent coal boilers. In terms of building type, the largest share of direct PM2.5 emissions for space heating will be from heating office buildings, which has the largest share of commercial floor space, followed by other commercial buildings, hotel and retail. 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 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.

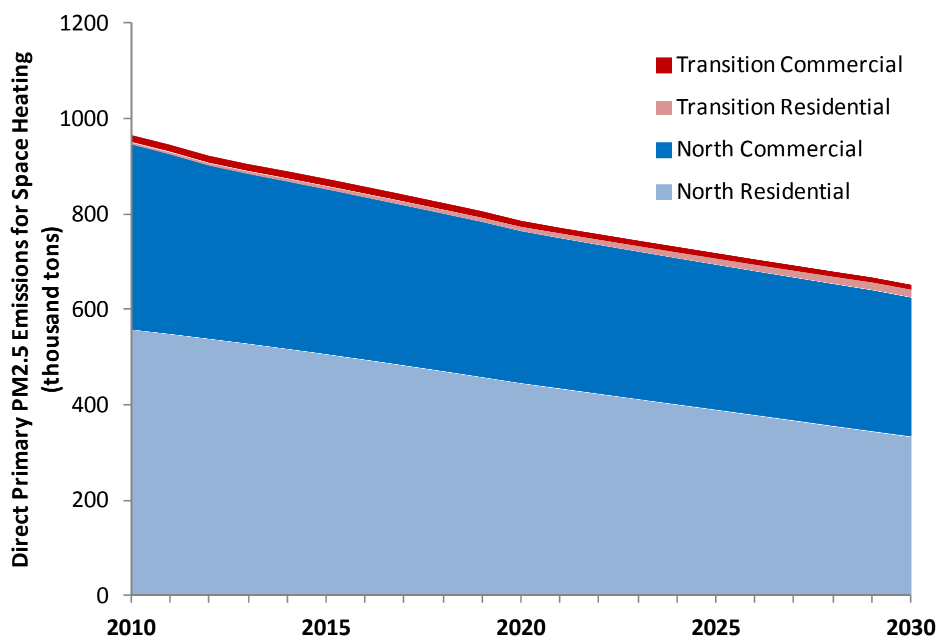

Figure 3. Direct primary PM2.5 from space heating by building type and region.

Indirect PM2.5 Emissions from Electric End-Uses

The indirect PM2.5 emissions from building-related electricity use for residential and commercial buildings are shown in Figure 4. 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. This is the result of the fuel and coal technology switching assumed to occur for the entire power sector based on the assumption of continued efficiency and renewable generation policies under the Reference scenario. This causes the average PM2.5 emission factor per kWh of electricity generated to decrease from 2010 to 2030.

Unlike direct PM2.5 emissions, indirect PM2.5 remains flat as a result of increased usage and rapidly rising electricity demand for end-uses in commercial buildings (as seen in Figure 2) 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, as seen in Figure 4. Despite moderate efficiency improvements in electric end-uses, commercial buildings' electricity demand for 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.

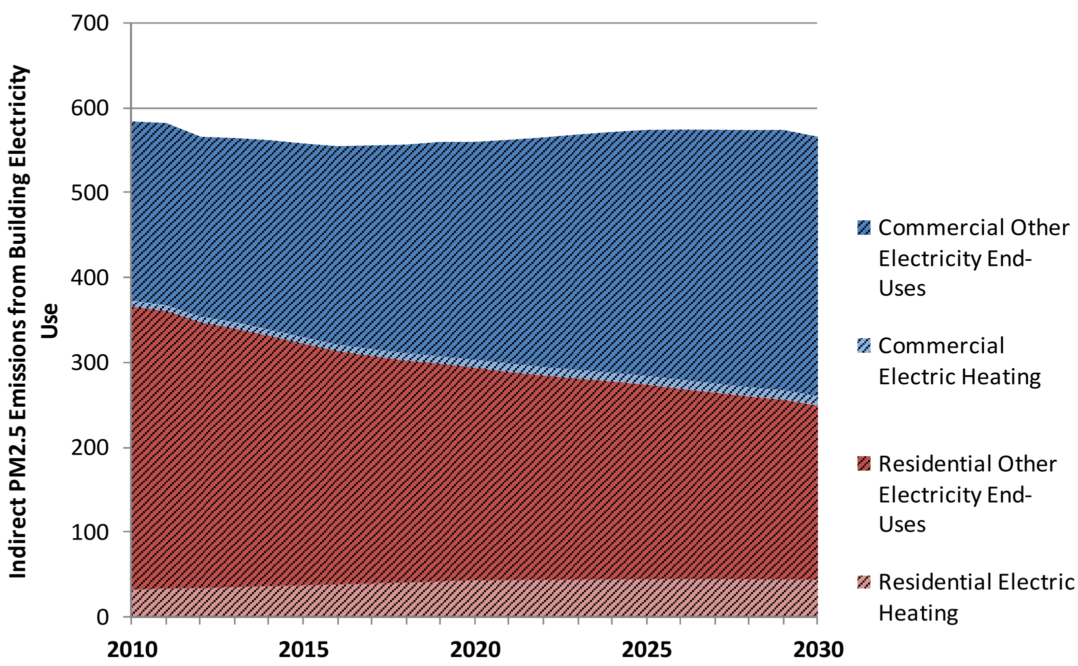

Figure 4 Indirect PM2.5 emissions from residential and commercial electricity use.

Total Building-related PM2.5 Emissions

In 2010, total building-related PM2.5 was 1.55 million metric tons (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.

Over time, however, the relative shares of indirect PM2.5 are expected to rise, as seen in Figure 5. By 2030, indirect PM2.5 from residential and commercial buildings will contribute 20% and 26%, respectively, of 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.

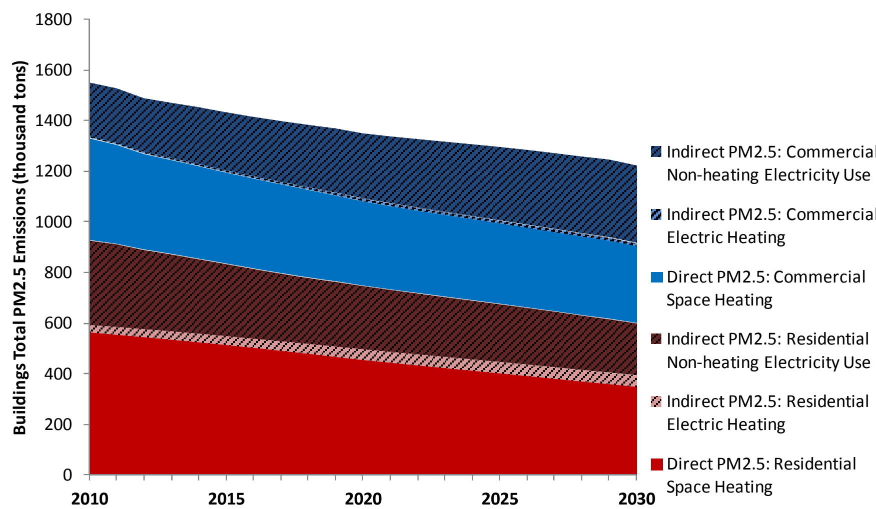

Figure 5. Direct and indirect PM2.5 by building type, 2010 to 2030.

Potential Co-benefits of PM2.5 Reduction Strategies

Figure 6 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 advanced PM control technologies in 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.

As seen in the subset bar chart, 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. 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.

Accelerated efficiency improvement and installing PM control technologies in the power sector are two additional strategies for further reducing PM2.5 emissions from the Reference scenario; both can achieve small incremental reductions in building-related PM2.5 emissions.

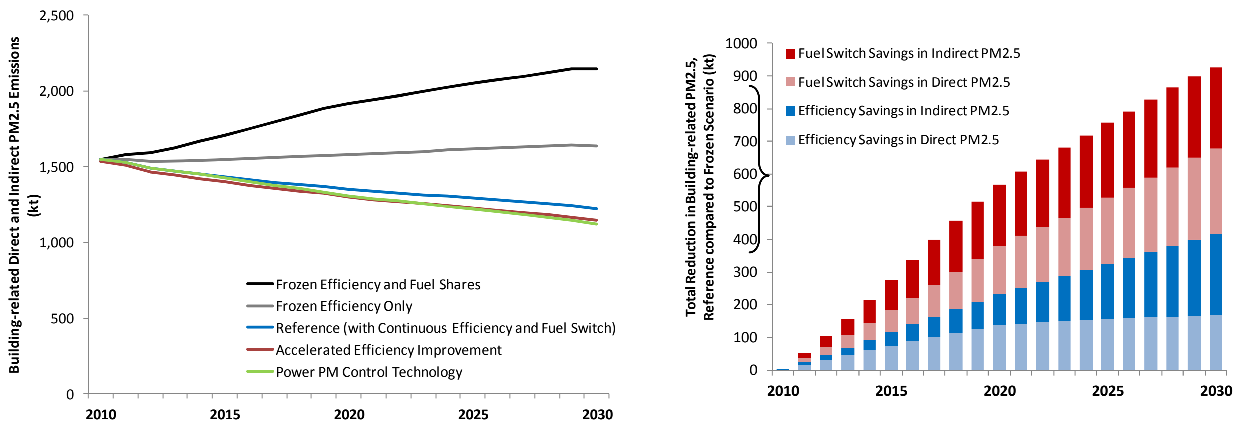

Figure 6. Comparison of total building-related PM2.5 emissions by strategy and break-out of direct and indirect PM2.5 emissions reduction under Reference Scenario.

Figure 7 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. 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.

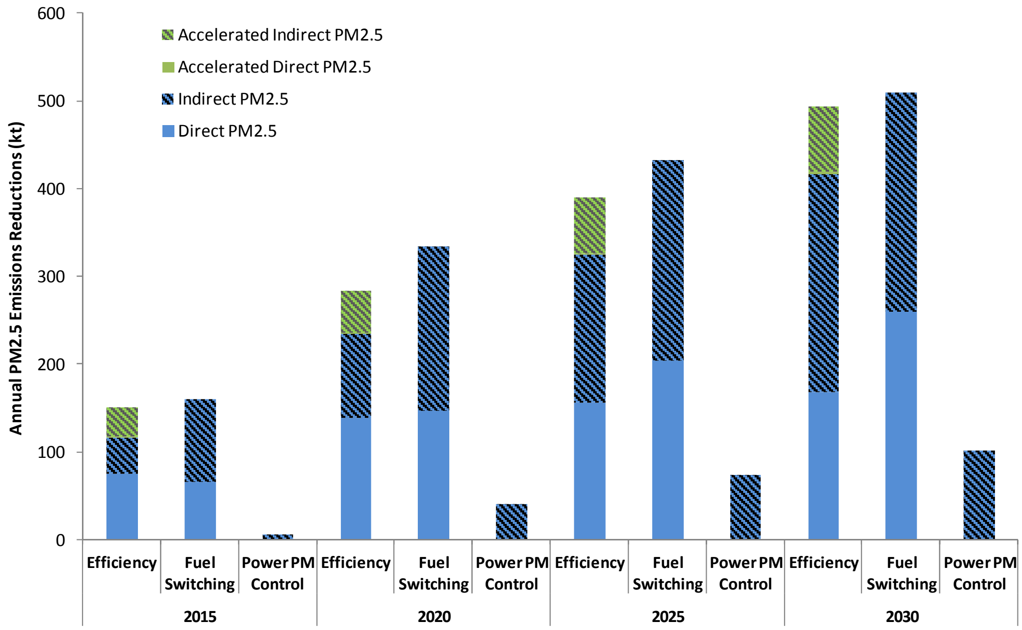

Figure 7. Annual building-related direct and indirect PM2.5 reduction potential by strategy.

Conclusions and Policy Implications

This study reflects a new bottom-up end-use modeling approach to quantifying buildings' direct and indirect contributions to primary PM2.5 emissions. 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 building sector development, annual total direct PM2.5 decreases 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 and power generation fuels, indirect PM2.5 emissions will not decline due to significant rise in commercial electricity demand but flattens at nearly 600,000 tons per annually between 2010 and 2030.

In this study, scenario analysis is used to evaluate and quantify the co-benefits of energy efficiency to PM2.5 reductions on a national scale with important policy implications. Comparing the reference scenario results to a frozen counterfactual baseline 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_2 and CO_2 emissions. However, the specific costs of different policies were not evaluated and considered within the scope of this study. 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 fuel switching is another possible strategy for further reducing PM2.5. But given China's limited domestic natural gas resources and the growing dependence on imported natural gas, more aggressive fuel switching is likely to run into supply constraints. Secondary PM2.5 emissions may also increase 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 further reductions in building-related PM2.5. Based on these findings, relevant policy recommendations for addressing the rising contribution of buildings to total PM2.5 emissions include:

- 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 advanced PM control technologies such as fabric filters 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 constrained supply for natural gas.

Acknowledgments

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