



Costs of Selected Policies to Address Air Pollution in China

Keith Crane, Zhimin Mao

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Preface

Air pollution has been one of the most pernicious consequences of China's last three decades of economic transformation and growth. Concentrations of pollutants exceed standards recommended by the World Health Organization in virtually every major urban area. The large costs of air pollution are driven by health impacts and loss of labor productivity, running 6.5 percent of China's gross domestic product each year between 2000 and 2010, and rising as China's population becomes more urbanized and productive.

If China is to improve urban air quality to the point where pollutant concentrations do not exceed levels that harm human health, aggressive implementation of clean-air policies will be necessary. However, these policies have costs.

The purpose of this report is to provide rough estimates of the potential costs to China of adopting extensive additional measures to reduce air pollution. It estimates the costs of three policy measures that could substantially reduce concentrations of major pollutants in urban areas:

1. substituting natural gas for coal for residential and commercial use
2. replacing coal with renewable and nuclear fuels to generate electricity
3. scrapping older, heavily polluting vehicles.

This report should be of interest to the Chinese government, the Chinese public, and other interested parties in China and elsewhere involved in the discussion regarding measures to reduce air pollution.

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Questions or comments about this report should be sent to the project leaders, Keith Crane (Keith_Crane@rand.org) and Debra Knopman (Debra_Knopman@rand.org). For more information about the Environment, Energy, and Economic Development Program, see <http://www.rand.org/energy> or contact the director at eed@rand.org.

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Summary

The Problem

Air pollution has been one of the most pernicious consequences of China's last three decades of economic transformation and growth. Although Chinese governments—federal, provincial, and municipal—have made considerable efforts in this field and air quality has improved by some measures, it remains a serious problem: Concentrations of pollutants exceed standards recommended by the World Health Organization (WHO) in virtually every major urban area. The large costs of air pollution are driven by health impacts and loss of labor productivity, running 6.5 percent of China's gross domestic product (GDP) each year between 2000 and 2010, and rising as China's population becomes more urbanized and productive.

The Chinese government has been implementing anti-pollution policy measures similar to those adopted by other industrialized economies:

1. subsidizing or mandating the use of fuels—such as natural gas, nuclear, and renewables—that emit fewer air pollutants when combusted than coal
2. mandating that motor vehicles, boilers, and other equipment that emit high levels of pollutants be scrapped
3. mandating the installation of pollution-control equipment on major point sources and motor vehicles.

If China is to improve urban air quality to the point where pollutant concentrations do not exceed levels that harm human health, more aggressive implementation of such policies will be necessary. However, these policies have costs. The purpose of this report is to assess the potential costs of adopting extensive additional anti-pollution measures compared with the benefits of improved air quality. The report is designed to contribute to the debate on these measures that is occurring among the Chinese government, the Chinese public, and other interested parties in China and elsewhere.

Solutions

Substituting Natural Gas or Propane for Coal for Residential and Commercial Use

For China's cities to meet WHO standards for air quality, residential and commercial users will have to stop burning coal, biomass, and plastic wastes in urban areas. Over the last several decades, most countries have found that effectively reducing emissions from boilers and stoves used for residential and commercial heating and cooking in urban areas requires that coal be replaced by natural gas, propane, or electric heat generated from fuels other than coal.

Households and commercial establishments in China burned 114 million tons of coal in 2011, which accounted for 3.2 percent of total national consumption. Coal-burning household furnaces and stoves are difficult to outfit with pollution control equipment, as are boilers used to heat residential and commercial buildings; in most instances, substituting natural gas or propane is the most efficient way to reduce pollution from these sources. But to effect such a substitution, China would need to procure an additional 88 billion cubic meters of natural gas—which would be a 60-percent increase over the total of 147 billion cubic meters of natural gas that China consumed in 2012.

Replacing Coal with Cleaner Fuels to Generate Electricity

Half of all the coal combusted in China is used to generate a very large share of its electricity, 79 percent in recent years. To reach healthy air quality levels, China will have to replace a substantial amount of coal-fired electric power, especially in or near major population centers, with generation from power plants that use other, less-polluting fuels, such as natural gas, nuclear, wind, or solar.

Coal accounts for a much smaller share of electricity generation in the United States and many countries in Europe—40 percent in the case of the United States in 2013. For China to match the U.S. figure, it would have needed to reduce coal-fired generation by 39 percentage points, or 1.918 trillion kilowatt hours (KWh), in 2012. This is not entirely unrealistic, however: Retiring China's worst-performing coal-fired power plants could reduce total national emissions of particulates and sulfur dioxide by well over 25 percent.

We have stated that China would have to substitute natural gas, renewables, or nuclear energy to reduce the use of coal in generating electricity. China has plans to expand hydroelectric power capacity from 249 gigawatts (GW) to 325 GW, which could generate 0.264 trillion KWh, equivalent to 5.3 percentage points of coal-fired power in 2012. Wind could generate 0.996 trillion KWh, 20 percent of the electricity China generated in 2012. China would need to install an additional 540 GW of wind capacity beyond its 2012 installed wind capacity of 62 GW to reach this goal, assuming that an additional GW of wind capacity generated levels of power similar to current farms. Nuclear power plants could supply the difference, 0.658 trillion KWh, or 15.2 percent of China's electric power output in 2012. We estimate that 84 GW of additional installed nuclear capacity would need to be built to generate this power, 45 percent more than China's current goal of an additional 58 GW by 2020. This goal does not take into account additional demand for generating capacity from continued economic growth.

Scrapping Older Vehicles

Motor vehicles have been a rapidly rising source of air pollution in China, especially emissions of nitrogen oxides. China has been addressing this problem by adopting and enforcing the stringent air pollution standards of the European Union. Most motor vehicles sold in China are manufactured by joint ventures between international car companies and Chinese companies,

which means domestic Chinese producers have access to the pollution-control technologies used by international manufacturers. Thus, there is no technological barrier in the motor vehicle industry to installing pollution-control equipment capable of meeting current European emission standards. In fact, the most stringent technologies are already available in China and being installed in vehicles sold in Beijing and other cities where reducing pollution from automobiles has been made a priority.

Scrapping highly polluting vehicles that have remained on China's highways is the most efficient way to reduce air pollution from motor vehicles already on the road. To dramatically reduce emissions from motor vehicles, China will need to scrap all the 14,514,000 vehicles that have rudimentary pollution control equipment or none at all. Scrapping such vehicles in 2009 would have eliminated 70 percent of carbon monoxide, 70 percent of volatile hydrocarbons, 61 percent of nitrogen oxides, and 76 percent of particulate matter emitted by automobiles in China in that year.

Approximate Costs of Improving Air Quality

The measures proposed here, all of which have already been partially implemented by national or municipal governments in China, would lead to substantial improvements in urban air quality. Concentrations of particulate matter, sulfur dioxide, and nitrogen oxides would be reduced by at least a quarter and probably much more, which would substantially reduce the annual health care and loss in productivity costs that air pollution imposes on the country.

As shown in Table S.1, these measures would not be costless. We estimate that, if implemented, recurring annual costs of these policies could run from \$32 billion to \$52 billion for replacing coal with natural gas for residential and commercial heating and \$184 billion for replacing half of China's coal-fired electric power generation with renewables or nuclear power, which adds up to total recurring costs ranging from \$215 billion to \$235 billion annually. Subtracting the value of the coal (\$75 billion) for which these fuels would substitute, net annual costs in aggregate would run \$140 billion to \$160 billion annually. If we estimate that the annual cost of air pollution in China is 6.5 percent of the nation's GDP, that comes out to roughly \$535 billion in 2012—and these investments represent less than one-third that amount.

Of the three policy initiatives discussed here, the near-term priority should be substituting natural gas for coal for residential and commercial use. Boilers and stoves fueled by coal, wood, or wastes are notorious for emitting pollution. The detrimental health effects of emissions from these sources on health and life expectancy in China, especially northern China, have been well documented. Ending the use of these fuels would substantially improve air quality in urban areas, especially in winter months, greatly reducing the number of days when air quality is extremely bad.

At \$32 billion to \$52 billion a year, the costs of ending residential and commercial use of coal would be substantially less than the \$184 billion we estimate for replacing coal-fired power

with hydro, wind, and nuclear. Replacing coal-fired power with other sources of energy is the most expensive policy measure of the three we evaluate, and would contribute most to reducing overall emissions of total suspended particulates (TSP) and sulfur dioxide in China. However, its impact on urban air quality might not be as great as suggested by the expected decline in emissions. Most power plants in China are not located in urban areas. Although wind-borne air pollution from coal-fired power plants is a major factor in determining urban air quality in China, sources of air pollution within the city limits generally have a more direct impact. Detailed modeling would be needed to specifically quantify the relative contributions of these regional sources versus local ones, but on balance, ending the use of coal for residential and commercial purposes within urban areas is likely to be the higher near-term priority.

Table S.1: Annual Costs of Policies to Reduce Air Pollution in China

Policy Measure	Quantity	Price (2012 \$)	Total Cost (in billions of 2012 \$)
Replacing coal for residential and commercial use with natural gas			
Average price of LNG in East Asia in 2012	88 billion cubic meters	360/cubic meter	32
Peak price of LNG in East Asia 2012	88 billion cubic meters	587/cubic meter	52
Replacing coal-fired electricity with other fuels			
Hydro	0.26 trillion KWh	90.30 per thousand KWh	24
Wind	0.89 trillion KWh	86.60 per thousand KWh	78
Nuclear	0.76 trillion KWh	108.40 per thousand KWh	82
Total			184
Gross total			
Low end (assumes lower price for natural gas)			215
High end (assumes higher price for natural gas)			235
Value of saved coal (million metric tons)	1,009	74	75
Net total annual direct costs			
Low end			140
High end			160

SOURCE: RAND calculations

China is well on the way to scrapping “yellow tag” vehicles, meaning older, highly polluting cars and trucks. More than a third of these vehicles that were on the road in 2012 are to be scrapped by the end of 2015; all should be gone by the end of 2017. However, getting the worst-polluting cars and trucks off the road as soon as possible would be beneficial. China may wish to implement limited buyback programs, like the one in Dongguan, Guangdong Province, to accelerate the retirement of these vehicles. Such programs would be of relatively short duration;

all these vehicles will have to be retired by 2017 under existing regulations. The one-off costs of scrapping highly polluting vehicles could run \$21 billion to \$42 billion (Table S.2).

Table S.2: One-Off Costs of Scrapping Older Vehicles to Reduce Air Pollution in China

Scrapping older vehicles	Quantity	Price (2012 \$)	Total Cost (in billions of 2012 \$)
Assuming all older vehicles are cars	14.5 million	1,430	21
Assuming all older vehicles are trucks	14.5 million	2,860	42

SOURCE: RAND calculations

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Abbreviations

BTU	British thermal unit
CO	carbon monoxide
GDP	gross domestic product
GW	gigawatt
KWh	kilowatt hour
LNG	liquefied natural gas
PM ₁₀	particulate matter less than 10 microns in diameter
PM _{2.5}	particulate matter less than 2.5 microns in diameter
RMB	renminbi
TSP	total suspended particulate matter
µg/m ³	micrograms per cubic meter
VOC	volatile organic compounds
WHO	World Health Organization

1. Introduction

Air pollution has been one of the most pernicious consequences of China's last three decades of economic transformation and growth. Although Chinese governments—federal, provincial, and municipal—have made considerable efforts in this field, and air quality has improved by some measures, it remains a serious problem: Concentrations of pollutants exceed standards recommended by the World Health Organization (WHO) in virtually every major urban area.¹

The Chinese government has been implementing anti-pollution policy measures similar to those adopted by other industrialized economies:

1. subsidizing or mandating the use of fuels—such as natural gas, nuclear, and renewables—that emit fewer air pollutants when combusted than coal
2. mandating that motor vehicles, boilers, and other equipment that emit high levels of pollutants be scrapped
3. mandating the installation of pollution-control equipment on major point sources and motor vehicles.

If China is to improve urban air quality to the point where concentrations of pollutants do not exceed levels that harm human health, more aggressive implementation of such policies will be necessary. However, these actions will have costs. Natural gas, nuclear energy, and renewables are more costly than coal in China, and large-scale substitutions would increase the cost of electricity. Polluting plants and vehicles will need to be shut down or cleaned up with the loss of that capital. Consumers and businesses will need to purchase and operate vehicles, equipment, and plants outfitted with pollution-control equipment, some of which will be more expensive than comparable, higher-polluting vehicles and equipment.

Purpose

The purpose of this paper is to provide rough estimates of the potential costs to China of adopting extensive additional measures to reduce air pollution and to compare these estimates with the costs of the status quo. The paper evaluates three policy measures that could substantially reduce concentrations of major pollutants in urban areas:

1. substituting natural gas or propane for coal in residential and commercial heating and other uses

¹ See Tables 2.1 and 2.2, which are based on WHO air-quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide.

2. replacing coal with renewable and nuclear fuels to generate electricity
3. scrapping older vehicles that lack adequate pollution control equipment.

Organization of This Report

In Chapter Two, we describe the magnitude of air pollution in China, focusing on air quality in major urban areas, aggregate emissions and sources of emissions, and the health costs of poor air quality. Chapter Three reviews the three policy options already mentioned, quantifying the shifts in fuel use and the numbers of vehicles that would need to be scrapped. In Chapter Four, we estimate the costs of these policy measures and conclude with a discussion of net benefits.

2. The Problem

Rapid economic growth in China has not only raised incomes, it has also resulted in massive increases in pollution of air, water, and land. The costs of this pollution are large, approaching 10 percent of gross domestic product (GDP) per year over the past decade. This ratio is several times higher than in developed Asian market economies such as Korea and Japan, and substantially higher than in the United States.² Air pollution accounts for the bulk of these costs, running 6.5 percent of China's GDP between 2000 and 2010; costs of water pollution ran an additional 2.1 percent of GDP, and soil degradation, 1.1 percent.³ Despite some reported reductions in pollution, as Chinese incomes rise, so will the costs of pollution.⁴ Urbanization, too, is driving an increase in the costs of pollution, as a larger share of the population is exposed to poor-quality air.⁵

The high costs of air pollution stem from its effect on human health. Table 2.1 shows World Health Organization (WHO) air quality standards for major pollutants. WHO recommends a limit on the annual mean of daily concentrations of particulate matter less than 10 microns in diameter (PM₁₀) of no more than 20 micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) of air and a limit on the annual mean of daily concentrations of particulate matter less than 2.5 microns in diameter (PM_{2.5}), which are even more deleterious to human health, of no more than 10 $\mu\text{g}/\text{m}^3$ of air (Table 2.1). Sulfur dioxide is not to exceed 20 $\mu\text{g}/\text{m}^3$ of air on average over the course of 24 hours, and nitrogen oxides are not to exceed 40 $\mu\text{g}/\text{m}^3$ of air per day on average over the course of the year. As can be seen in Table 2.2, all major Chinese cities exceed these levels except for a few that meet WHO standards for nitrogen oxides; most exceed average daily limits for PM₁₀ by five times or more.

² World Bank and Development Research Center of the State Council, the People's Republic of China, *China 2030: Building a Modern, Harmonious, and Creative High-Income Society*, Washington, D.C.: World Bank, 2012, p. 39; Nicholas Z. Muller and Robert Mendelsohn, *Measuring the Damages of Air Pollution in the United States*, Princeton, N.J.: Yale University School of Forestry and Environmental Studies, January 9, 2007.

³ World Bank et al., 2012, p. 39; Ministry of Environmental Protection and Chinese Academy of Engineering, *MacroStrategy for China's Environment: Strategy for Protection of China's Environmental Factors* (in Chinese), Beijing: China Environmental Sciences Press, 2011.

⁴ As incomes rise, so do the costs of pollution. Workers are more productive and make more money, so when they are ill and not working, greater costs are incurred. For a discussion of the increasing costs of pollution stemming from economic growth, see Nicholas Z. Muller, Robert Mendelsohn, and William Nordhaus, "Environmental Accounting for Pollution in the United States Economy," *American Economic Review*, Vol. 101, No. 5, 2011, pp. 1649–1675; and Dora L. Costa and Matthew E. Kahn, "Changes in the Value of Life, 1940–1980," *Journal of Risk and Uncertainty*, Vol. 29, No. 2, 2004, pp. 159–180.

⁵ For a discussion of the implications of urbanization on the costs of pollution, see Ying Zhou, Jonathan I. Levy, John S. Evans, and James K. Hammitt, "The Influence of Geographic Location on Population Exposure to Emissions from Power Plants Throughout China," *Environment International*, Vol. 32, No. 3, 2006, pp. 365–373.

Failure to reduce concentrations of air pollutants to below WHO standards has substantial costs in terms of health. A recent study found that in China, life expectancy falls 3.0 years for every additional 100 micrograms of total suspended particulate matter (TSP) of all sizes, including PM₁₀ and PM_{2.5}, per cubic meter of air averaged over the course of a year.⁶ The same study found that very high levels of TSP have reduced life expectancy in northern China (where air quality tends to be worst), by an average of 5.5 years compared to the south, which itself is heavily polluted. In addition to its effects on human health, air pollution imposes other costs, including degradation of agricultural lands and damage to the health of forests, plants, farm animals, and wildlife. It also degrades exteriors of buildings and other structures.

Table 2.1: WHO Air Quality Standards

		Annual Mean	24-Hour Mean	8-Hour Mean
Particulate matter	PM _{2.5}	10 µg/m ³	25 µg/m ³	
	PM ₁₀	20 µg/m ³	50 µg/m ³	
Ozone				100 µg/m ³
Sulfur dioxide			20 µg/m ³	
Nitrogen oxides	nitrogen dioxide and other nitrogen compounds	40 µg/m ³		

SOURCE: World Health Organization, *WHO Air Quality Guidelines For Particulate Matter, Ozone, Nitrogen Dioxide And Sulfur Dioxide: Global Update 2005*, Geneva, Switzerland: World Health Organization, 2006.

⁶ Yuyu Chen, Avraham Ebenstein, Michael Greenstone, and Hongbin Li, *Evidence on the Impact of Sustained Exposure to Air Pollution on Life Expectancy from China's Huai River Policy*, Proceedings of the National Academy of Science, May 28, 2013..

Table 2.2: Average Concentrations of Air Pollutants in Selected Chinese Cities in 2011 (in $\mu\text{g}/\text{m}^3$)

City	Particulate Matter (PM ₁₀)	Sulfur Dioxide	Nitrogen Oxides
WHO Standards	Annual average of 20 per day	Daily mean of 20	Annual average of 40 per day
Beijing	113	28	56
Tianjin	93	42	38
Harbin	99	41	46
Shanghai	80	29	51
Nanjing	97	34	49
Hefei	113	22	25
Wuhan	100	39	56
Changsha	83	40	47
Guangzhou	69	28	49
Chongqing	93	38	31
Chengdu	100	31	51
Xi'an	118	42	41

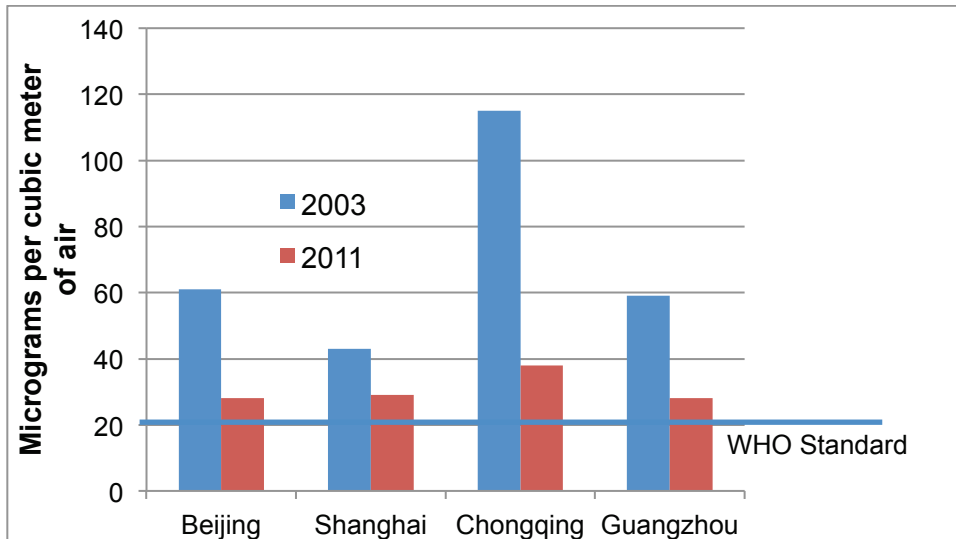
SOURCE: *China Statistical Yearbook*, 2012, Table 12–19.

Trends

According to Chinese statistics, air quality has improved in most Chinese cities over the last decade.⁷ Figure 2.1 shows trends in air quality as measured by concentrations of sulfur dioxide and Figure 2.2 shows trends in air nitrogen oxides in China's four largest cities: Beijing, Chongqing, Guangzhou, and Shanghai. Average annual concentrations of sulfur dioxide and nitrogen oxides per cubic meter of air have fallen in these four cities since 2003 according to Chinese official statistics. Despite these reported improvements, concentrations of TSP, nitrogen oxides, and sulfur dioxide still exceed WHO standards. China's use of average concentrations of pollutants over the course of the year to measure pollution is not considered the best way to measure air quality; WHO sets standards for 24-hour and 8-hour periods (Table 2.1). The number of days of severe pollution is another important indicator.

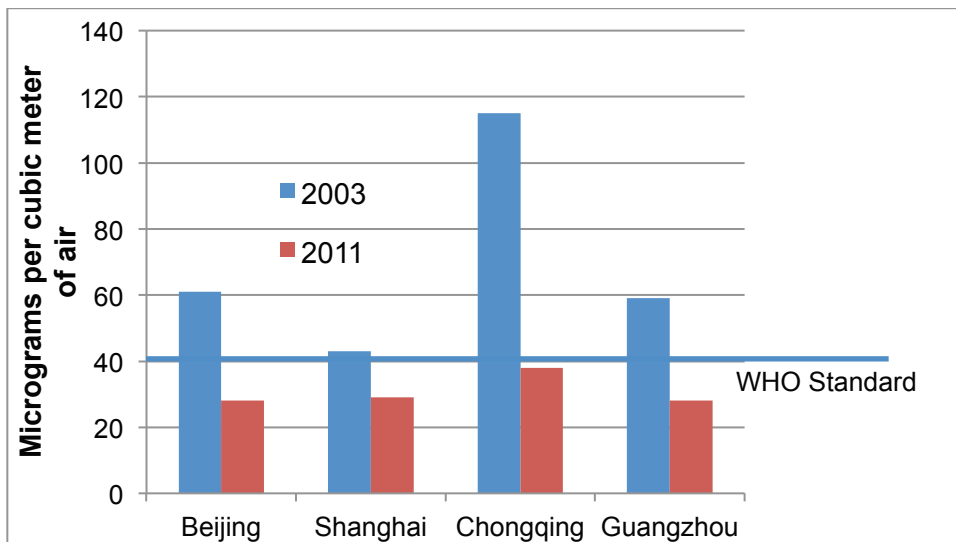
⁷ *China Statistical Yearbook*, 2012, Table 12-19.

Figure 2.1: Average Mean Concentrations of Sulfur Dioxide in China's Largest Cities



SOURCE: *China Statistical Yearbook*, 2004 and 2012 Table 12–19.

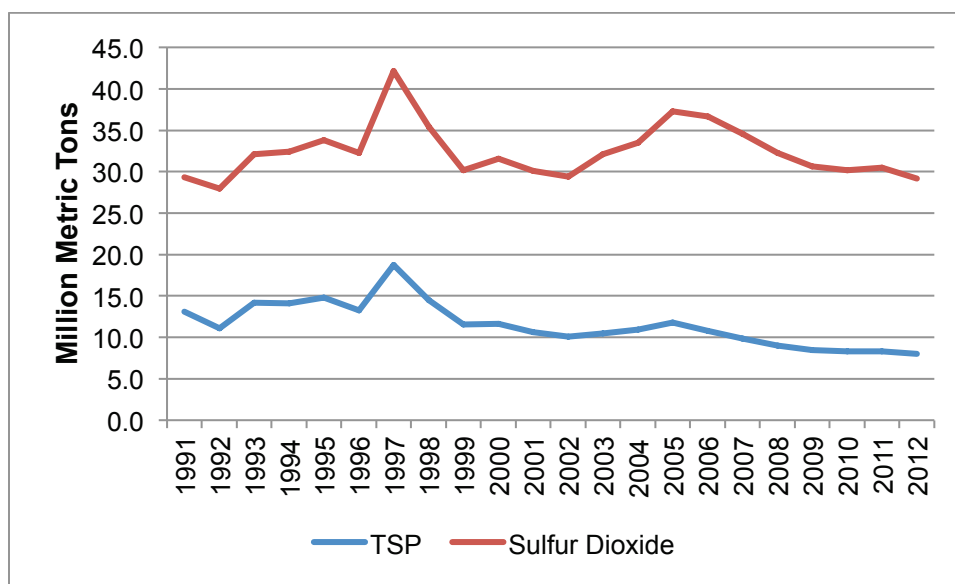
Figure 2.2: Average Mean Concentrations of Nitrogen Oxides in China's Largest Cities



SOURCE: *China Statistical Yearbook*, 2004 and 2012, Table 12–19.

Figure 2.3 shows total emissions of sulfur dioxide and TSP for all of China in terms of millions of tons of pollutants. Here, too, China shows improvements. The overall quantities of both TSP and sulfur dioxide have fallen since 2005, down 32 percent and 17 percent, respectively.

Figure 2.3: China's Emissions of TSP and Sulfur Dioxide (1991–2012)



SOURCE: *China Statistical Yearbook*, 1995, 2000, 2005, 2010, 2014, Table 12–15.

Figures 2.1–2.3 are based on official Chinese statistics. Several studies have reported that air pollution data in China are dubious. In some cities, officials have manipulated pollution data to meet regulatory targets.⁸ Data concerning nitrogen oxide and sulfur dioxide emissions may be understated. O’Hara et al. found that, in 2003, China’s emissions of sulfur dioxide might have been 70 percent higher than reported in official statistics.⁹ If emissions and concentrations of pollutants are underreported, the reductions we propose for coal use would lead to even greater reductions in emissions and improvements in air quality.

Sources

As can be seen in Figure 2.4, electric power generation accounts for most emissions of sulfur dioxide in China. Adding emissions from cement and metallurgy to this accounts for almost three quarters of the total. The fuel primarily responsible for these emissions is coal, which accounts not only for most of China’s emissions of sulfur dioxide but also TSP. Between 1990 and 2010, China’s consumption of coal tripled.¹⁰ Despite this substantial increase, emissions of

⁸ Y. Chen, G. Z. Jin, et al., “Gaming in Air Pollution Data? Lessons from China,” *BE Journal of Economic Analysis & Policy* Vol. 12, No. 3, 2012; S. Q. Andrews, “Inconsistencies in Air Quality Metrics: ‘Blue Sky’ Days and PM₁₀ Concentrations in Beijing,” *Environmental Research Letters*, Vol. 3, No. 3, 2008; D. Ghanem and J. Zhang, “‘Effortless Perfection:’ Do Chinese Cities Manipulate Air Pollution Data?” *Journal of Environmental Economics and Management*, Vol. 68, No. 2, 2014.

⁹ T. O’Hara et al. “An Asian Emission Inventory of Anthropogenic Emission Sources for the period 1980–2020,” *Atmospheric Chemistry and Physics*, Vol. 7, No. 16, 2007, pp. 4419–4444.

¹⁰ *China Statistical Yearbook 2011, 2012*, Table 7-5.

TSP from coal-fired power plants have fallen by close to 40 percent over this period, as the Chinese national government has mandated that coal-fired power plants install bag houses and scrubbers to reduce emissions of these pollutants.¹¹ Nonetheless, emissions of sulfur dioxide from power plants have risen 31 percent and concentrations of TSP remain high.¹² Dust generated by industry and construction has also fallen sharply, down by two-thirds between 1991 and 2012, as city governments have taken steps to reduce dust from construction by mandating covers for dump trucks and watering down construction sites and streets.

In China's urban areas, households and small businesses account for disproportionate shares of TSP emissions, especially compared to the share of energy consumed by these users.¹³ The primary problem is that residential and commercial establishments burn coal, industrial and household waste, and wood and biomass for heat, generating greater emissions. Historically, the Chinese government provided coal below cost (or sometimes for free) to households for use in heating and cooking. In 2011, households and commercial establishments burnt 114 million tons of coal a year, equivalent to 3.2 percent of all the coal consumed in China (114 million tons was 12.6 percent of total U.S. consumption in 2011).¹⁴ The boilers or stoves in which this coal is combusted lack effective pollution-control equipment. Further, small businesses and households often dispose of plastic, discarded chemicals and oils, and other such products by burning them outdoors or in household furnaces. Much of the material is only partially combusted, emitting large quantities of often-toxic emissions, such as polyaromatic hydrocarbons. In addition, agricultural practices contribute to higher concentrations of TSP in urban and rural areas: After harvest, Chinese farmers often set their fields on fire to kill weed seeds and reduce stubble, emitting substantial quantities of TSP.

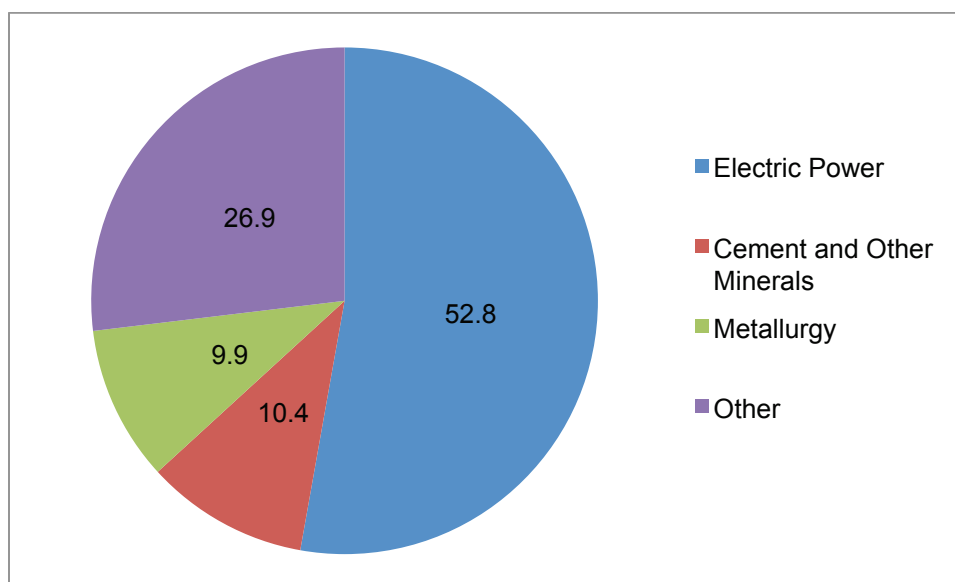
¹¹ Bag houses are fabric filters that retain particles from waste gas when they pass through the fabric. The filter operates cyclically between filtering and cleaning. During the cleaning stage, the accumulated dusts will be removed from the surface of the fabric, and be deposited for disposal. Scrubbers are used to remove particulates and sulfur dioxide from exhaust streams from facilities that combust coal, often using water-based solutions. *China Environmental Statistical Yearbook*, 2005, 2006, 2007, 2008, 2009, and 2010, Emission and Treatment of Waste Gas tables.

¹² *China Environmental Statistical Yearbook*, 2005, 2006, 2007, 2008, 2009, and 2010, Emission and Treatment of Waste Gas tables.

¹³ *China Statistical Yearbook 2011*, 2012, Table 7–5.

¹⁴ *China Statistical Yearbook*, 2012, 2013, Table 12–15; Energy Information Administration (EIA), *International Energy Outlook*, 2014a.

Figure 2.4: Percentage of Sulfur Dioxide Emissions from Major Point Sources in 2010



SOURCE: *China Environmental Statistical Yearbook*, 2010, Emission and Treatment of Waste Gas tables.

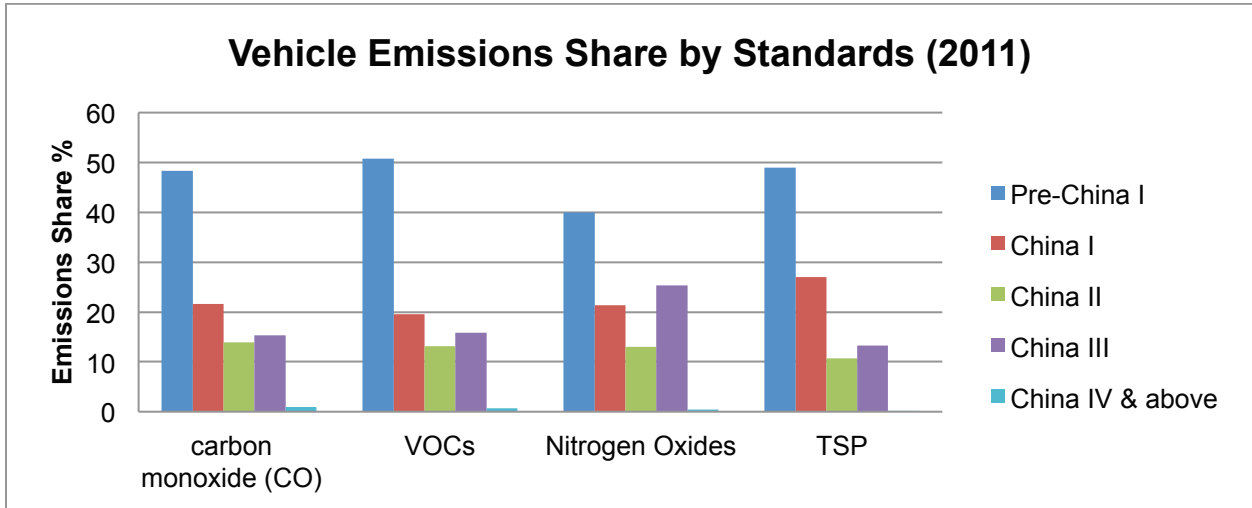
The number of cars in China rose from 17.4 million vehicles in 2004 to 74.8 million vehicles in 2011.¹⁵ Since 2011, the fleet has continued to expand by 20 million vehicles per year. The number of trucks, 17.9 million in 2011, has risen less dramatically, doubling between 2004 and 2011.¹⁶ As the numbers of cars and trucks in China have risen, motor vehicles have become an increasing source of urban air pollution, especially nitrogen oxides, volatile organic compounds, and TSP from diesel engines. China has followed European Union standards for cars and trucks. The EU has tightened emissions standards over time; each more stringent set of emissions standards has been designated by a number. Current emission standards, the fifth set, are called Euro 5/V, and the EU is in the process of introducing Euro 6/VI this year. China, following suit, also has progressively tightened its emission standards. China's first emission standard, China I, corresponded to Euro 1/I; China IV is now in effect. These standards set limits on automobile emissions of carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides and TSP. Because all new cars have to be sold with this pollution-control equipment installed and installation takes place at the assembly plant, emissions from new cars meet these standards.¹⁷ Over time, it is possible that inspection regimes in China may fail to ensure that vehicles continue to meet these standards. However, as shown in Figure 2.5, most emissions are generated by older vehicles that lack pollution-control equipment.

¹⁵ *China Statistical Yearbook 2012*, 2013, Stock of Vehicles.

¹⁶ *China Statistical Yearbook 2012*, 2013, Stock of Vehicles.

¹⁷ Ministry of Environmental Protection of the People's Republic of China, *China Vehicle Emission Control Annual Report*, National Environmental Management of New Production Vehicles, 2014, Part III.

Figure 2.5: Sources of Motor Vehicle Emissions According to Pollution Control Technology



SOURCE: Calculated from data from *China Statistical Yearbook, 2012*; and Ministry of Environmental Protection of the People's Republic of China, 2014.

3. Solutions

A number of countries have succeeded in greatly reducing air pollution. According to official statistics, China has already made some progress in reducing emissions of TSP, sulfur dioxide, and nitrogen oxides, resulting in some improvements in air quality in major cities, as shown in Figures 2.1 and 2.2 in the previous chapter. That said, levels of particulate air pollution in China are still above those that prevailed in the United States before the passage of the Clean Air Act in 1970.¹⁸ Although all developed nations have successfully reduced air pollution, none has faced quite the scale of reductions that China needs.

Measures to reduce air pollution that have had some success in China and in other countries include:

- 1) ending residential and commercial use of coal by substituting natural gas or propane
- 2) installing and operating pollution-control equipment on major point sources
- 3) closing coal-fired electric power plants and replacing them with power plants that run on cleaner fuels such as natural gas, nuclear power, or renewables
- 4) mandating the installation and operation of pollution-control equipment on new motor vehicles while retiring older vehicles that lack this equipment
- 5) closing industrial plants where pollution-control equipment cannot be installed economically or that are located in densely populated areas.

China has already employed all of these policy measures. In this report, we provide order-of-magnitude estimates of the extent to which some of these measures would need to be expanded to make major additional improvements in air quality in Chinese cities possible.

Substituting Natural Gas or Propane for Coal in Residential and Commercial Use

If China's cities are to meet WHO standards for air quality, the practice of burning coal, biomass, and plastic wastes in urban areas by residential and commercial users will have to end. Burning biomass and waste outside or in household stoves produces very large volumes of pollutants per kilogram of combusted material in close proximity to population centers.¹⁹ Many boilers and furnaces in China's urban areas that burn these fuels are not equipped with pollution-control equipment. In light of the age and small scale of these units, installing and operating pollution-control equipment so that emissions can be reduced to levels consistent with WHO air

¹⁸ Calculated from information from Chen, Ebenstein, Greenstone, and Li, 2013.

¹⁹ Environmental Protection Agency, "The Hidden Hazards of Backyard Burning," Washington, D.C., 2003.

quality standards either would not be feasible or would be more expensive than moving to alternative sources for larger units. It would also be difficult to ensure that these units are operating correctly. Over the last several decades, most countries have found that coal needs to be replaced by natural gas or electric heat generated by fuels other than coal to effectively reduce emissions from boilers used for residential and commercial heating. In the last century, London and Budapest mandated that coal be replaced by natural gas or other fuels for heating as a means of reducing air pollution. Beijing is already replacing all of its coal-fired facilities, including combined heat and power plants, with gas-fired plants. All coal-fired plants were to be closed by the end of 2014.²⁰

Burning natural gas or propane emits virtually no particulate matter or sulfur dioxide, although it does produce nitrogen oxides and carbon monoxide. If natural gas were to be substituted for coal, biomass, or plastic and other refuse in all boilers in Chinese cities, urban concentrations of particulate matter and sulfur dioxide would drop sharply, as occurred in cities in the United States and Europe.

City and district governments would need to implement such a measure. The governments of larger cities—especially Beijing, where air pollution has become a severe political problem—have demonstrated the political will and wherewithal to enforce such a measure, at least for apartment buildings and commercial establishments. As the Chinese government has declared “war” on pollution, municipal governments of smaller cities are caught in the middle: Lacking the financial resources of Shanghai and Beijing, they might be more reluctant to impose these costs on businesses, but they are also under pressure to implement pollution-reduction measures.²¹ For reasons of habit and cost, many households and establishments are likely to resist replacing coal and trash with natural gas or propane, especially if they need to buy a new furnace or stove and, in the case of natural gas, install a connection. In these instances, local governments would need to confirm the activities of inspectors, who have shown themselves willing to look the other way in exchange for a bribe.²² Setting up hotlines or other means of reporting violations would probably be a necessary additional step.

Table 3.1 shows our estimates of the additional natural gas that China would need to purchase to replace all the coal currently used by residential and commercial users. (For ease of calculation, we chose to focus only on natural gas, not propane, but in East Asia the cost per BTU of the two fuels is similar.) To calculate these figures, we assumed that the energy content of a standard metric ton of coal is 27.8 million British thermal units (BTUs) and the energy

²⁰ EIA, *China*, web page, February 2014b.

²¹ Michael Martina et al., “China to ‘Declare War’ on Pollution, Premier Says,” Reuters, March 5, 2014.

²² Yuan Xu, “Improvements in the Operation of SO₂ Scrubbers in China’s Coal Power Plants,” *Environmental Science & Technology* Vol. 45, No. 2, 2011, pp. 380–385.

content of a thousand cubic meters of natural gas is 36.1 million BTUs.²³ We then make the assumption that one BTU of natural gas would substitute for one BTU of coal in household and commercial uses. This assumption is conservative, as we would expect new natural gas furnaces to be more efficient than coal-fired boilers for residential or commercial applications.

Table 3.1: Replacing Coal with Natural Gas for Residential and Commercial Use

Use	Coal Use (million tons of standard coal equivalent)	Conversion (thousand cubic meters per metric ton)	Natural Gas Equivalent (billion cubic meters)
Commercial	22.1	0.77	17.0
Residential	92.1	0.77	70.8
Total	114.2		87.8

SOURCE: *China Statistical Yearbook*, 2013, Table 8-5; EIA, *Energy Equivalent Conversions*, web page, undated.

Total coal consumption in China was 3.61 billion tons of standard coal equivalent in 2011. Of this, 114 million tons (3.2 percent of total consumption) were consumed by households and commercial establishments. Because boilers and furnaces that burn this fuel frequently lack pollution-control equipment and because the coal is burnt within cities, switching natural gas for coal would have a highly disproportionate effect on improving urban air quality; concentrations of TSP and sulfur dioxide would fall by much more than 3.2 percent in urban areas.

But to do so, China would need to procure an additional 88 billion cubic meters of natural gas. This is a substantial amount, especially considering China consumed a total of 147 billion cubic meters of natural gas in 2012—meaning this policy measure would entail procuring 60 percent more natural gas than China consumed that year. This increment is equal to about 13 percent of total U.S. consumption of natural gas in 2012. Chinese projections of increased natural gas supply (domestic production and imports) envision an increase of 48 billion cubic meters by 2015. China would have to produce or import an additional 40 billion cubic meters of natural gas over and above currently planned increases in order to substitute it for all the coal currently consumed by households and commercial establishments.²⁴

²³ EIA, undated.

²⁴ EIA, 2014b.

Installing and Operating Pollution Control Equipment and Replacing Coal with Cleaner Fuels to Generate Electricity

About 90 percent of China's coal-fired power plants have installed pollution-control equipment to reduce emissions of sulfur dioxide.²⁵ This equipment has contributed to China's reported declines in these emissions (Figure 2.3). Because of the greater efficiency of its new supercritical and ultra-supercritical coal-fired power plants, along with the installation and use of scrubbers, China now emits less sulfur dioxide per kilowatt hour (KWh) from coal-fired power plants than the United States does. On newer plants, China uses the most advanced pollution-control technology that is commercially available. China has also installed pollution-control equipment to reduce emissions of particulates. Ninety percent of Chinese coal-fired capacity uses electrostatic precipitation to reduce emissions of particulates; 10 percent of capacity uses bag houses. These measures have contributed to a decline in emissions of particulate matter from coal-fired power plants from 16.5 grams per KWh in 1980 to 0.39 grams in 2012.²⁶

Even with pollution-control equipment, it is difficult to capture all emissions of sulfur dioxide and particulates from coal-fired power plants. As shown in Table 2.2, average levels of PM₁₀ in China's major cities remain five times what WHO stipulates are compatible with human health. Concentrations of sulfur dioxide and nitrogen oxides in most Chinese cities also substantially exceed WHO standards.

To reduce concentrations of particulates and sulfur dioxide, virtually all countries have used a combination of substituting less-polluting fuels for coal as well as installing pollution-control equipment on coal-fired plants. Half of all the coal combusted in China is used to generate electricity and these plants are responsible for half of all the sulfur dioxide emissions (Figure 2.3). To attain levels of air pollutants that fall within WHO standards, China will likely have to replace a substantial amount of coal-fired power, especially in or near major population centers, with generation from power plants that use other, less-polluting fuels, such as natural gas, nuclear, wind, or solar. Most countries that have attempted to seriously address air pollution have adopted this strategy.

In 2012, 79 percent of China's electricity (3.91 trillion KWh) was generated by fossil fuels, almost all of which was from coal-fired power plants.²⁷ If China were to reduce its use of coal to generate electricity to match the 2013 U.S. figure of 40 percent—a percentage more common in industrialized countries—it would need to reduce coal-fired generation by 39 percentage points, or 1.918 trillion KWh. Using estimated 2012 data as a baseline, this would entail reducing coal

²⁵ Calculated from Pan Li, "Current Status of Pollutant Control for Coal-fired Power Plants in China," Research Office (Center of Power Industry Environmental Protection & Climate Change), China Electricity Council, May 2014.

²⁶ Li, 2014.

²⁷ Li, 2014.

consumption in the power sector from 1,824 million metric tons annually to 929 million tons, or 49 percent. If the worst-performing coal-fired power plants were retired first, such a policy could reduce China's total emissions of particulates and sulfur dioxide by well over 25 percent (half of the half of all coal burned to generate electricity).

Our estimates of the increase in the use of natural gas necessary to cease using coal for residential and commercial heating and other uses in China were large. There are limits on the global availability of liquefied natural gas (LNG), and cost is also a factor. For the next several years, we do not see a substantial role for natural gas to replace coal in electric-power generation in China, if China is also making a concerted attempt to reduce coal use by the household and commercial sectors. To reduce the use of coal in electric-power generation, we argue that China would have to substitute renewable or nuclear energy.

Hydroelectricity provided China with 0.866 trillion KWh in 2012, 17.4 percent of all the electricity generated in the country. China has plans to expand hydroelectric power capacity from 249 gigawatts (GW) to 325 GW.²⁸ This additional capacity could generate 0.264 trillion KWh, equivalent to 5.3 percentage points of coal-fired power in 2012. Wind generated 0.102 trillion KWh of electricity in 2012. As of 2012, China had 61 GW in wind capacity connected to the grid. China has been rapidly expanding capacity, planning to have a total of 100 GW connected to the grid by 2015. This additional capacity could generate 0.064 trillion KWh, equivalent to 1.6 percentage points of coal-fired power in 2012. Solar power remains a marginal source of electricity, with only 3 GW installed as of 2012. However, the Chinese government plans to expand capacity to 35 GW by 2015.

Both wind and solar power are intermittent. Wind speeds fluctuate and sometimes fall off completely. Solar cells stop operating when the sun goes down and generate little power on cloudy days. Grid operators have had difficulty keeping electric power supplies on an even keel when the share provided by intermittent renewables becomes large. Based on industry discussions, the authors have adopted a rule of thumb that wind or solar power would need to be constrained to provide a maximum of 20 percent of China's power; above this threshold, difficulties arise in managing the grid. If China were to use wind to generate 0.996 trillion KWh (20 percent of the electricity China consumed in 2012), it would need to install an additional 540 GW of capacity to reach this goal, assuming that each additional GW of capacity generates similar levels of power as is currently the case. This is nearly nine times more than current installed capacity of wind and solar.

New nuclear power plants could also be constructed to provide electricity currently generated by coal. If hydro power were to provide an additional 0.264 trillion KWh and wind an additional 0.894 trillion KWh, that would mean that additional nuclear power plants would have to supply 0.658 trillion KWh, or 15.2 percent of China's electric power output as of 2012, to allow China

²⁸ EIA, 2014b.

to reduce coal-fired power by 39 percentage points. In 2012, 2.0 percent (0.098 trillion KWh) of China’s power consumption was generated by nuclear power. We estimate that in 2012, Chinese nuclear power plants achieved capacity utilization of 90 percent, slightly better than the United States, where nuclear power plants achieved an 86 percent capacity utilization rate in that year.²⁹ Assuming that China maintains its performance of 2012, China would need to build 84 GW of additional installed nuclear capacity, somewhat more than the current goal of an additional 58 GW by 2020.³⁰

Based on this discussion, Table 3.2 shows how China might substitute renewables and nuclear energy for 1.918 trillion KWh of electricity generated by coal-fired power plants. We note that these estimates are based on generation of electric power in 2012. Although increases in Chinese electricity consumption slowed dramatically in 2013 and 2014, the capacity expansion plans we have discussed are predicated on continued increases in demand. Those increases would need to be satisfied by capacity additions above and beyond those shown in Table 3.2.

Table 3.2: Replacing 1.9 Trillion KWh of Electricity Generated by Coal with Nuclear and Renewables

Fuel	Additional Capacity (GW)	Additional Output (trillion KWh)	Increase Over 2012 Output (%)
Hydro	76	0.264	31
Wind	540	0.894	890
Nuclear	84	0.758	769
Total	700	1.918	

SOURCES: RAND calculations using *China Statistical Yearbook*, 2013, Table 8-6; EIA, 2014b; and Li, 2014.

Installing Pollution-Control Equipment on Motor Vehicles and Scrapping Older Vehicles

Motor vehicles have been a rapidly increasing source of air pollution in China, especially emissions of nitrogen oxides. As already noted, China has been addressing this problem by adopting and enforcing the more stringent air pollution standards of the EU. Most motor vehicles sold in China are manufactured by joint ventures between international car companies and Chinese companies,³¹ which means domestic Chinese producers have access to the pollution-

²⁹ Chinese figure calculated from data on generating capacity and kilowatt hours generated by nuclear, *China Statistical Yearbook*, 2013; U.S. data are from EIA, *How Much Electricity Does a Typical Nuclear Power Plant Generate?* web page, updated December 2013b.

³⁰ EIA, 2014b. Note that the capacity additions posited only substitute for coal-fired power plants operating in 2012. They do not account for likely growth in Chinese demand for electricity, which will necessitate additional capacity.

³¹ Angelo Young, “China New Auto Sales 2013: Chinese Consumers Bought Over 20 Million Vehicles in 2013 as Foreign Automakers Jockey for Market Share,” *International Business Times*, January 7, 2014.

control technologies used by international manufacturers and there are no technological barriers to installing this equipment on motor vehicles. All Chinese cars are designed to be capable of meeting European emission standards. The most-stringent technologies are already available to China and installed in vehicles sold in Beijing and other cities where reducing pollution from automobiles has been made a priority.

These technologies operate effectively only when the fuel used meets stipulated standards. The National Development and Reform Commission has set strict specifications for lower-sulfur gasoline and diesel so that pollution-control technologies can function as designed. The European Union's Euro 4/IV standards for transportation fuels have been adopted for all of China for the end of 2014; and Euro 5/V standards have already been adopted for motor vehicle fuels sold in Shanghai and Beijing and are to be adopted for all of China by the end of 2017.³²

As shown by the sources of motor vehicles emissions in Figure 2.3, these measures will only lead to dramatic reductions in emissions if highly polluting vehicles are scrapped. The worst offending vehicles are marked by yellow license plates in China and are referred to as "yellow-tagged" vehicles. To dramatically reduce motor vehicle emissions, China will need to scrap all such vehicles—those that lack pollution-control equipment altogether or only have rudimentary equipment, such as China I category equipment. In 2012, there were 14,514,000 of these vehicles.³³ The Chinese government has already committed to scrapping 5,000,000 of them by 2015 and the rest by 2017.³⁴ As shown in Figure 2.5, scrapping motor vehicles that do not have any pollution-control equipment or only China I equipment would have eliminated 70 percent of carbon monoxide, 70 percent of volatile hydrocarbons, 61 percent of nitrogen oxides, and 76 percent of particulate matter emitted by automobiles in China in 2009.

³² EIA, "China", 2014b.

³³ Ministry of Environmental Protection, 2014.

³⁴ Ministry of Environmental Protection, 2014.

4. Costs of Reducing Air Pollution

We have noted that the cost of air pollution in China has been estimated at 6.5 percent of GDP. Applying that figure to China's GDP of \$8,227 trillion dollars in 2012, the year on which we base much of our analysis, implies that reducing air pollution in China to levels considered acceptable by WHO would yield annual benefits of \$535 billion. As incomes rise and China becomes more urbanized, these costs are rising. Although the actions we have outlined would probably not serve to attain levels considered acceptable by WHO, they would certainly result in substantial improvements in China's air quality; measures to halt the burning of coal and refuse by residential and commercial users in urban areas would be especially helpful.

Adopting these measures would make a substantial dent in the volume of coal consumed in China. Replacing coal used for residential and commercial use and about half of all coal used to generate electricity in 2012 would have resulted in a decline in coal use of 1.009 million metric tons, representing 27 percent of Chinese coal consumption that year. Valued at marginal cost (i.e., the cost of imported coal, which ran \$74 per metric ton in 2012), such a reduction in coal use would have resulted in \$75 billion less spent on coal that year.³⁵

We estimate the costs of three measures to reduce air pollution in China:

1. substituting natural gas or propane for coal for residential and commercial use
2. replacing coal with renewable and nuclear fuels to generate electricity
3. scrapping older vehicles.

Substituting Natural Gas or Propane for Coal for Residential and Commercial Use

Emissions from boilers and furnaces for heating apartment buildings and commercial establishments are a major source of Chinese urban air pollution. China could substantially improve this by substituting natural gas or propane for coal. In 2011, 114 million tons of coal were consumed for residential and commercial uses. To replace this coal, China would have had to use 88 billion cubic meters (7.84 trillion cubic feet) of natural gas or propane. In 2012, China paid, on average, \$360 per cubic meter (\$10.20 per cubic foot) of natural gas; prices spiked in 2013 because of increased demand in East Asia for LNG, pushing prices to \$587 per cubic meter (\$16.60 per cubic foot).³⁶ At average 2012 prices, the cost of an additional 221 billion cubic

³⁵ RAND calculations based on EIA, *Quarterly Coal Report, April-June 2014*, 2014c, Table 10.

³⁶ EIA, "China," May 2014b.

meters of natural gas would be \$80 billion; at the higher price, the cost would be \$130 billion. Table 4.1 shares these annual costs.

Table 4.1: Annual Costs of Policies to Reduce Air Pollution in China

Policy Measure	Quantity	Price (2012 \$)	Total Cost (in billions of 2012 \$)
Replacing coal for residential and commercial use with natural gas			
Average price of LNG in East Asia in 2012	88 billion cubic meters	360/cubic meter	32
Peak price of LNG in East Asia 2012	88 billion cubic meters	587/cubic meter	52
Replacing coal-fired electricity with other fuels			
Hydro	0.26 trillion KWh	90.30 per thousand KWh	24
Wind	0.89 trillion KWh	86.60 per thousand KWh	78
Nuclear	0.76 trillion KWh	108.40 per thousand KWh	82
Total			184
Gross total			
Low end (assumes lower price for natural gas)			215
High end (assumes higher price for natural gas)			235
Value of saved coal (million metric tons)	1,009	74	75
Net total annual direct costs			
Low end			140
High end			160

SOURCE: RAND calculations

Replacing Coal with Renewable and Nuclear Fuels to Generate Electricity

Drivers of the cost of electricity differ greatly depending on the source. For example, the cost of wind power is driven by the capital cost of installing wind turbines. The cost of natural gas-fired power plants is primarily driven by the cost of the natural gas. Nuclear power costs are driven by costs of construction; fuel costs are relatively modest.

To estimate the cost of replacing coal-fired power with the three sources of electricity discussed (water, wind and nuclear) we use the *levelized cost* of electricity for each type of power. By this, we mean the average cost of generating a KWh of electricity over the life of the facility; that is, when the capital costs of constructing the facility are averaged over the electricity generated over the lifetime of the plant. EIA periodically estimates the levelized costs of each of these sources of electricity.

We assumed that new hydroelectricity could replace 0.264 trillion KWh of coal-fired electricity, new wind could replace 0.895 trillion KWh, and new nuclear could replace

0.758 trillion KWh. EIA estimates that in 2012, new hydro cost \$90.30 per thousand KWh, onshore wind cost \$86.60, and advanced nuclear cost \$108.40.³⁷ Although costs in China might be somewhat different because of differences in wages and potentially more rapid permitting processes, we believe that similarities in costs warrant the use of these figures. China uses similar technologies, materials—and, in many cases, equipment—as U.S. companies in this field. In the wake of the Fukushima disaster in Japan, China is adopting similar inspection, permitting, and safety procedures as utilities that have built and operate reactors in the United States. Based on these cost estimates, using these sources of energy to generate the projected amounts of electricity would result in recurring annual costs in 2012 dollars of \$23.9 billion, \$77.5 billion, and \$82.2 billion, respectively.

Scrapping Older Vehicles

As was shown in Figure 2.4, vehicles with rudimentary or no pollution controls account for most emissions from motor vehicles. There were 14,514,000 of these “yellow-tagged” vehicles in China in 2012. Although the Chinese national government has already mandated that 5,000,000 of these vehicles be scrapped by 2015 and the rest by 2017, eliminating these vehicles immediately would result in substantial reductions in pollution. Most of these vehicles have been completely depreciated and have limited resale value. The city of Dongguan in Guangdong province has introduced a program to purchase and scrap these older vehicles. The maximum price provided by Dongguan is 9,000 renminbi (RMB) for cars and 18,000 RMB for trucks, about \$1,430 and \$2,860, respectively, in 2012 dollars. Multiplying the number of remaining “yellow-tagged” vehicles by these prices yields a total cost to China from \$21 billion to \$42 billion for scrapping these vehicles immediately, if the national government were to adopt Dongguan’s program for the entire country (Table 4.2). Note that in contrast to the costs of substituting natural gas or other fuels for coal, the costs of immediately scrapping “yellow-tagged” vehicles are one-off costs that would not be repeated.

Table 4.2: One-Off Costs of Scrapping Older Vehicles to Reduce Air Pollution in China

Scrapping older vehicles	Quantity	Price (2012 \$)	Total Cost (in billions of 2012 \$)
Assuming all older vehicles are cars	14.5 million	1,430	21
Assuming all older vehicles are trucks	14.5 million	2,860	42

SOURCE: RAND calculations

³⁷ EIA, “Levelized Cost of New Generation Resources in the Annual Energy Outlook 2013”, January 2013a.

Net Benefits

As shown in Tables 4.1 and 4.2, these measures would not be costless. Recurring annual costs could run from \$32 billion to \$52 billion for replacing coal with natural gas for residential and commercial heating, and \$184 billion for replacing half of China's coal-fired electric power generation with renewable or nuclear power—for total recurring costs ranging from \$215 billion to \$235 billion annually. Subtracting the value of the coal (\$75 billion) that would not be used, net annual costs in aggregate would run \$140 billion to \$160 billion.

These measures, all of which have already been partially implemented by national and city governments, should lead to substantial improvements in urban air quality. Concentrations of particulate matter, sulfur dioxide, and nitrogen oxides would be reduced by at least a quarter and probably much more, substantially reducing the annual costs of air pollution in China. Net economic benefits are likely to be large. The net annual costs of the first two measures are less than one-third the estimated costs of air pollution in China; roughly \$535 billion in 2012 (6.5 percent of China's GDP).

We do not delve into the proportional contributions to urban air pollution from residential and commercial burning of coal, coal used to generate electricity, or motor vehicles because, in addition to limitations stemming from availability of data, the primary causes of urban air pollution vary from city to city depending on climate, industrial structure, motor vehicle ownership, and topography. Despite these caveats, we argue that of the three policy initiatives discussed, the near-term priority should be substituting natural gas or propane for coal in residential and commercial use. Chen et al. have documented the detrimental effects of emissions from boilers and stoves fueled by coal, wood, or wastes on health and life expectancy in northern China.³⁸ Ending the use of these fuels in urban areas would go a long way toward reducing urban air pollution, especially in winter months.

The cost of this policy would primarily fall on urban residents, and, to a lesser extent, retail and other commercial establishments. However, these are precisely the individuals who suffer most from this air pollution. As in other countries, municipal subsidies for expansion of natural gas distribution networks or the purchase of new furnaces would alleviate some of these burdens. At \$32 billion to \$52 billion a year, the costs of this policy would run about \$50 to \$100 per capita for urban dwellers, or \$4 to \$9 per month. Although not inconsequential, such costs are manageable for most urban dwellers in China. Reductions in health costs (which could conceivably offset the cost of the policy) suggest this would be a very beneficial move from both economic and health perspectives.

We estimate the cost of replacing half of coal-fired power with water, wind, and nuclear power at \$184 billion. Replacing coal-fired power with other sources of energy is the most

³⁸ Chen, Ebenstein, et al., 2013.

expensive policy measure of the three we evaluate, and this measure would contribute most to reducing overall emissions of TSP and sulfur dioxide in China. However, its impact on urban air quality might not be as great as suggested by the expected decline in emissions. Most power plants in China are not located in urban areas. Although wind-borne air pollution from coal-fired power plants is a major factor in determining urban air quality in China, sources of air pollution within each city's limits have a more direct impact. Thus, we rank this policy measure as the second-highest priority, after ending the use of coal for residential and commercial purposes.

Costs of this policy would be borne more widely than the policy of ending coal use for residential and commercial activities. The cost of electricity would rise, cutting into the profitability of energy-intensive manufacturing, as well as increasing energy costs of all Chinese households.

Finally, motor vehicles are already on a path to improvement. China is well on the way to scrapping "yellow-tag" vehicles; more than a third of these vehicles that were on the road in 2012 are to be scrapped by the end of 2015 and all should be gone by the end of 2017. However, eliminating the worst-polluting cars and trucks as soon as possible would be beneficial. In cities such as Zhuhai where motor vehicles are a major source of air pollution, China may wish to implement limited buyback programs like the one in Dongguan to accelerate retirement of these vehicles. The program would be of relatively short duration, as the advantage of scrapping these vehicles disappears in 2017 when all these vehicles have to be retired.

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