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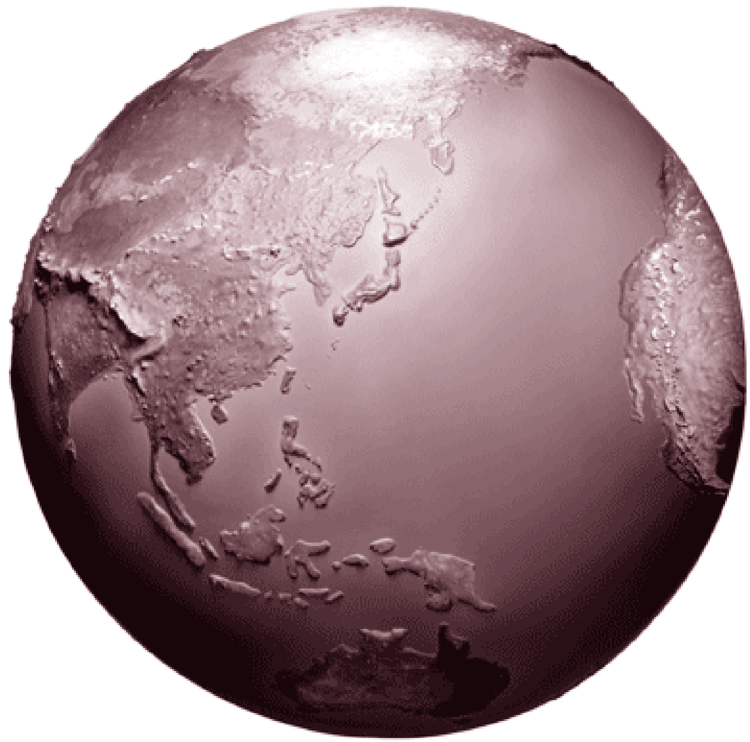

Household Air Pollution and Noncommunicable Disease

SUMMARY FOR POLICY MAKERS

Health Effects Institute

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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. This report was made possible by funding from Bloomberg Philanthropies. HEI has funded more than 340 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 1,000 articles in the peer-reviewed literature.

HEI's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization. For Communication 18 on which this summary is based, the draft final report was reviewed by independent external peer reviewers, who were selected by HEI for their expertise.

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SUMMARY FOR POLICY MAKERS

Household Air Pollution and Noncommunicable Disease

INTRODUCTION

Globally, millions of households — representing a third of the global population — continue to rely on burning solid fuels to meet their energy needs, including for cooking, heating, and lighting. Exposure to household air pollution (HAP*) in these homes ranges widely, with some studies reporting levels that exceed World Health Organization (WHO) Air Quality Guidelines by several orders of magnitude. Over the last several years, leading Global Burden of Disease (GBD) studies from the WHO and the Institute for Health Metrics and Evaluation (IHME) systematically reviewed the evidence examining associations between HAP and various health outcomes. Using a number of careful assumptions, these comparative risk assessments highlight HAP as a leading public health risk factor for noncommunicable diseases (NCDs). In many low- and middle-income countries in Asia and Africa where reliance on solid fuels is prevalent, HAP is also a key contributor to ambient air pollution and, therefore, to the public health burden more broadly on regional and national spatial scales.

In this summary based on HEI Communication 18, we present the main conclusions about exposures to household air pollution and about its contribution to noncommunicable diseases globally. Given the importance of understanding the strength of the scientific evidence linking HAP to NCDs to public health decisions, the report summarized here provides a synthesis of both previous reviews of the scientific literature and the most recently published studies of HAP and NCDs in low- and middle-income countries. More specifically, it offers a critical assessment of the state of the science for the effects of HAP on different types of NCDs, HAP burden-of-disease estimates, and health benefits of reduced exposures.

Highlights

- In 2016, a total of 2.5 billion people — a third of the global population — were exposed to household air pollution (HAP) from the use of solid fuels for cooking and heating. Most live in low- and middle-income countries in Asia and Africa.
- Exposures to particulate matter from HAP often exceed WHO ambient Air Quality Guidelines by orders of magnitude.
- ***HEI's latest synthesis:*** a growing number of epidemiological studies and systematic science reviews find that HAP exposures increase the risk of several noncommunicable diseases, including respiratory and cardiovascular diseases and lung cancer.
- Consequently, HAP contributes substantially to the global burden of disease, resulting in 2.6 million deaths and over 77 million years of healthy life lost (disability-adjusted life-years, or DALYs) in 2016. Seventy-six percent of the deaths and 60% of the DALYs resulted from noncommunicable diseases. Since HAP also contributes to ambient air pollution, populations relying on solid fuels face a *double burden* — from indoor as well as outdoor air pollution.
- The economic consequences of HAP-attributable health burden are substantial; the best available estimate from the World Bank suggests an annual global welfare loss in 2013 of about $1.5 trillion in 2011 U.S. dollars from HAP exposures alone.
- The effectiveness of interventions introducing improved solid fuel cookstoves to reduce HAP exposures and health burden has been mixed.
- ***Clean energy solutions are necessary to reduce disease burden substantially:*** HEI's Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project estimates that, in China and India alone, policies that shift to reliance on clean fuels could decrease the burden of disease from ambient air pollution attributable to residential burning of solid fuels by at least 30% and possibly by more than 95%, depending on the policy.

This Summary for Policy Makers is based on HEI's Communication 18, Household Air Pollution and Noncommunicable Disease, a report by the HEI Household Air Pollution Working Group.

This document was made possible by funding from Bloomberg Philanthropies. The final contents of this document have not been reviewed by private party institutions, including those that support the Health Effects Institute; therefore, it may not reflect the views or policies of these parties, and no endorsement by them should be inferred.

*A list of abbreviations appears at the end of this Summary.

THE EXPOSURE AND HEALTH EVIDENCE, AND ESTIMATES OF GLOBAL BURDEN OF DISEASE

Exposures to particulate matter from household air pollution often exceed levels in ambient air by orders of magnitude.

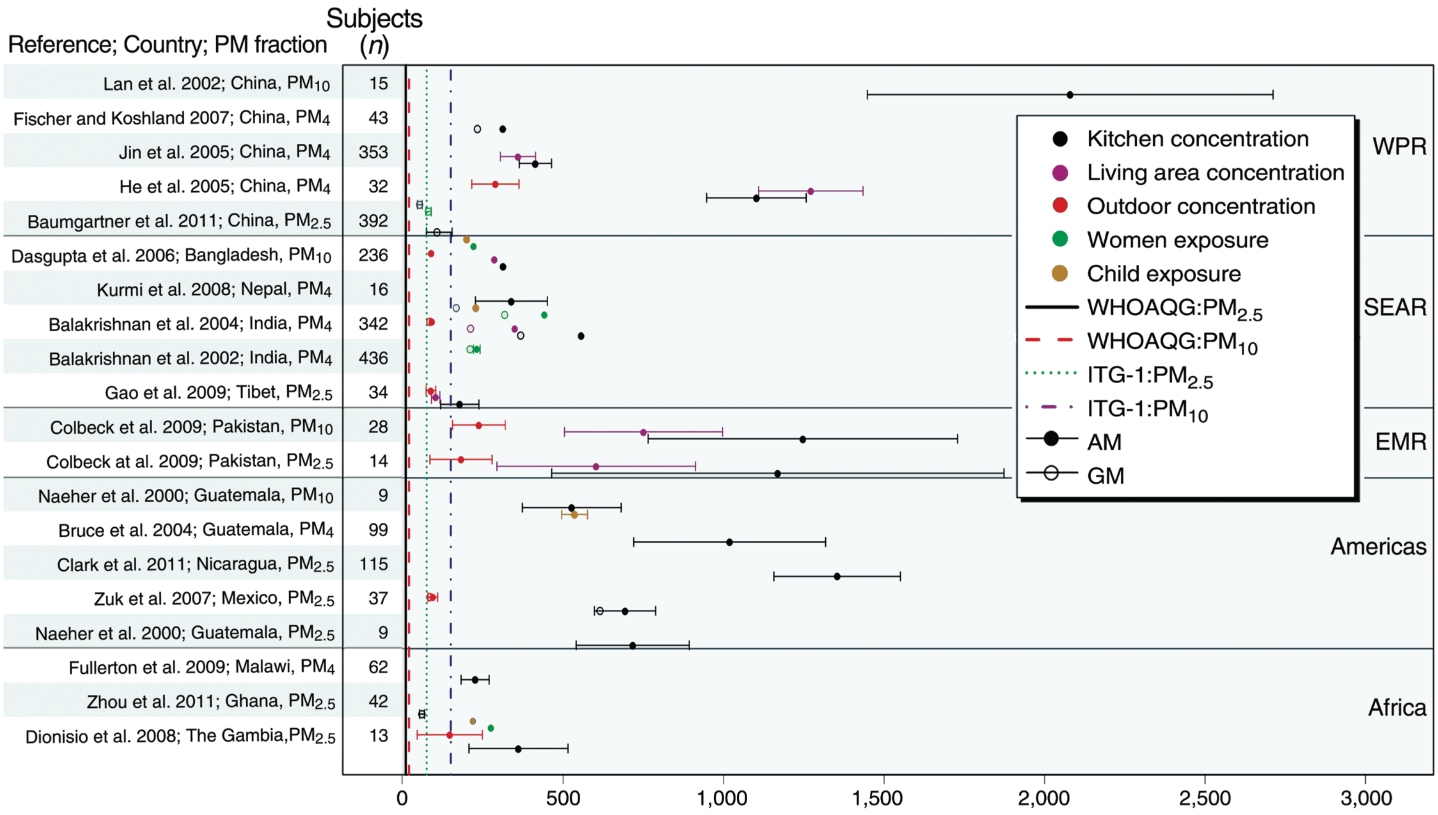
The concentrations of particulate matter in homes where solid fuels are burned often far exceed ambient levels of this pollutant as well as guideline levels for protecting health. This disparity is illustrated graphically in Summary Figure 1, which shows that the daily average particulate matter concentrations (μg/m^3) measured in various households often exceed WHO Air Quality Guideline and Interim Targets for annual average exposures by several orders of magnitude. These findings have been corroborated by a more recent study showing that average exposures to $PM_{2.5}$ (particulate matter $\leq$ 2.5 μm in aerodynamic diameter) were 220 μg/m^3 in the absence of interventions, a level approximately 6 times higher than the WHO Interim Target 1 of 35 μg/m^3 and over 20 times the WHO ambient Air Quality Guideline of 10 μg/m^3.

To date, widespread and systematic measurement of exposures to HAP has been limited. Many measurements rely on qualitative indicators of fuel use, which increases the challenge of characterizing quantitatively the relationships between the levels of HAP-related pollutants and health outcomes. Not surprisingly, systematic global measurements of household exposures to air pollution, which would enhance burden-of-disease estimates, do not exist. The IHME GBD project carefully models HAP population exposures based on estimates of the proportion of homes using solid fuels in each country (Summary Figure 2), the relationships between solid fuel use and HAP $PM_{2.5}$ indoor concentrations, and patterns of activity in homes.

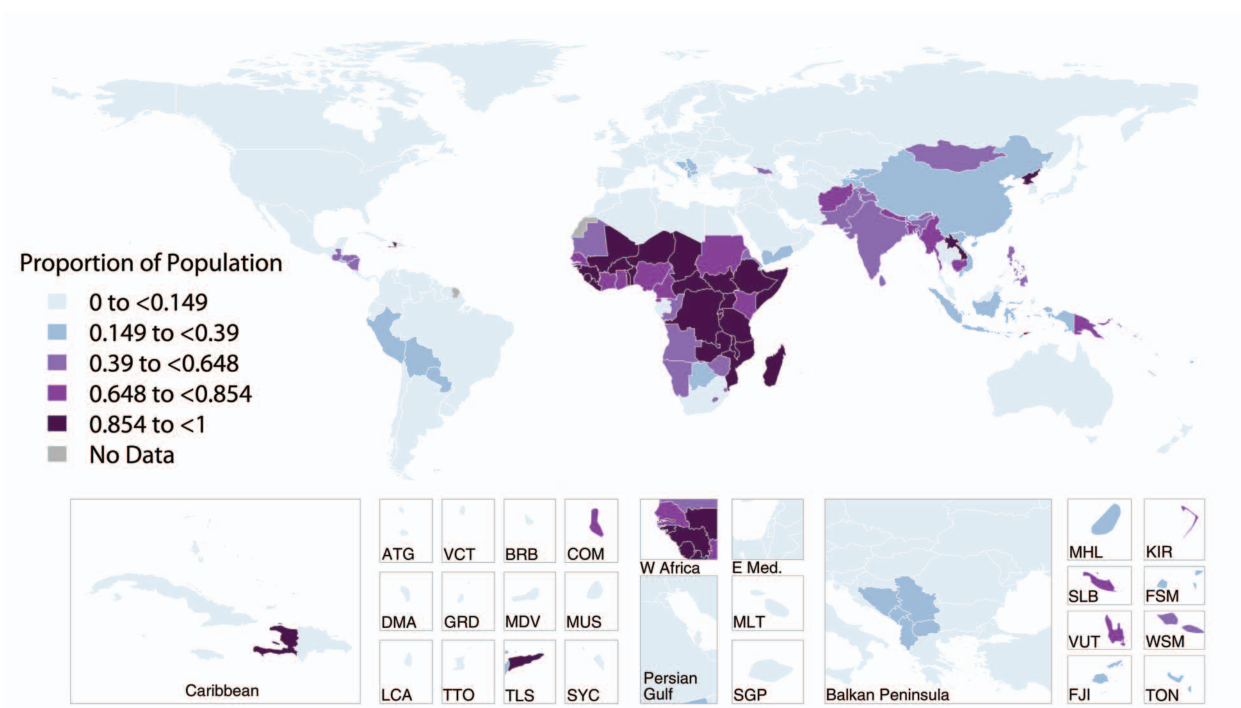
Many studies, including both epidemiological assessments and a number of careful systematic reviews and meta-analyses, have found evidence associating HAP exposures with several adverse health outcomes, broadly categorized as noncommunicable diseases.

The high household exposures to particulate matter experienced by populations burning solid fuels have been the subject of numerous studies designed to characterize the risk of disease. Particular focus has been given to NCDs that are leading causes of death and disability worldwide and that have long been associated with other particulate matter exposures in ambient air or directly inhaled or secondhand tobbaco smoke. These include chronic obstructive pulmonary disease (COPD); lung cancer; and cardiovascular disease. Cataracts and adverse pregnancy and birth outcomes as well as neurological outcomes are also of concern. The strength of the scientific evidence base varies by health outcome.

- *Chronic obstructive pulmonary disease:* COPD is a lung disease characterized by chronic obstruction of lung airflow that interferes with normal breathing and that is not fully reversible; it is the 3rd leading cause of death globally. Systematic reviews of the literature by the WHO and the American Thoracic Society have concluded that HAP exposure is likely to cause COPD and related respiratory conditions, particularly in women. These findings are also broadly supported by large population-based studies showing that exposures to lower levels of ambient particulate matter, as well as high levels of exposure to tobacco smoke, are associated with increased risks of COPD. The systematic reviews of HAP exposures have, however, reported significant variation among the sizes of the effect estimates and some evidence of publication bias favoring positive results. Evidence on the association of HAP with COPD is continuing to emerge from the large multicountry Burden of Obstructive Lung Disease (BOLD) study, one of the largest studies to use high-quality measures to diagnose COPD in association with use of solid fuel for cooking and heating in the home. Some analyses have been supportive of an effect of household fuel use on COPD, particularly in women, but evidence on related outcomes has been less conclusive.
- *Lung cancer:* The International Agency for Research on Cancer (IARC) has classified indoor burning of coal as a known human carcinogen (IARC Group 1) and indoor burning of biomass as a probable human carcinogen (IARC Group 2A). Recent research has strengthened the evidence for a link between lung cancer and biomass cooking smoke, in part by more careful efforts to rule out the role of active smoking. Studies that either statistically account for smoking status or restrict their analyses to subjects that have never smoked have reported associations between HAP from biomass and lung cancer, including some evidence that the risk of cancer increases with exposure to HAP.
- *Cardiovascular disease*: Cardiovascular disease, which comprises ischemic heart disease, stroke, and related diseases, is the leading cause of death globally according to the IHME GBD study. Much of the evidence linking HAP to cardiovascular disease comes from studies of ambient air pollution, secondhand smoke, and cigarette smoking showing that exposures to particles similar to HAP are important causes of cardiovascular disease; direct evidence from HAP studies is still limited. A recent study conducted in a cohort of over 50,000 adults in rural Iran provides the clearest evidence to date of an association between cardiovascular disease burden and exposure to some sources of HAP. It was the first study to directly link cardiovascular mortality to household energy, though the relationship was limited to fossil fuels (kerosene and diesel). However, strong evidence has recently emerged from a large prospective study in China showing increased risk of cardiovascular mortality associated with solid fuel use for both heating and cooking and reduced risks among those who switched to cleaner fuels or used vented cookstoves. A growing number of studies that link HAP exposure to increased blood pressure, a known risk factor for cardiovascular disease, also provide indirect evidence of cardiovascular risk.
- *Cataracts:* Growing evidence links exposure to HAP with cataracts. A WHO review in 2014 concluded that the evidence then available made a reasonable case that HAP exposure could be causally linked to cataracts despite lacking experimental evidence. This conclusion is now further supported by a major population-based study in India finding a strong relationship between nuclear cataracts and both biomass fuel and kerosene use among women. However, the



Summary Figure 1. Summary of global HAP measurements showing both high concentrations and wide variation among studies and locations. Taken from selected studies included in the WHO Global Household Air Pollution Measurement database (*www.who.int/indoorair/health_impacts/databases_iap/en/*). Abbreviations: AM = arithmetic mean; EMR = Eastern Mediterranean Region; GM = geometric mean; ITG-1 = Interim Target Guideline-1; $PM_{2.5}$ = particulate matter ≤ 2.5 µm in aerodynamic diameter; PM_4 = particulate matter ≤ 4 µm in aerodynamic diameter; PM_{10} = particulate matter ≤10 µm in aerodynamic diameter; SEAR = Southeast Asian Region; WHO AQG = World Health Organization Air Quality Guideline; WPR = Western Pacific Region. Source: Clark et al. 2013.



Summary Figure 2. Proportion of global population exposed to household pollution using solid fuels in 2016. Data source: IHME.

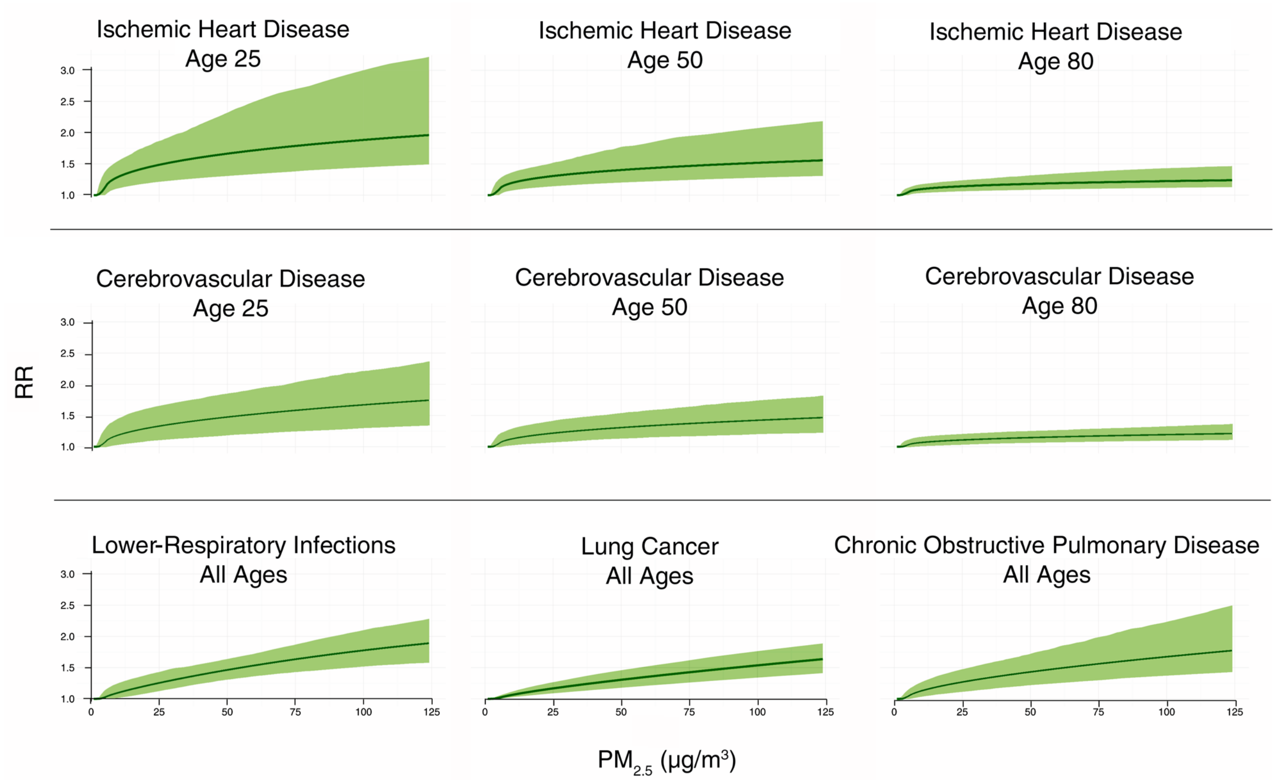
potential contributions by other risk factors for cataracts in these studies merit further exploration, including diabetes and ultraviolet light exposure.

- *Emerging evidence for other outcomes:* Additional evidence suggests associations between HAP exposure and adverse pregnancy and birth outcomes, including stillbirth and low birth weight, but only a limited number of studies have examined these relationships. More evidence indicating associations with combustion particles comes from studies of ambient air pollution, albeit at much lower exposure levels and mostly in developed countries. Evidence for associations of HAP with neurological and cognitive conditions and with diabetes is currently limited, although evidence for associations of these outcomes with exposure to lower levels of ambient air pollution is growing.

To bridge gaps in scientific understanding of the effects of HAP exposure on mortality and disease, scientists have relied on recent advances integrating evidence from studies of exposure to a range of complex mixtures of inhaled fine particles: ambient air pollution, HAP, environmental tobacco smoke, and cigarette smoke.

Despite the high $PM_{2.5}$ concentrations observed in homes due to HAP, important gaps in the evidence from long-term studies linking exposure to HAP and chronic disease and mortality remain. At the same time, similar complex particle mixtures — from both lower particulate exposures from ambient air pollution and higher exposures from smoking — have been associated with these same diseases. This evidence, developed over decades, has enabled scientists to quantitatively describe the relationship between a wide range of $PM_{2.5}$ exposures, including those related to household air pollution and smoking, and the risks from specific disease. The mathematical functions that describe these relationships are known as *integrated exposure–response (IER) curves* and enable a conceptually consistent approach for estimating and comparing the global burden of disease from different types of particulate matter exposures, including HAP. The integrated exposure–response curve showing the change in relative risk with increasing exposure for ischemic heart disease, cerebrovascular disease (stroke), lower-respiratory infection (pneumonia), lung cancer, and COPD can be found in Summary Figure 3.

Two features of this relationship are worth noting given their implications for the efforts to study and to achieve reductions in the risks associated with HAP exposures. One is the uncertainty bounds, which reflect uncertainty not only in the relative risk for any given exposure but also in the shape of the exposure–response curve. The second is that the exposure–response relationships between $PM_{2.5}$ exposure and cardiovascular health outcomes (ischemic heart disease and cerebrovascular disease) are estimated to be nonlinear. That is, the curves rise more steeply at lower concentrations, and then flatten out at higher concentrations. The curves for respiratory disease and lung cancer are more linear. The nonlinearities imply that major reductions in exposure — approaching levels near the WHO Air Quality Guideline of 10 μg/m^3 — would be needed to substantially reduce relative risks.



Summary Figure 3. Integrated exposure–response functions for ischemic heart disease, cerebrovascular disease, lower-respiratory infection, lung cancer, and chronic obstructive pulmonary disease. Curve shows the relationship between annual average ambient pollution and the central risk estimate (solid line) and 95% uncertainty intervals (shaded areas). Cohen et al. 2017. License: Creative Commons Attribution CC BY 4.0.

Summary Figure 4. Portion of HAP global burden of disease in 2016 from communicable and noncommunicable diseases, estimated by IHME. Source: IHME 2017.

Using the relationships described by the $PM_{2.5}$ IER curves, GBD studies estimate that HAP contributes substantially to the global burden of disease, resulting in 2.6 million deaths and over 77 million years of healthy life lost (DALYs) in 2016. Seventy-six percent of the deaths and 60% of the DALYs resulted from NCDs.

The burden of disease is measured most often in terms of the number of deaths or in the years of healthy life lost (specifically, disability-adjusted life-years, or DALYs) that are attributable to different classes of disease. Noncommunicable diseases account for much of the burden of disease attributable to all risk factors, and HAP, as an individual risk factor, is no exception. For 2016, the IHME Global Burden of Disease project estimated that, of the total global burden of disease attributable to exposure to HAP, NCDs accounted for approximately 76% of deaths and 60% of DALYs, with the remainder of the burden attributable to communicable diseases such as respiratory infections (Summary Figure 4). Globally, HAP ranked eighth among all risk factors; the burden for NCDs is largest in South Asia and sub-Saharan Africa, where HAP ranked sixth and fourth, respectively, among all risk factors contributing to NCD deaths. While the percentage of homes using solid fuels for cooking has generally declined in most countries since 1990, the estimated total burden of disease from HAP has remained relatively constant, driven primarily by population growth and aging.

Household air pollution is also a major contributor to outdoor air pollution exposures and, by extension, to its disease burden. Most of this disease burden is also associated with NCDs.

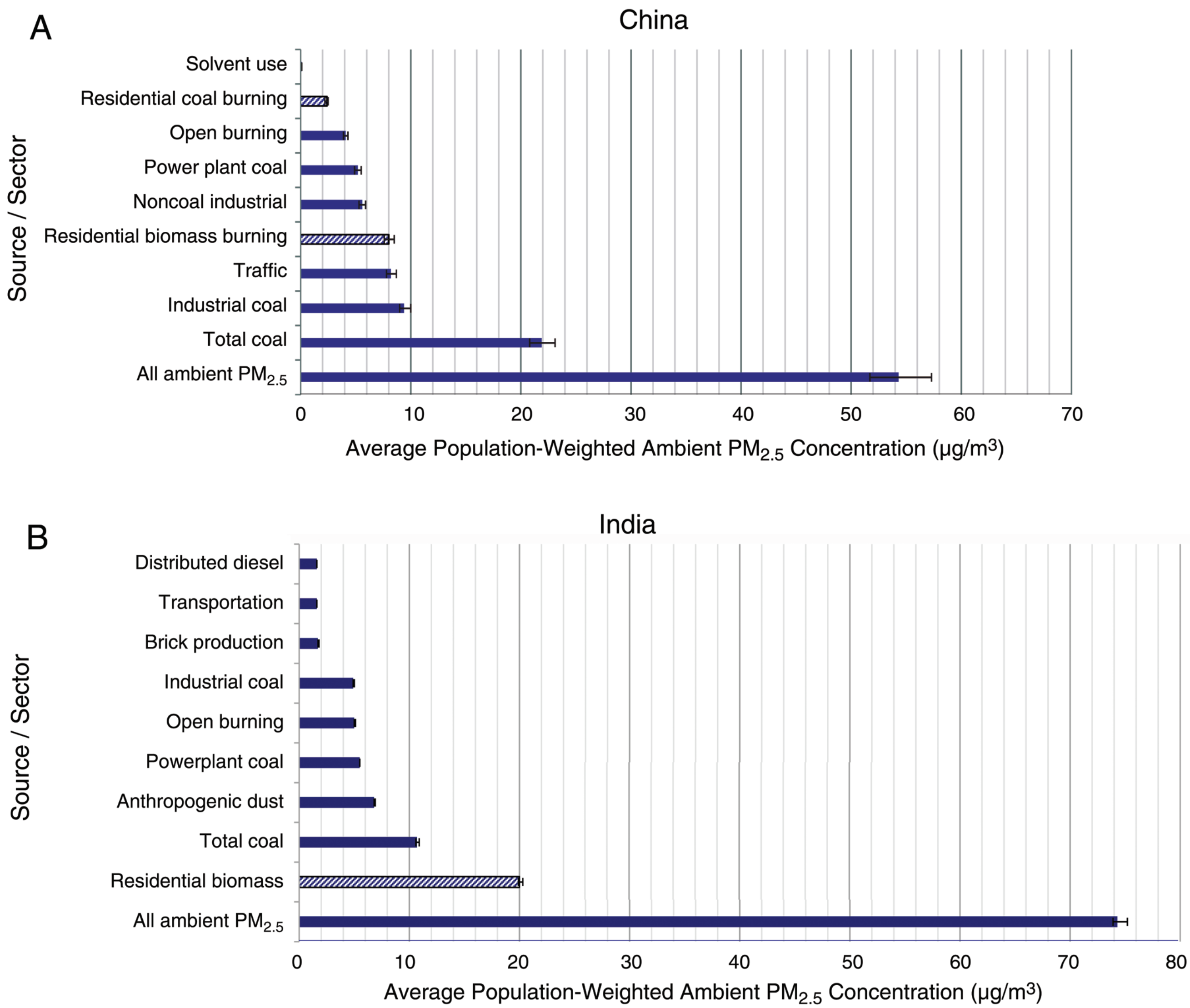
Two recent country-level analyses of the major sources of air pollution in China and in India have demonstrated that household burning of solid fuels is a major source of ambient air pollution in each country. Household air pollution's contributions to ambient air pollution exposures translate into equivalent contributions to the public health burden in both countries. In China, of the total 916,000 deaths attributable to $PM_{2.5}$ in 2013, about 19% of deaths (or about 177,000) were attributable to household burning of biomass and coal, which was more than from industrial or power plant combustion of coal (see Summary Figure 5A). Similarly, in India, of the total 1,090,400 deaths attributable to $PM_{2.5}$ in 2015, 24.5% (267,700) was attributable to household burning of biomass (see Summary Figure 5B). The percentage contributions of HAP to years of healthy life lost were comparable. The populations relying on solid fuels for cooking and heating in these and other countries, therefore, bear a "double burden" from exposure to both indoor and outdoor air pollution (HEI 2018).

The combined global burden of HAP has not been estimated, neither through exposures in the home nor from its specific contributions to outdoor air. However, the IHME GBD project does estimate the collective impact on global health from exposure to both ambient air pollution (both $PM_{2.5}$ and ozone) and HAP, assuming that the exposures are independent and to some degree additive. In 2016, the GBD project estimated that ambient and household air pollution collectively account for nearly 6.1 million deaths, a figure that has changed little over the last 25 years.

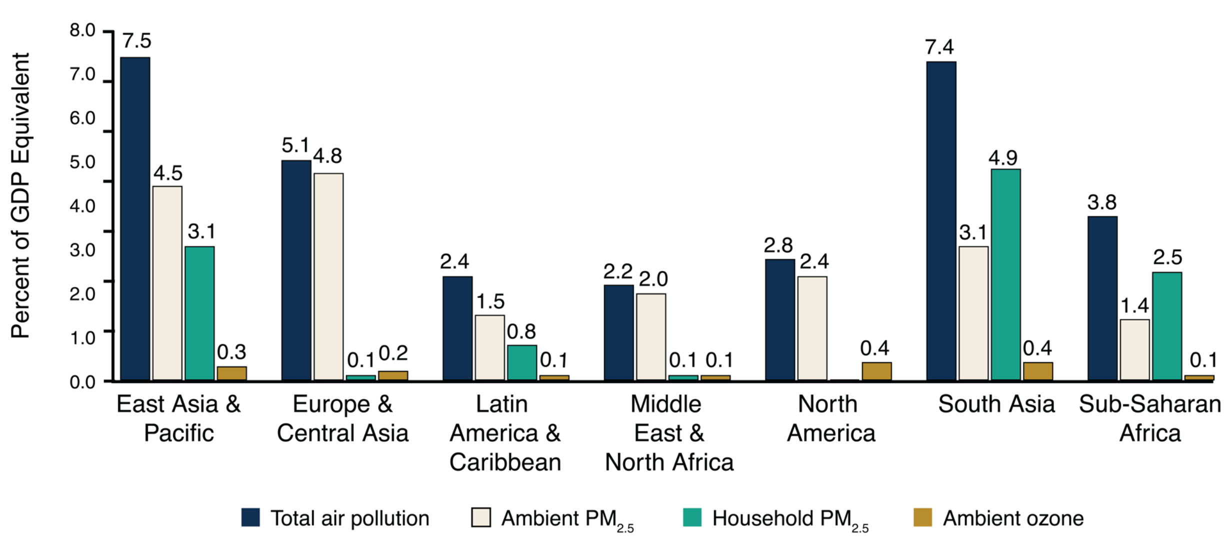
Globally, ambient air pollution and household air pollution are the leading environmental risk factors for premature mortality and years of healthy life lost. When their impacts were combined in the IHME GBD 2016 study and compared with all other risk factors, they were shown to be the fourth leading risk factor globally. Again, NCDs accounted for most of this public health burden.

The economic consequences of HAP-attributable health burden are substantial; the best available estimate suggests an annual global welfare loss in 2013 of about $1.5 trillion in 2011 dollars.

In 2016 the World Bank and IHME estimated the economic cost of the burden of disease from HAP and ambient air pollution using two methods: a welfare-based approach that builds on a standard estimate of willingness-to-pay and value of a statistical life, and a lost-labor approach that estimates the expected loss of income experienced by those who die prematurely. The World Bank–IHME effort focused on mortality, given that regulatory impact analyses in the United States have consistently found that avoided mortality dominates the economic benefits of air pollution reduction. Welfare losses as a percentage of gross domestic product (GDP) attributable to HAP, as well as to ambient $PM_{2.5}$ and ozone, are summarized for seven world regions in Summary Figure 6. The results of these analyses show strong regional differences in the economic burden attributable to HAP, with the largest burdens borne by countries in South Asia, East Asia and the Pacific, and sub-Saharan Africa. Although not



Summary Figure 5. Contribution to $PM_{2.5}$ exposure attributable to different sources: A. China 2013; **B.** India 2015. Source: GBD MAPS Working Group 2018.



Summary Figure 6. Welfare losses from air pollution exposure. Total air pollution damages include ambient $PM_{2.5}$, household $PM_{2.5}$, and ozone. GDP = gross domestic product. Source: World Bank and IHME. License: Creative Commons Attribution CC BY 3.0 IGO.

estimated for this study, HAP's economic impact is likely even greater because of its additional contribution to ambient air pollution, which was not estimated separately in this study.

EVIDENCE FROM STOVE AND FUEL INTERVENTIONS TO REDUCE EXPOSURE AND BURDEN

The effectiveness of interventions introducing improved solid fuel cookstoves to reduce HAP exposures has been mixed; few interventions reduce levels enough to meet WHO Air Quality Guidelines.

Substantial resources devoted to providing communities with cleaner cookstoves have met with mixed success. A recent systematic review evaluated 42 studies that were designed to quantify reductions in HAP concentrations in kitchens and in personal HAP exposures attributable to cookstove interventions. These interventions ranged from low-cost rocket stoves to clean fuels (liquefied petroleum gas [LPG], ethanol, and electricity). The authors included only those studies that assessed cookstove effectiveness in real-life use situations and that used valid exposure assessment techniques. Most interventions — particularly interventions using clean fuels — reduced HAP levels by large percentages, ranging from a reduction of 41% in $PM_{2.5}$ kitchen concentrations for advanced combustion biomass cookstoves to 83% for ethanol-fueled cookstoves. Given the high initial concentrations in these homes, however, these reductions generally failed to bring concentrations close to the WHO Air Quality Guidelines or even to the lower WHO Interim Target 1 for annual $PM_{2.5}$ (35 $\mu g/m^3$). Only three studies have quantified kitchen concentration reductions from specific efforts to introduce the most promising clean fuels — LPG and ethanol — and no studies have yet reported changes in personal exposures resulting from clean fuels interventions.

Why have cookstove interventions largely failed to deliver the exposure reductions that would be necessary to achieve the health benefits implicit in the GBD estimates?

Three factors may help explain:

- *Low levels of adoption and sustained use.* Many cookstove programs have failed because households decline to adopt the intervention technology, or because they abandon use shortly after adoption.
- *Stove stacking.* Even if households use clean stoves consistently, they may continue to use polluting solid-fuel cookstoves for some cooking tasks.
- *Community-level exposures.* Neighborhood sources of pollution (including both nearby households that continue to use solid fuels and other combustion sources such as rubbish and agricultural burning) may result in exposure levels that exceed WHO Air Quality Guidelines and interim targets.

Weaknesses in current studies point the way for future studies, which are necessary to increase confidence in the epidemiological evidence.

While these results from well-designed studies of interventions are disappointing, they should not undermine efforts to promote transitions to clean cooking. Rather, they suggest that rigorous evaluation and adaptive management of these efforts are critical. At the same time, high-quality study designs that undertake state-of-the-art exposure assessment, focus on key outcomes like cardiovascular disease and COPD, and minimize the role of potential confounders are necessary to strengthen the evidence base linking HAP exposure with NCDs. These include well-designed long-term observational studies, randomized control trials, and case–control studies. While strong evidence supports associations of cardiovascular disease with ambient particulate matter and cigarette smoking, new studies are only beginning to observe these relationships for HAP exposures specifically. Additional research is also needed to strengthen the evidence base for understanding the associations between HAP and respiratory diseases (e.g., COPD), cancers other than lung cancer, cataracts and other eye diseases in populations other than women in South Asia, and a range of other adverse health outcomes.

Notwithstanding the significant limitations in the current evidence from interventions, the finding of the potential for exposure reductions in a number of studies suggests substantial opportunities for reducing exposure and improving public health if the challenges to full-scale adoption of cleaner fuels and energy sources can be overcome.

Ultimately, household decisions to use cleaner stoves and fuels are driven by economics, customs, and other societal factors that differ across populations and are often poorly understood. Finding effective approaches to reduce real-world exposures thus remains a major challenge, especially in areas with limited access to modern fuels and/or electricity, but a challenge that — if overcome — promises substantial opportunity.

OPPORTUNITIES

HEI's Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) project estimates that, in China and India alone, policies that shift to reliance on clean fuels could decrease the burden of disease from ambient air pollution attributable to residential burning of solid fuels by at least 30% and possibly by more than 95%, depending on the policy.

Two recent analyses of the major sources of air pollution in China and India have projected the potential benefits of reducing reliance on solid fuels (biomass and coal in China, and biomass in India) for household energy use. Both studies evaluated the outdoor air quality and estimated the health impacts of major sources under baseline conditions and under the assumptions of increasingly stringent policy scenarios that were aimed at reducing exposures. These estimates did not include the health burden attributable to exposures within the home resulting from household burning of solid fuels.

Summary Table 1. Reductions in Health Impacts from Ambient Air Pollution Attributable to Residential Burning of Biomass and Coal in China by Scenario and Year

	2013 Baseline	2030 BAU	2030 Alternative PC	Burden Reduction PC−BAU (%)
Deaths	177,490	142,540	52,850	−89,690 (63)
DALYs	3,563,502	2,353,050	888,250	−1,464,800 (62)

BAU = business-as-usual scenario; PC = policy-control scenario.

Summary Table 2. Reductions in Health Impacts from Ambient Air Pollution Attributable to Residential Burning of Biomass in India by Scenario and Year

	2015	2050	2050	2050	Burden Reduction	
	Baseline	REF	S2	S3	S2−REF (%)	S3−REF (%)
Deaths	267,700	526,400	366,800	19,300	−159,600 (30)	−507,100 (96)
DALYs	7,373,200	10,696,300	7,450,000	391,400	−3,246,300 (30)	−10,304,900 (96)

REF = reference scenario; S2 = ambitious scenario; S3 = aspirational scenario.

As indicated earlier, in China, residential burning of both biomass and coal was one of the largest contributors to ambient $PM_{2.5}$-attributable mortality in 2013— with a combined impact (about 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). In India, where reliance on residential burning of biomass was more prevalent, the estimated number of deaths attributable to ambient air quality was greater — 267,700 deaths in 2015. Again, of the several major sources evaluated in India, residential biomass burning was the largest contributor to mortality attributable to ambient air pollution, accounting for 24% of the deaths.

In China, two sets of energy policy scenarios for controlling emissions and ambient exposures to all sources were evaluated for the year 2030 in the GBD MAPS project. The *business-as-usual scenario* was based on then current legislation and implementation status, including existing energy uses, but it also assumed gradual penetration of low-sulfur coal, replacement with advanced coal stoves and advanced biomass stoves (e.g., better combustion conditions or catalytic stoves), as well as transition to the use of clean fuels in both urban and rural areas. The *policy-control scenario* assumes much higher rates of adoption of new technologies and fuels than the business-as-usual scenario. The more significant shifts to cleaner energy envisioned by the policy-control scenario are projected to decrease the expected disease burden attributable to residential use of solid fuels in 2030 by about 63%, or over 89,000 deaths, and over 1.4 million DALYs (Summary Table 1) compared with the business-as-usual scenario.

In India, in addition to a reference, or business-as-usual, scenario, two scenarios were designed to reflect different strategies for reducing emissions from major sources; they differ in the contributions of different energy sources and their prioritization and aggressiveness of source-specific emission reductions. They were projected to the year 2050, under the assumption that a longer time was needed to implement the new policies in India. For residential biomass burning, the scenarios reflect different percentages of households converted to clean energy use, with the most aspirational scenario (S3) involving nearly complete elimination of the use of traditional solid fuels in favor of LPG, electricity, and gasifiers, resulting in an over 95% reduction in mortality (> 500,000 deaths) (Summary Table 2).

Residents of households burning solid fuels face a double burden from exposure to both outdoor air pollution and the high levels of pollutants indoors. If the improvements for outdoor air in China and India described above could be applied across all indoor environments, the potential for reducing the health impact of household air pollution would be substantial. Enhanced assessments of the benefits and costs from reducing this double burden are critical to informing government decisions to accelerate the shift to clean fuels.

There are currently no systematic analyses of future trends in household air pollution exposures and health burdens and of the potential for reductions in exposure. But it is possible to envision that if household energy policies resulted in similar reductions in disease burden from HAP as have been projected for outdoor air pollution, the health benefits in China and India alone could be substantial. For example, if the projected 30% and 95% reductions in disease burden for India could be applied to the 783,000 deaths and 22.4 million DALYs attributable to HAP in the IHME GBD 2016 study, as many as 234,000 to 750,000 deaths and 6.7 million to 21.5 million DALYs could be avoided above and beyond those estimated for reduced outdoor air pollution exposure.

The potential net economic benefits of such an intervention could also be substantial. Although the recent World Bank–IHME analysis did not consider the costs that would have to be incurred to achieve the exposure reductions assumed in the GBD estimates, one previous older study examined the global costs and benefits of transitioning half of the HAP-exposed population to either LPG or improved cookstoves and found large net benefits. For the LPG scenario, the authors estimated benefits of $101 billion and costs of $24 billion. This prior analysis drew on older 2002 GBD estimates and considered the following benefit categories: avoided mortality; avoided cost of health care; productivity gains; time savings; and reduced deforestation and greenhouse gas emissions.

To inform national and global decisions to accelerate transitions to clean household energy sources, it will be critical to have new analyses and enhanced analytic tools that can provide credible and convincing estimates of the potential health benefits of interventions and practical estimates of the costs of such interventions.

CONCLUSION: HIGH EXPOSURES, SIGNIFICANT HEALTH BURDENS, AND POTENTIAL FOR IMPROVEMENT; MAJOR IMPLEMENTATION CHALLENGES REMAIN

The exposures and health burdens from household air pollution are substantial, despite the limitations of the current evidence. The potential for significant improvement is high, and accelerating transitions to modern fuels and electricity would be an ideal path forward. However, access to modern fuels remains out of reach for many communities that rely on solid fuels for household energy needs. Solid fuel stoves that burn fuel more efficiently and reduce emissions may be available, but data from the field suggest that use of improved technologies alone would not reduce exposures in the real world to WHO guideline levels. The next steps toward mitigation should simultaneously address the economic and behavioral barriers to sustained adoption of clean stoves and fuels and evaluate other sources of combustion-related pollution in affected communities. Approaches that provide scattered households with access to clean fuels without addressing the challenge of sustained, exclusive use of those fuels and technologies are unlikely to deliver meaningful public health benefits. These issues point to the need for strategic efforts to pivot energy systems to deliver high-quality energy services to low-income households. Further exploration of different approaches for informing decisions on achieving low HAP exposures on a sustained basis is needed.

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ABBREVIATIONS AND OTHER TERMS

BOLD	Burden of Obstructive Lung Disease (study)
COPD	chronic obstructive pulmonary disease
DALY	disability-adjusted life-year
GBD	Global Burden of Disease (study)
GBD MAPS	Global Burden of Disease from Major Air Pollution Sources
HAP	household air pollution
IARC	International Agency for Research on Cancer
IER	integrated exposure–response
IHME	Institute for Health Metrics and Evaluation
LPG	liquefied petroleum gas
NCD	noncommunicable disease
$PM_{2.5}$	particulate matter $\leq$2.5 µm in aerodynamic diameter
WHO	World Health Organization

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