HEI

Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China

GBD MAPS Working Group

EXECUTIVE SUMMARY

Health Effects Institute
Boston, MA

ABOUT HEI

The Health Effects Institute is a nonprofit corporation chartered in 1980 as an independent research organization to provide high-quality, impartial, and relevant science on the effects of air pollution on health. To accomplish its mission, the institute

- Identifies the highest-priority areas for health effects research;

- Competitively funds and oversees research projects;

- Provides intensive independent review of HEI-supported studies and related research;

- Integrates HEI's research results with those of other institutions into broader evaluations; and

- Communicates the results of HEI's research and analyses to public and private decision makers.

HEI typically receives balanced funding from the U.S. Environmental Protection Agency and the worldwide motor vehicle industry. Frequently, other public and private organizations in the United States and around the world also support major projects or research programs. GBD MAPS is funded by the William and Flora Hewlett Foundation and the Oak Foundation. HEI has funded more than 330 research projects in North America, Europe, Asia, and Latin America, the results of which have informed decisions regarding carbon monoxide, air toxics, nitrogen oxides, diesel exhaust, ozone, particulate matter, and other pollutants. These results have appeared in more than 260 comprehensive reports published by HEI, as well as in more than 1000 articles in the peer-reviewed literature.

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EXECUTIVE SUMMARY

Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China

WHAT THIS STUDY ADDS

- This report provides the first comprehensive assessment of the current and predicted burdens of disease attributable to coal-burning and other major sources of air pollution in China at the national and provincial levels.

- **Coal-burning was the most important contributor to ambient PM$_{2.5}$**, responsible for 40% of population-weighted PM$_{2.5}$ in China. Given the large impact of coal combustion on ambient PM$_{2.5}$ concentrations, coal combustion was an important contributor to disease burden in China, causing an estimated 366,000 deaths in 2013.

- **Industrial sources**, from both coal (155,000 deaths) and noncoal (95,000 deaths) emissions, **were the largest sectoral contributor to disease burden in China**, responsible for 27% of the mortality attributable to ambient PM$_{2.5}$ in 2013.

- **Household solid fuel combustion, of both coal and biomass, is also an important source of disease burden in China.** Domestic biomass and coal combustion were together the next greatest contributor to ambient PM$_{2.5}$-attributable mortality in 2013 — with a combined impact (177,000 deaths; 19% of the mortality attributable to ambient PM$_{2.5}$ in 2013) larger than that of industrial coal (155,000 deaths), transportation (137,000 deaths), or coal combustion in power plants (86,500 deaths).

- **Under four different energy efficiency and air pollution control scenarios, population-weighted mean exposure to PM$_{2.5}$ is projected to decrease significantly** (from 54 µg/m^3 in 2013 to 50, 38, 38, and 27 µg/m^3 in 2030 for BAU1, BAU2, PC1, and PC2, respectively).

- **Despite these air pollution reductions, the overall health burden is expected to increase by 2030** as the population ages and becomes more susceptible to diseases most closely linked to air pollution.

- **Even under the most stringent energy-use and pollution-control future scenario, coal will remain the single largest source contributor to ambient PM$_{2.5}$ and health burden in 2030.** This finding highlights the urgent need for even more aggressive strategies to reduce emissions from coal combustion along with reductions in emissions from other sectors, strategies that are beginning to be incorporated in the Thirteenth Five-Year Plan.

- **The GBD MAPS estimates suggest that emissions reductions in the industrial and domestic sectors should be prioritized for future energy and air quality management strategies.** Because domestic combustion also leads to a large disease burden due to household air pollution exposure, reductions in domestic biomass and coal emissions would be particularly beneficial to public health.

INTRODUCTION AND BACKGROUND[1]

The Global Burden of Diseases, Injuries, and Risk Factors Study 2013 (GBD 2013[2]) estimated that exposure to ambient fine particulate air pollution (PM$_{2.5}$[3]) contributed to 2.9 million premature deaths in 2013 with 64% of those deaths occurring in China, India, and other developing countries of Asia, and also with large burdens of disease in Eastern Europe[4]. The GBD is the largest and most comprehensive effort to date to measure epidemiological levels and trends worldwide (*http://www.healthdata.org/gbd*). It currently involves more than 1000 collaborators from 108 countries. GBD 2013 estimated the burden of disease attributable to 79 risk factors including ambient and household air pollution for 1990–2013 in 188 countries and at subnational levels for China, the United Kingdom, and Mexico (Forouzanfar et al. 2015).

Estimating and communicating the burden of disease attributable to air pollution from coal combustion and other major sources is a critical next step to support the control of *both* air pollution and climate-forcing emissions. The GBD analytic framework is uniquely suited to develop such estimates for coal-burning and other key emission sources, including for example, transportation, industrial, and domestic combustion, which all contribute to high levels of air pollution. The GBD allows estimates at subnational, national, regional, and global scales of both current burden due to past exposure and predictions of future burden based on projected trends in mortality and air pollution emissions and concentrations.

GBD MAPS (Global Burden of Disease from Major Air Pollution Sources) is designed to estimate the current and future burdens of disease attributable to ambient air pollution from coal-burning and other major PM$_{2.5}$ sources in China, India, and Eastern Europe using the GBD framework, and to disseminate the estimates to inform planned policy decisions in these locales. The ultimate objective is to apply the methods developed as part of this project to multiple air pollution sources on a global scale, and to integrate them into the GBD framework so that they can be updated on a regular basis to track progress. GBD MAPS is a multiyear collaboration between the Health Effects Institute (HEI), the Institute for Health Metrics and Evaluation, Tsinghua University, the University of British Columbia and other leading academic centers.

This report describes the objectives, methods, and results of the GBD MAPS analysis for China and its provinces. Subsequent reports will report on similar analyses for India and Eastern Europe.

HEI Review Process

A draft final version of this report was reviewed for accuracy, quality, and appropriateness of interpretation by three independent external reviewers selected by HEI for their expertise in air quality, atmospheric chemistry and modeling, and health effects. The external reviewers were Tong

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[2] A list of abbreviations and the citation of the full report appear at the end of this Executive Summary.

[3] Particulate matter ≤ 2.5 µm in aerodynamic diameter.

[4] Cohen A, Brauer M, Burnett R, Anderson HR, Estep K, Frostad J, et al. The Global Burden of Disease attributable to ambient air pollution: estimates of current burden and 23-year trends from the GBD 2013 study. Submitted.

Zhu (Peking University), Markus Amman (IIASA Institute), and John Evans (Harvard University). The draft was also reviewed by experts on the GBD MAPS Steering Committee. The Working Group prepared the final report in response to the comments received. The report's major findings were also presented at the American Association for the Advancement of Science in February 2016 and HEI Annual Conference in Denver in May 2016.

AIR POLLUTION EMISSIONS AND EFFECTS

Chinese air pollution levels have increased over the last two decades and are now among the highest in the world. Estimates from the GBD indicate that in 2013 the population-weighted mean concentration of $PM_{2.5}$ for China as a whole was 54 µg/m^3, with 99.6% of the population estimated to live in areas where the World Health Organization (WHO) Air Quality Guideline of 10 µg/m^3 was exceeded (Brauer et al. 2016). At the provincial level, population-weighted mean concentrations ranged from 6.4 µg/m^3 (Tibet) to 83.5 µg/m^3 (Henan) in 2013. (Executive Summary Figure 1). Population-weighted $PM_{2.5}$ concentrations in China increased by 38% from 1990 to 2013, with increases of over 40% in some provinces, such as Tianjin where levels increased by 45%.


Executive Summary Figure 1. 2013 Chinese provincial-level population-weighted PM$_{2.5}$ concentrations.

These concentration increases reflect large increases in emissions of $PM_{2.5}$ and its precursors. With regard to coal, China's consumption increased from 1055.2 million tons in 1990 to 3623 million tons in 2013. China is the world's largest producer and consumer of coal, accounting for nearly half of the total global coal consumption, and coal combustion is widely recognized as an important contributor to ambient air pollution in China. In response, the State Council established a medium- and long-term national coal cap targets in the Air Pollution Prevention and Control Action Plan in September 2013, which were reinforced in the new Air Pollution Prevention and Control Law that took effect on January 1, 2016. The State Council Air Pollution Action Plan set regional coal

consumption caps for key air pollution regions such as Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta, requiring them to reduce their coal consumption and achieve reductions in average $PM_{2.5}$ levels of 25%, 20%, and 15%, respectively, by 2017.

The health effects of exposure to particulate matter (PM) in ambient air are widespread and substantial, and they have been reviewed and summarized in detail (WHO 2005; U.S. Environmental Protection Agency [U.S. EPA] 2009). Long-term (months to years) exposure to $PM_{2.5}$ was determined by the U.S. EPA to be a cause of cardiovascular mortality, and adverse respiratory effects such as decreased lung function and development of asthma were likely to be causally linked to PM exposure. Further, the International Agency for Research on Cancer, concluded in 2014 that airborne PM was a cause of cancer in humans (Loomis et al. 2013). Chinese studies constitute an important and growing component of the international literature. In a comprehensive review published in 2010, HEI identified over 100 Chinese studies of the adverse effects of air pollution published as of 2007, including studies of mortality and morbidity from respiratory and cardiovascular disease due to short-term exposure to particles, lung cancer, and chronic respiratory disease (HEI 2010). Since then the Chinese epidemiologic literature on the adverse effects of air pollution has grown substantially, including new multicity studies of short-term exposure to air pollution and mortality and morbidity from cardiovascular and respiratory disease (Chen et al. 2012; Wong et al. 2008), and cohort studies of long-term exposure to air pollution and mortality (Cao et al. 2011; Zhou et al. 2014).

Of the 2.9 million premature deaths estimated globally in GBD 2013, 916,000 deaths took place in China. Cardiovascular disease, heart disease, and stroke account for the majority of these deaths, which have increased since 1990 (Executive Summary Figure 2) (Cohen et al. under review). In populated regions, a large fraction of $PM_{2.5}$ originates from combustion processes, and it includes both primary PM (direct emissions) and secondary PM (resulting from atmospheric transformations of gaseous precursors). Additionally the disease burden in China attributable to household air pollution from the combustion of solid fuels (e.g., coal, biomass) for cooking and heating is substantial, with an estimated 807,000 attributable deaths in 2013.
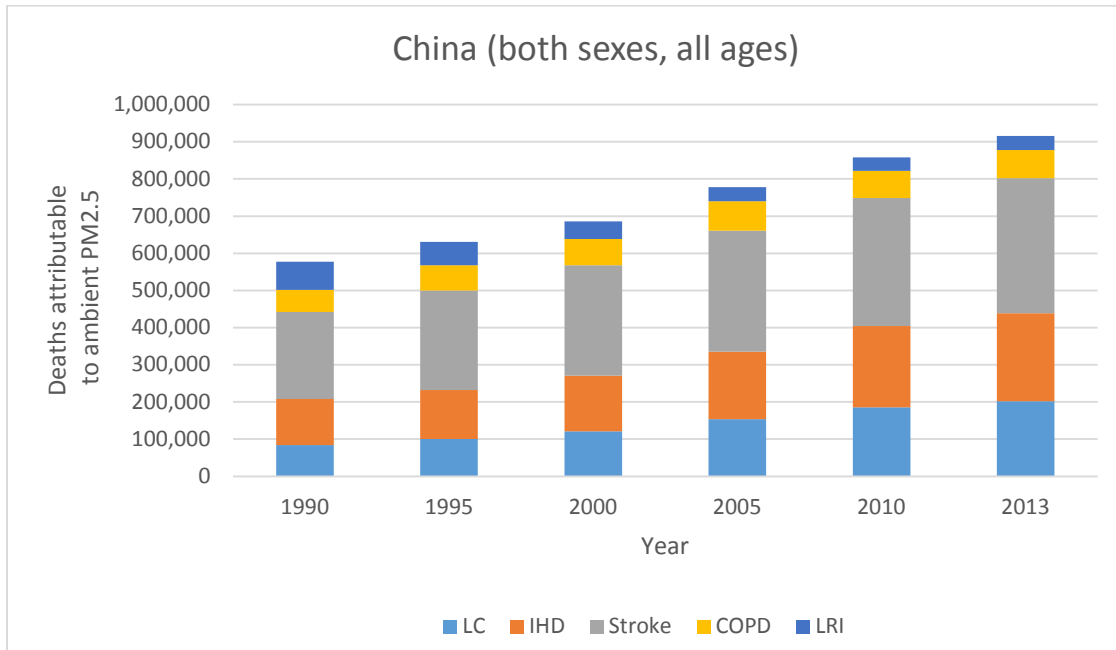

Executive Summary Figure 2. Deaths in China attributable to $PM_{2.5}$ 1990–2013 by year and cause. (LC = lung cancer, IHD = ischemic heart disease, COPD = chronic obstructive pulmonary disease, LRI = lower respiratory infection.)

ESTIMATING THE BURDEN OF DISEASE DUE TO COAL-BURNING AND OTHER MAJOR AIR POLLUTION SOURCES

The overall analytic approach in GBD MAPS has three main components: (Executive Summary Figure 3)

1. Estimate the fractional contributions to ambient $PM_{2.5}$ from coal-combustion and other major emissions sources using the chemical transport model GEOS-Chem for the year 2013 and for 2030 under four different scenarios of energy use and pollution control.

2. Combine these fractional contributions with high-resolution ambient $PM_{2.5}$ concentration estimates developed for the GBD to estimate the fractional contributions to population exposure.

3. Estimate source contributions to disease burden for China at the national and provincial levels by combining the estimates of coal combustion and other source-specific ambient $PM_{2.5}$ with (a) cause-specific disease burden estimates from the GBD, and (b) integrated exposure–response (IER) functions describing air pollution mortality risk estimates for heart and lung diseases.
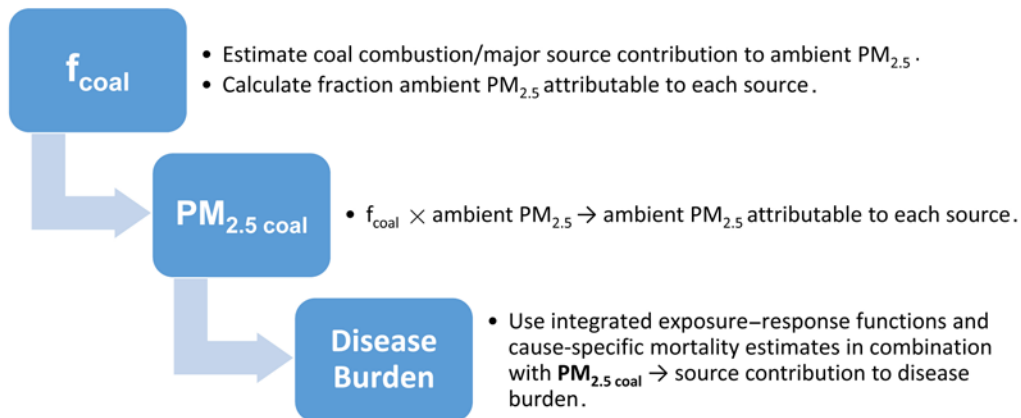
Executive Summary Figure 3. Schematic representation of GBD MAPS methodology for estimating the burden of disease attributable to coal-burning and other major sources for 2013 and for four scenarios for 2030.

Current Burden of Disease from Coal and Other Major Sources

The disease burden attributable to the contribution of coal combustion to ambient $PM_{2.5}$ in 2013 for China as a whole and for all provinces was estimated in a core analysis and in separate analyses for major sectoral contributions — specifically transportation, noncoal industrial, domestic biomass, open biofuel burning, and solvent use.

First, an emissions inventory of sulfur dioxide (SO_2), nitrogen oxides (NO_x), PM_{10}, $PM_{2.5}$, black carbon (BC), organic carbon (OC), nonmethane volatile organic compound (NMVOC), and ammonia (NH_3) was developed for China for the year 2013, based upon the model intercomparison study (MICS) Asia III emissions inventory for 2010 and updated to 2013. Emissions from each sector, stratified by province, were calculated from activity data (energy consumption, industrial products, solvent use, etc.), technology-based emission factors, and penetrations of control technologies. The activity data and technology distribution for each sector were derived based on

the Chinese statistics, a wide variety of Chinese technology reports, and an energy-demand modeling approach.

Simulations were conducted using the Goddard Earth Observing System chemical transport model GEOS-Chem (version v9-01-03) to estimate the coal-combustion (and other sector) contributions to current and future ambient $PM_{2.5}$. Standard simulations were first conducted using the emission inventories of the base year, 2013. For sensitivity simulations, the total coal-related emissions and sector-specific coal-related emissions were removed respectively from the inventory in each simulation. The global and nested grid model of GEOS-Chem was run in sequence using the new inventories. The simulation results therefore depict the ambient $PM_{2.5}$ concentrations with the coal-related emission sources shut off. The differences between the standard and sensitivity simulations are analyzed to produce contributions of the total coal combustion and coal combustion from each specific source to ambient $PM_{2.5}$ concentration. In this way, the complexity of atmospheric transformations and formation of $PM_{2.5}$ from precursors are accounted for in the analyses. Sensitivity simulations include model runs to estimate the contributions of total coal, power plant coal, industrial coal, and domestic coal emissions.

The spatially resolved fractional contributions of coal combustion and other sources estimated with GEOS-Chem simulations were then multiplied by the high-resolution ($0.1° \times 0.1°$) ambient $PM_{2.5}$ concentration estimates developed for GBD 2013. These estimates combine: (a) satellite-based estimates + GEOS-Chem, (b) TM5–FASST (Fast Scenario Screening Tool) chemical transport model simulations, and (c) available annual average PM measurements to estimate the amount of ambient $PM_{2.5}$ resulting from coal combustion. This approach explicitly incorporates the available Chinese surface measurements of $PM_{2.5}$ (in 2013) including approximately 80 $PM_{2.5}$ measurements as well as ~300 additional locations with PM_{10} measurements that were used to estimate $PM_{2.5}$ based on $PM_{2.5}$:PM_{10} ratios.

The spatially resolved estimated levels of coal combustion and other source-specific ambient $PM_{2.5}$ concentrations were then used with IER functions (which estimate the relative risk of $PM_{2.5}$ and adult ischemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer; and childhood and adult acute lower respiratory infections) to estimate sector contributions to disease burden for China as a whole and for each province.

Future Burden of Disease from Coal-Burning

Four different energy scenarios and air pollution control scenarios were developed that reflect different future emission pathways and incorporate changes in energy use and in emissions control (Executive Summary Table). These were used for analysis of mortality and disease burden projections in the year 2030. We estimated both coal and other major source contributions to ambient $PM_{2.5}$ and their associated disease burdens under each of the future scenarios for the year 2030 — considering both future mortality projections and future emissions scenarios.

Executive Summary Table. Definitions of Four Future Scenarios for 2030

Energy Policy	End-of-Pipe Emission Control Policy	
	[1] Twelfth Five-Year Plan for Environmental Protection	[2] Maximum Feasible Emission Controls Regardless of Cost
BAU: Current Legislation and Implementation Status as of end of 2012.	BAU[1]	BAU[2]
PC: Additional energy saving policies will be implemented, including life style changes, structural adjustments and energy efficiency improvements.	PC[1]	PC[2]

To estimate future (year 2030) mortality and disease burden for each of the four future scenarios, future population-weighted $PM_{2.5}$ concentrations and future mortality were estimated by scaling GBD 2013 estimates of exposure by the ratios of simulated ambient $PM_{2.5}$ in 2030 for each scenario with the simulated 2013 levels, and for mortality, according to observed temporal trends mortality rates and attributable fractions from 1990–2013, applied to 2030.

FINDINGS AND CONCLUSIONS

This report provides the first comprehensive assessment of the current and predicted burdens of disease attributable to coal-burning and other major sources in China at the national and provincial levels.

Coal-burning was the most important single source contributor to ambient $PM_{2.5}$, responsible for 40% of population-weighted $PM_{2.5}$ in China. In specific provinces (Chongqing, Guizhou, Sichuan) the contribution was nearly 50%. We compared our estimates with limited available source-apportionment analyses for three major Chinese cities and with model-based estimates in selected Chinese cities. Our estimates of the contribution of coal combustion to ambient $PM_{2.5}$ were remarkably similar to the source-apportionment study, although we estimated slightly higher contributions (3%–4%). Our estimates were somewhat lower than the model-based estimates.

Ambient $PM_{2.5}$ is a major contributor to mortality and disease burden in China, estimated to be responsible for 916,000 deaths in 2013, the 5th leading risk factor for mortality. Given the large impact of coal combustion on ambient $PM_{2.5}$ concentrations, coal combustion was an important contributor to disease burden in China, causing an estimated 366,000 deaths in 2013 (Executive Summary Figure 3). $PM_{2.5}$ from coal combustion specifically was the 12th leading risk factor for mortality in China in 2013 and accounted for more deaths than high cholesterol, drug use, or second-hand smoking.

Household solid fuel combustion, of both coal and biomass, is an important source of disease burden in China. Domestic biomass and coal combustion were together the next largest contributor to ambient $PM_{2.5}$ attributable mortality in 2013 — with a combined impact (177,000 deaths) larger than that of industrial coal (155,000 deaths), transportation (137,000 deaths), or coal combustion in power plants (86,500 deaths). Mortality attributable to ambient air pollution from domestic biomass combustion (136,000 deaths) was at the same level as that from industrial coal and transportation. Given the large contributions of domestic combustion to disease burden via household air pollution exposure and its important contribution to the burden attributable to ambient $PM_{2.5}$, reductions in domestic biomass and coal emissions would be expected to lead to large reductions in disease burden and should be prioritized for future energy and air quality management strategies.

Future Scenarios

Population-weighted mean exposure to PM$_{2.5}$ is projected to decrease under all scenarios (from 54 µg/m^3 in 2013 to 50, 38, 38, and 27 µg/m^3 in 2030 for BAU1, BAU2, PC1 and PC2, respectively) (Executive Summary Figure 4).
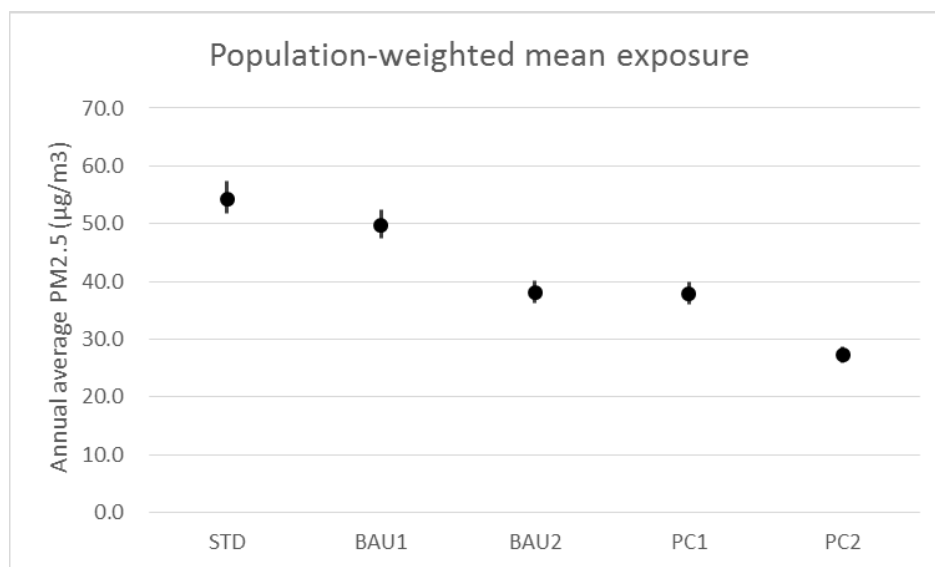

Executive Summary Figure 4. Population-weighted mean exposure to PM$_{2.5}$ under four future scenarios.

Despite reductions in PM$_{2.5}$ levels in all future scenarios, all of the future scenarios are predicted to lead to increases in future deaths attributable to ambient PM$_{2.5}$ with increases of 38%, 25%, 24%, and 8% for BAU1, BAU2, PC1, and PC2, respectively, compared to attributable mortality in 2013 (916,000). Specifically, ambient PM$_{2.5}$ was projected to be responsible for 1.3, 1.1, 1.1, and 0.99 million deaths in 2030, for the BAU1, BAU2, PC1, and PC2 scenarios, respectively.

The projected increase in mortality is due to the aging population and increased prevalence of ischemic heart disease, stroke, chronic obstructive pulmonary disease, and lung cancer, leading to increases in the number of deaths attributable to exposure to ambient PM$_{2.5}$ (Executive Summary Figure 5). These projections illustrate the importance of population dynamics in determining temporal trends in mortality attributable to ambient PM$_{2.5}$. GBD 2013 estimated increases in exposure, the numbers of deaths, and the death rate attributable to PM$_{2.5}$ between 1990 and 2013, but future projections predict increased attributable mortality, even with declining exposures.

Differences between 2013 and 2030 largely reflect the impact of population aging and changes in the prevalence of diseases affected by exposure to air pollution. Differences between the different 2030 scenarios reflect the impact of energy policies and pollution control.

Importantly however, if normalized for age and population size, death rates from air pollution exposure would be predicted to decrease in 2030 in all scenarios, with the greatest reductions for the most stringent scenarios. Strict control of PM levels is therefore critical to stabilizing or reducing burden in the face of changing demographics.
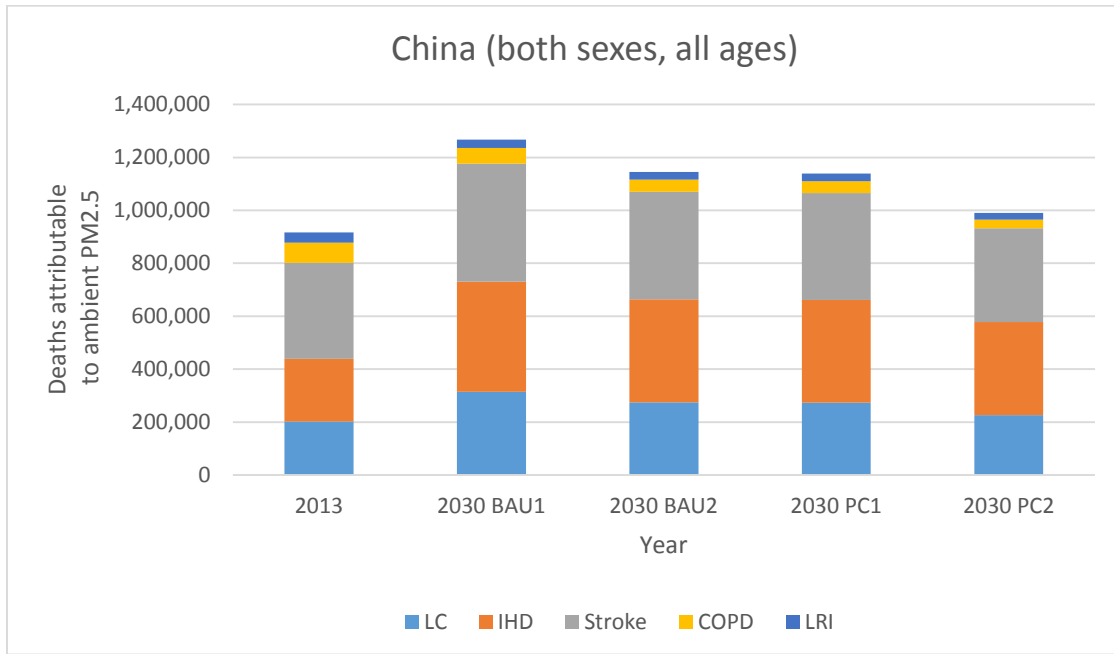
Executive Summary Figure 5. Deaths in China attributable to PM$_{2.5}$ 2013-2030 by year and cause. Deaths in 2030 are predicted under four scenarios of pollution reduction developed for GBD MAPS.

The importance of coal combustion as a contributor to deaths attributable to PM$_{2.5}$ is projected to increase under all future scenarios, such that coal combustion will remain the single largest source contributor to ambient PM$_{2.5}$ (Executive Summary Figure 6).
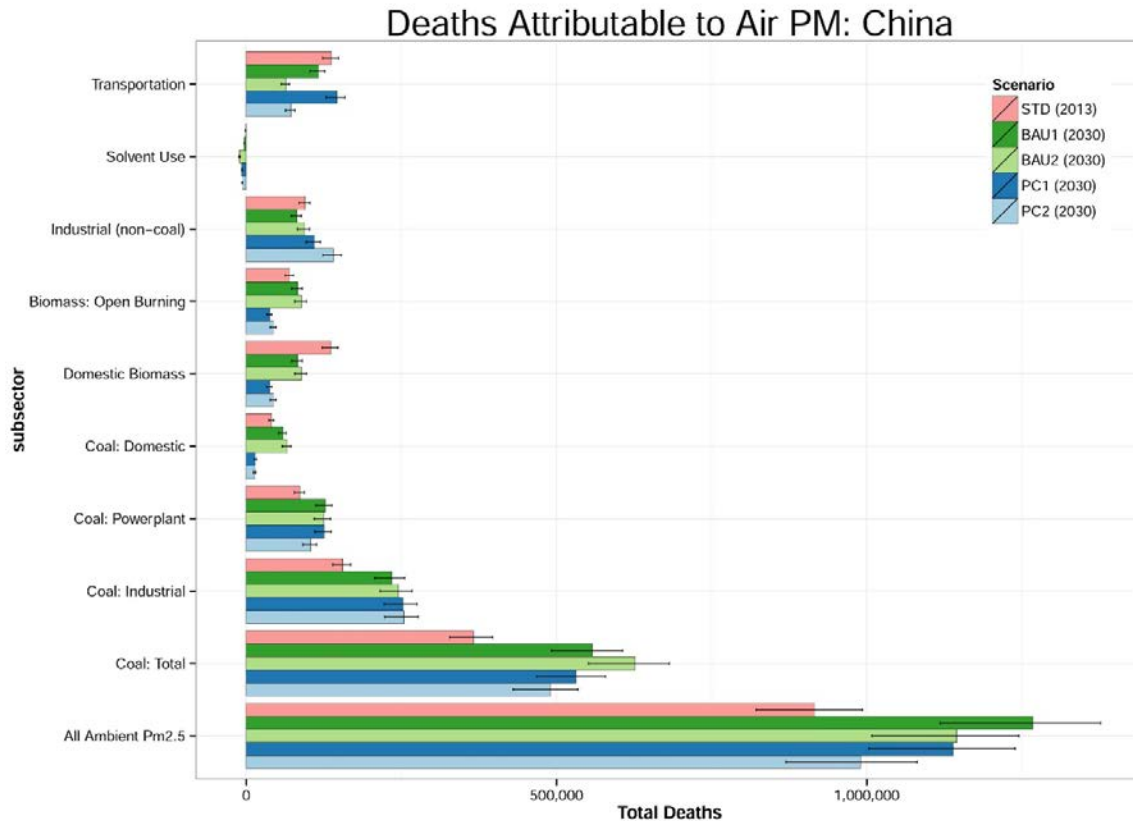
Executive Summary Figure 6. Deaths attributable to PM$_{2.5}$ from major air pollution sources in 2013 and in 2030 under four alternative scenarios.

Indeed, even under the most stringent energy use and pollution control future scenario, coal will remain the single largest source contributor to ambient $PM_{2.5}$ and health burden in 2030. Whereas coal combustion was responsible for 40% of the mortality attributable to $PM_{2.5}$ in 2013, it is estimated to contribute to 44%, 55%, 47%, and 49% for BAU1, BAU2, PC1, and PC2, respectively. Further, the reductions in ambient $PM_{2.5}$ attributable to coal are lower than the reductions projected for the other sectors, resulting in an expected increase in the relative contribution of coal combustion to attributable disease burden. This finding highlights the urgent need for even more aggressive strategies to reduce emissions from coal combustion along with reductions in emissions from other sectors, strategies which are beginning to be incorporated in the Thirteenth Five-Year Plan.

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ABBREVIATIONS AND OTHER TERMS

BAU	business as usual scenario
BC	black carbon
GBD MAPS	global burden of disease from major air pollution sources
GEOS-Chem	Goddard Earth Observing System global chemical transport model
HEI	Health Effects Institute
IER	integrated exposure–response
NH$_3$	ammonia
NMVOC	nonmethane volatile organic compound
NO$_x$	nitrogen oxides
OC	organic carbon
PC	(alternative) policy scenario
PM	particulate matter
PM$_{10}$	particulate matter ≤ 10 µm in aerodynamic diameter
PM$_{2.5}$	particulate matter ≤ 2.5 µm in aerodynamic diameter
SO$_2$	sulfur dioxide
U.S. EPA	U.S. Environmental Protection Agency
WHO	World Health Organization

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