

Energy and Health in Low-Income and Middle-Income Countries 3



Household energy use and health in low-income and middle-income countries

Ajay Pillarisetti*, Misbath Daouda*, Carlos F Gould, Annelise Gill-Wiehl, Thomas Clasen, Daniel M Kammen, Adeladza Kofi Amegah, Kalpana Balakrishnan



At the household level, energy powers human health and wellbeing, enabling essential services such as cooking, lighting, communications, heating, cooling, and ventilation. Despite the recognised need for reliable clean energy, access remains deeply unequal, with high-income households benefiting from modern energy sources while over 600 million people do not have access to electricity and 2–3 billion people rely on biomass fuels as an energy source to meet basic household needs. 2–3 million deaths annually are attributed to household air pollution (HAP) from the combustion of these fuels. HAP degrades ambient air quality and contributes to climate change. Studies of household energy and HAP largely focus on cooking-related emissions and might underestimate the true effect of energy use at home to meet a variety of needs, such as heating and lighting. This Series paper reviews the methods used to estimate the HAP disease burden, evaluates the current epidemiological evidence, and examines the health effects of interventions aimed at cleaner energy adoption. Despite differences in methodology, exposure assessment approaches, or the specific health outcomes considered, estimates of global deaths attributable to HAP exposure consistently remain in the millions each year. Thus, this Series paper also identifies areas for future research, emphasising the need for equitable access to clean energy, especially in low-income and middle-income countries.

Lancet Glob Health 2026;
14: e612–25

This is the third in a **Series** of five papers on energy and health in low-income and middle-income countries. All papers in the Series are available at www.thelancet.com/series-do/energy-health-2026

*Contributed equally

Division of Environmental Health Sciences, School of Public Health, University of California, Berkeley, Berkeley, CA, USA (A Pillarisetti PhD, M Daouda PhD); School of Public Health, University of California San Diego, La Jolla, CA, USA (C F Gould PhD); Mailman School of Public Health, Columbia University, New York, NY, USA (A Gill-Wiehl PhD); Gangarosa Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, GA, USA (Prof T Clasen JD PhD); Department of Civil and Systems Engineering, Johns Hopkins University, Baltimore, MD, USA (Prof D M Kammen PhD); Ralph O'Connor Sustainable Energy Institute, Johns Hopkins University, Baltimore, MD, USA (Prof D M Kammen); Paul Nitze School of Advanced International Studies, Johns Hopkins University, Baltimore, MD, USA (Prof D M Kammen); Department of Biomedical Sciences, University of Cape Coast, Cape Coast, Ghana (A K Amegah PhD); Department of Environmental Health Engineering, Faculty of Public Health, Sri Ramachandra Institute of Higher Education and Research, Chennai, India (Prof K Balakrishnan PhD)

Introduction

Energy access defines and enables services important to human wellbeing and development. Specific services—such as cooking and heating, lighting and telecommunications, and manufacturing and transportation—are crucial to quality of life. Energy use has been described as “the only universal currency... necessary for getting anything done”,¹ as a driving factor towards the evolution of human culture,² and as “the golden thread that connects economic growth, social equity, and environmental sustainability”.³

Despite long recognition of the necessity of reliable and affordable energy to meet these needs, vast disparities exist in who can access clean energy to power their livelihoods. Truly equitable and just development would find the entire global population moving, at a similar pace, towards clean, reliable energy supplies and equitable rates of consumption. The reality, however, is starkly different. Today's energy sources mirror the range of those found throughout human history, from animal power and biomass to processed biofuels, fossil fuels, and electricity. Modern sources are accessed primarily by high-income countries and the rich in low-income and middle-income countries (LMICs).

For many others, however, basic energy needs—heating, cooking, and lighting—remain met by use of methods that have not changed in decades or centuries. Between 2 billion and 3 billion people rely on biomass fuels—wood, dung, coal, charcoal, and agricultural residues—as primary fuels for cooking and heating.^{4–6} In 2024, over 745 million people did not have access to electricity.⁷ Transitions to

cleaner household energy are unevenly distributed, with access increasing in upper-middle-income and high-income countries, whereas access for households in LMICs has remained largely unchanged in recent decades.⁷ Based on WHO analyses for Sustainable Development Goal (SDG) 7 tracking, at current rates, nearly 1·8 billion (95% CI 1·6–2·2) people would be without clean cooking energy in 2030.⁶ Analyses of these transitions, typically performed at the country level, mask substantial within-country heterogeneity, especially where internal income disparities exist. In these settings, as is the case globally, people with lower income are typically left behind as people with high income modernise their energy use. In the second paper of this Series,⁸ Annelise Gill-Wiehl and colleagues address energy access metrics and trends. Here, we focus on pathways between energy use at home and health.

Key messages

- Despite widespread transitions to cleaner household energy, between 2 billion and 3 billion people continue to rely on biomass fuels
- Progress in access to cleaner household energy is unevenly distributed and inequitable
- Exposures in households regularly using biomass fuels far exceed health-protective national standards and global guideline values
- Multiple estimates indicate a large burden of disease—2 million to 3 million deaths yearly—related to household air pollution exposure

Correspondence to:
Dr Ajay Pillarisetti, Division of
Environmental Health Sciences,
School of Public Health,
University of California, Berkeley,
Berkeley, CA 94720, USA
ajaypillariseti@berkeley.edu

Reliance on biomass fuels as an energy source for cooking and heating profoundly impacts health. Exposure to household air pollution (HAP) from these activities contributes to 2–3 million deaths yearly from cardiovascular, pulmonary, and other outcomes.^{5,6,9} Effects are concentrated in LMICs, gendered,^{10–12} and result in lost economic potential.¹³ Women and children are of particular concern, as women are typically primary cooks and their young children tend to stay close by. Smoke emitted indoors goes outside, leading to additional ill health through degraded ambient air quality.¹⁴ Combustion of biomass fuels also contributes to climate change via emissions of climate-altering particles and gases, including black carbon.^{15–19} Policies and technological interventions to transition households to cleaner sources of energy thus promise multiple wins for health, climate, gender equity, and justice. These large burdens might also be underestimated: they focus mainly on cooking-related impacts; scarce research and literature has quantified the effects of heating and lighting on human health and the climate.

In this Series paper, we focus on the burden imposed by use of polluting biomass fuels for cooking and other energy needs. We first review how estimates of HAP disease burden are made. Because these estimates use data from global household energy surveys and studies, they provide an opportunity to critique the current evidence base and highlight areas for future efforts. We discuss exposure assessment strategies and measurements and epidemiological research linking HAP with health. As polluting fuel use at home is a modifiable risk factor, interventions have been proposed and evaluated around the world; we review observational epidemiological studies and randomised controlled trials of these interventions.

We then turn to what is known of the health impacts of household transitions to cleaner energy sources. We discuss potential data sources that could enhance our ability to track health outcomes related to household energy use and other areas for future research. Where possible, we highlight knowledge gaps, for instance on the indirect health benefits of household energy transitions mediated through gender, income, time use, and other pathways. We focus primarily on household energy transitions in LMICs, where the exposure and disease burden is highest. Although this Series paper focuses on the impacts of cooking with polluting fuels, we also draw attention to a need to better understand other potential energy-related contributors to ill-health at the household level.

From burning to burden: what we know and how we know it

Estimates of the Global Burden of Disease (GBD) due to HAP exposure were first released in 2002 as part of WHO's Comparative Risk Assessment.²⁰ The history of burden assessments has been discussed by Smith and

Mehta²¹ and Desai and colleagues.²² Since then, GBD estimates have become more sophisticated; they rely on similar input data, but with higher spatial and temporal resolution.

For 2023, the Institute for Health Metrics and Evaluation (IHME), in partnership with the Health Effects Institute, estimated as part of their GBD exercise that 2·8 million (95% uncertainty interval 2·1–3·7) deaths and 105 million (95% uncertainty interval 82–131) disability-adjusted life-years (DALYs) were attributable to HAP exposure.⁵ These estimates are now quite similar to those generated by WHO for SDG monitoring; by WHO's accounting, in 2021, HAP exposure was responsible for 2·9 million (95% CI 2·3–3·7) deaths and 95 (77–116) million DALYs.⁶

In this Series paper, we review how these GBD estimates are generated, including exposure estimation (in terms of solid fuel use prevalence and exposure concentrations) and epidemiological evidence relating exposure to disease. Other aspects of GBD methodology, including selection of a counterfactual,⁹ estimation of background health status,^{23,24} and strength-of-evidence weighting are outside the scope of this Series paper.^{9,25}

Breathing fire: HAP emissions, concentrations, and exposures

HAP is a mixture of health-damaging and climate-altering pollutants, including particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO₂), volatile organic compounds (eg, formaldehyde and benzo[a]pyrene), and many other hazardous species.^{15,19,26} Although many pollutants have been detected from biomass combustion, only PM_{2.5} and CO have been extensively studied. This focus on PM_{2.5} is due in part to historical epidemiological evidence linking it with a range of health effects and, for both PM_{2.5} and CO, the development of validated measurement techniques (circularly motivated by epidemiological evidence). Estimates of black carbon concentrations are becoming more common,^{27–30} again due to available measurement technology and impacts on climate and health.

Before we describe how HAP exposure estimates are made, we should first distinguish between the terms emissions, concentrations, and exposures. Emissions are typically quantified in terms of the rate of release of a pollutant per unit time or per unit fuel, and are often measured directly from an activity that generates them (eg, emissions measured from the plume above a cooking fire or from a tailpipe). We refer to concentrations in terms of mass of pollutants per volume air as assessed in a microenvironment (eg, in a kitchen, bedroom, or outdoors). Exposures account for the duration, intensity, and frequency of human contact with polluted environments; that is, exposures are the pollution people experience directly.

As an example, consider a study in which we are trying to understand a cook's exposure to HAP. Imagine a

house with a pot simmering over a biomass-fuelled stove, releasing substantial plumes of smoke (emissions) into the kitchen microenvironment. An air pollution sensor in that kitchen would measure high concentrations, but if the cook did not frequent the kitchen during assessment, this value would misclassify exposure. To measure exposure, we should account for where the cook spends time, and for how long. Measuring personal exposure thus captures all experienced air pollution, whether indoors or outdoors or from cooking or transit. In contexts where solid fuel use is common, biomass stoves are often the strongest driver of exposure. Direct measurement of personal exposure is difficult, time-consuming, expensive, and burdensome for participants.

Although the collection of data on personal exposures has increased over time, they are not available at sufficient temporal or spatial scale to estimate exposures for all households that use solid fuels. As such, proxies are often used in place of measured personal exposures.

One widely used proxy is the proportion of a population that use biomass as a primary cooking fuel (figure 1). Much of our knowledge of the potential for exposure arises from these estimates as ascertained from surveys, including multiple indicator cluster surveys, demographic and health surveys, and national censuses. Household energy questions in these surveys focus on primary fuels for cooking, heating, and lighting; however, the mixed use of polluting and cleaner technologies, known as stacking, has been well documented^{32–36} and remains uncaptured by these surveys. Reliance on simplified metrics, such as primary fuel categories, downplays mixed use and might result in exposure misclassification and inaccurate summaries of clean energy use patterns, as discussed in the second paper in this Series.⁸ For example, a household might report reliance on a clean fuel, such as liquefied petroleum gas (LPG) or electricity, but in reality, use wood, dung, and LPG as their cooking fuels.^{37,38}

To estimate the burden of disease attributable to solid fuel use, a multi-step modelling process begins with reliance on survey-based estimates of primary fuel use. The IHME GBD 2021 and GBD 2023 incorporates solid fuel use prevalence estimates from 161 countries, defined in two ways: as a binary variable (eg, solid fuel use or not) and separately by fuel category (wood, dung, charcoal or coal, crop residues, or mixed use).^{9,39} The mixed-use category is omitted from downstream burden analyses owing to insufficient data, leading to model instability. Overall, multiple GBD studies estimate that about one third of the global population relied on solid fuels as a primary energy source for cooking in 2023.^{4–6}

Translating solid fuel prevalence estimates into PM exposures relies on HAP measurements. Quantifying concentrations and exposures, by use of industrial hygiene and ambient air pollution equipment, began in the 1960s. HAP was first assessed in 1968 in Papua New Guinea⁴⁰ and in Lagos, Nigeria,⁴¹ documenting extreme concentrations of CO and PM. These measurements

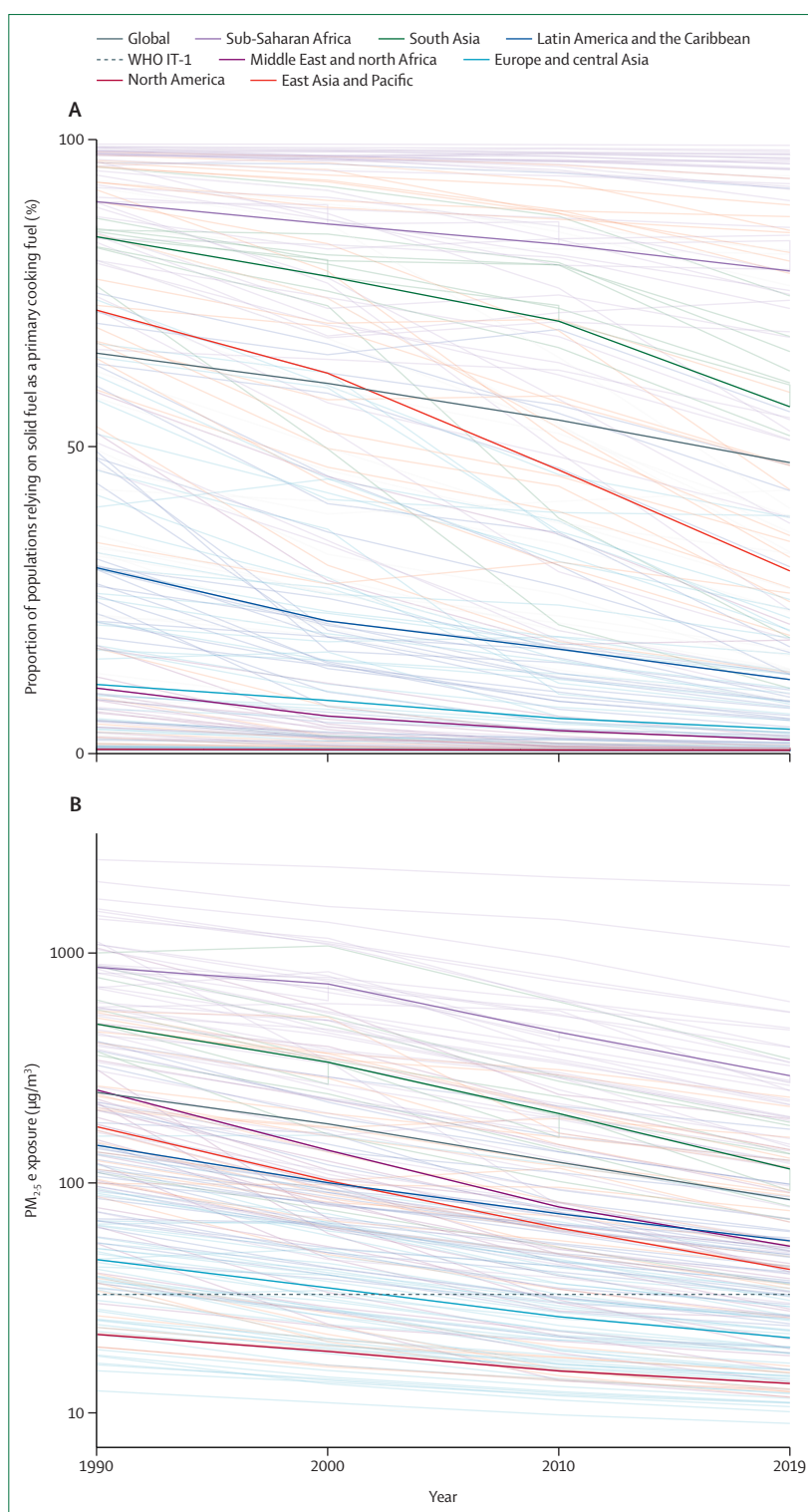


Figure 1: Solid fuel use and related exposures between 1990 and 2019

Changes in the fraction of populations relying on solid fuel as a primary cooking fuel (A) and changes in exposure to PM_{2.5} for women (B) between 1990 and 2019, including global trends and trends by World Bank region and individual countries. Translucent lines are data for individual countries, coloured by region. WHO IT-1 is the annual average WHO interim target guideline value for PM_{2.5} of 35 µg/m³. Data are from modelled estimates generated for the GBD 2019.³¹ GBD=Global Burden of Disease.

were made with stationary monitors in kitchens for relatively short durations of time—an approach still used today to measure area concentrations of HAP. Although these measurements are useful to assess kitchen concentrations, they are poor proxies of an individual's exposure, because they omit behavioural or time activity patterns.^{42–44} When real-time loggers are simultaneously used in multiple microenvironments—for instance in the kitchen, living area, and bedroom—exposures can be reconstructed based on the amount of time an individual spends in each room.^{45–47}

Alternatively, monitors can be worn by people, to measure the personal exposure we lauded previously. Assessment of HAP personal exposures were first made in 1983.⁴⁸ In these early assessments,⁴⁹ as with area monitoring, measurements were made for a few hours to capture exposure during cooking, when emissions were high. Since then, technological and methodological advances have led to an increase in the number of personal air pollution exposure studies.⁵⁰ Small, quiet, pollutant-specific sensors are used, with measurements now typically spanning 24 h or 48 h.

Globally, data on kitchen concentrations of and personal exposures to $PM_{2.5}$ in households using solid fuel are sparse, partly due to the cost and burdens of monitoring. Although modern microelectronics^{51–53} have simplified monitor use, estimating long-term personal exposures remains methodologically and empirically challenging given the short duration of measurements, their infrequent repetition, and the high variability both within and between households.^{54–56}

Since the early 2000s, WHO has maintained the global household air pollution measurement database,⁵⁷ which now contains data from 43 countries and 196 studies.^{58,59} This resource has been used to model exposures in regions where no data are present based on fuel use patterns, sociodemographics, and measurements from similar locations.⁶⁰ In the currently available database (from May, 2018), among households that use wood as fuel, mean $PM_{2.5}$ kitchen concentrations are 395 $\mu g/m^3$ (95% CI 148–1039). Mean exposures are 161 $\mu g/m^3$

(61–431) for women, 116 $\mu g/m^3$ (44–310) for men, and 140 $\mu g/m^3$ (53–375) for children. Households using cleaner fuels, such as electricity and gas, fared better: $PM_{2.5}$ kitchen concentrations were 104 $\mu g/m^3$ (39–273), and exposures were estimated at 42 $\mu g/m^3$ (16–114) for women, 30 $\mu g/m^3$ (12–82) for men, and 37 $\mu g/m^3$ (14–99) for children.^{58,59}

In modelling for GBD 2021 and GBD 2023,^{9,39} IHME expanded the WHO database with a large set of measurements from the PURE-AIR study,^{43,61} which provided data from 120 communities in eight countries. In total, the GBD 2021 included approximately 400 concentration and exposure measurements from 47 locations. IHME GBD exposure estimates for 1990–2019 are visualised in figure 1. For context, the WHO annual average $PM_{2.5}$ guideline is 5 $\mu g/m^3$, with interim targets—the least stringent being 35 $\mu g/m^3$ —for settings where meeting the guideline is impractical.

As part of the Household Air Pollution Intervention Network (HAPIN) randomised controlled trial larger-scale exposure assessments were undertaken in India, Rwanda, Guatemala, Peru,^{27,62–64} Ghana,⁶⁵ and Bangladesh.⁶⁶ Tens of thousands of exposure measurements were conducted as part of HAPIN, but these data have not yet been incorporated into the exposure models, where they hold potential to improve exposure estimates.

Inside out: HAP contributions to ambient air pollution

HAP emitted indoors escapes through chimneys and windows, and is a leading source of outdoor particulate pollution, especially in LMICs. Approximately 20% of all global $PM_{2.5}$ arises from household sources,^{14,67} with wide spatial heterogeneity. Although the magnitude of households' contribution to ambient air pollution varies by modelling approach, all find substantial ambient air pollution resulting from household solid fuel combustion.^{14,68}

Before GBD 2017, exposure estimates were made separately for ambient pollution and HAP, resulting in double-counting and inflated disease burdens.^{9,39} To resolve this overestimation, IHME GBD now models excess exposure from HAP by subtracting time-matched and location-matched ambient exposures from estimated HAP values. For populations that use solid fuels, a total exposure (ie, ambient exposures plus excess HAP) is used in exposure-response curves (described later in this Series paper). The total burden is apportioned to ambient or household sources by the fraction of total exposure coming from each source. The household contribution to ambient air pollution is part of the burden associated with the IHME ambient PM pollution GBD risk factor.

Health effects associated with HAP exposure

HAP exposure has been consistently associated with adverse health outcomes in observational studies. In IHME GBD 2021, HAP-associated $PM_{2.5}$ exposure was

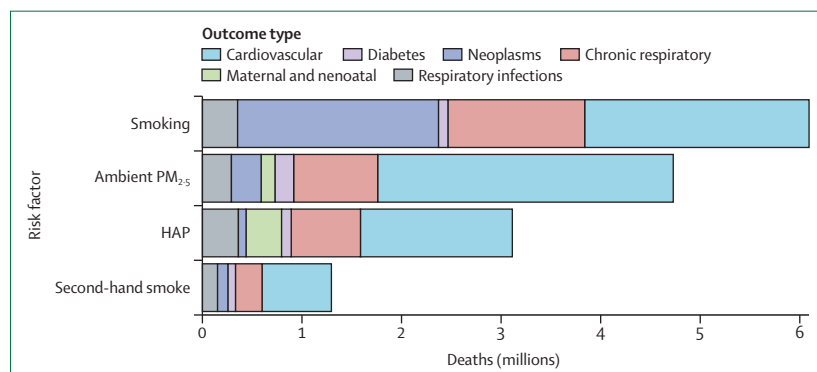


Figure 2: Mortality from smoking, ambient $PM_{2.5}$, HAP, and second-hand smoke as estimated in GBD 2021
Note that some fraction of ambient $PM_{2.5}$ arises from household sources; this portion of the burden could be allocated to the overall HAP burden. GBD=Global Burden of Disease. HAP=household air pollution.

linked with cataract, chronic obstructive pulmonary disease (COPD), ischaemic heart disease, lower respiratory infections, stroke, lung cancer, type 2 diabetes, and, through mediation analysis, with adverse outcomes associated with low birthweight and short gestation.^{9,69} Figure 2 depicts disease burdens for HAP and related risk factors, including active tobacco smoking, ambient PM_{2.5} exposure, and second-hand smoke exposure.

In GBD 2021 and GBD 2023 for all outcomes except cataract, meta-analytical techniques were used to create curves relating PM_{2.5} exposure with outcome-specific risk.^{9,39} These models integrate exposure–outcome data from both studies of HAP and ambient air pollution and have undergone substantial iteration.⁷⁰ The meta-regression Bayesian, regularised, trimmed risk curves used in GBD 2021 use third-order splines with three interior knots that are constrained to be biologically plausible (concave and monotonically increasing; figure 3). A full description of curve fitting procedures is available in the study by the GBD 2021 Risk Factors Collaborators.⁹ The curves assume that particulates from different sources are equitoxic and that risk increases monotonically with exposure. The curves and their assumptions have profound policy implications: to realise health benefits, exposures should be brought down to relatively low concentrations, where the marginal health benefit of unit decreases in air pollution are meaningful and larger in magnitude than at higher air pollution concentrations.

WHO also performs its own fuel use and burden of disease modelling exercises. Estimates from WHO and IHME are reasonably well aligned; although IHME is more regularly updated, WHO's estimates are used as the official reference for global reporting and SDG monitoring, and are subject to country consultation. Although the IHME GBD modelling is the most comprehensive and regularly updated for HAP and related health outcomes, other systematic reviews and meta-analyses exist. For instance, children exposed to biomass smoke were found to have an increased risk of pneumonia compared with clean-fuel users.⁷¹ A meta-analysis concluded that household combustion of solid fuels resulted in a 86.43 g (95% CI 55.49–117.37) reduction in birthweight, a 35% (23–48) increased risk of low birthweight, and a 29% (18–41) increased risk of stillbirth.⁷² A comprehensive 2020 systematic review and meta-analysis⁷³ evaluated the risk of respiratory and cardiovascular diseases and adverse pregnancy outcomes from polluting fuels. Their review included 476 studies from 123 countries (99 [80%] of 123 countries were from LMICs). Unlike the IHME GBD, this systematic review and meta-analysis included kerosene as a polluting fuel and did not attempt to estimate exposures or use exposure–response functions to evaluate risk and burden, rather relying on a binary categorisation of primary polluting fuel use and a counterfactual of no polluting fuel use. In this study, HAP was associated with asthma (relative risk 1.23, 95% CI 1.11–1.36), lower

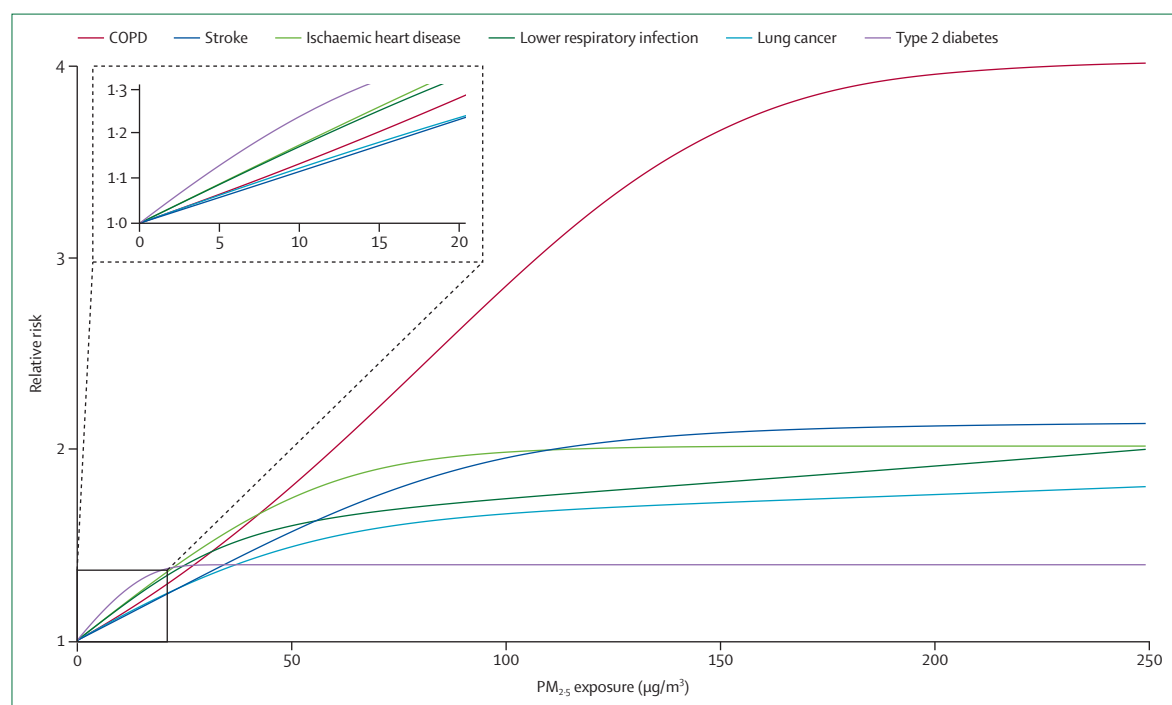


Figure 3: Bayesian, regularised, trimmed exposure–response curves relating PM_{2.5} exposure with risk of health outcomes, as used by GBD 2021

Colours are different health outcomes. Further details on curve fitting procedures and input data are available elsewhere.⁹ COPD=chronic obstructive pulmonary disease. GBD=Global Burden of Disease.

respiratory infections in adults (1·53, 1·22–1·93) and children (1·39, 1·29–1·49), COPD (1·70, 1·47–1·97), lung cancer (1·69, 1·44–1·98), tuberculosis (1·26, 1·08–1·48), cerebrovascular disease (1·09, 1·04–1·14), ischaemic heart disease (1·10, 1·09–1·11), low birthweight (1·36, 1·19–1·55), stillbirth (1·22, 1·06–1·41), mortality in children younger than 5 years (1·25, 1·18–1·33), and all-cause mortality (1·08, 1·04–1·13). The mortality burden from HAP exposure estimated by this study was approximately 1·8 million deaths in 2017. Numerous other reviews come to similar conclusions.^{74–76}

Regardless of methodology, exact exposure estimation techniques, or health effects estimated, the global mortality burden attributable to HAP has consistently been estimated to be in the millions yearly. This value might be an underestimate; in many places around the world where cooking and lighting have already become less polluting, heating with solid fuels persists.

Cleaning up cooking

This substantial morbidity and mortality burden associated with HAP leads naturally to the question of what can be done to reduce risk and protect health. Attempts to mitigate indoor exposures to air pollution began in the 1950s⁷⁷ and continue to date.⁷⁸ Given the high disease burden, WHO issued the *Guidelines for Indoor Air Quality: Household Fuel Combustion* in 2014,⁷⁹ which established emissions rate targets for stoves that could help populations attain the health protective annual WHO air quality guideline values.

Clean cooking interventions have historically focused on two paradigms: replacing polluting technologies with improved stoves that increase combustion efficiency and reduce emissions or with cleaner burning fuels or with electric cooking. Most early intervention work focused on biomass stoves with lower emissions than typical simply constructed stoves or open fires. Although these stoves have been shown to reduce emissions in laboratory testing,^{80–82} in real-world contexts they are not performant, due to heterogeneity in stove operation behaviours and variability in fuel quality.^{83,84} In most instances, these stoves reduce exposures compared with open fires, but not to the extent of health-relevant targets.^{85–90} By contrast, exposures from cleaner burning fuels, such as LPG or ethanol, can be equal to or lower than the intermediate WHO guideline value, but not if mixed use of polluting and cleaner fuels is common or if background air pollution concentrations are elevated.

Cooking intervention trials have evaluated the ability of various technologies and fuels to improve health via reduced exposure. These trials have widely varied in design, size, objective, intervention package, and exposure and health outcome assessment (table).⁹¹ They have typically focused on health outcomes that could be improved over short periods of time (eg, 1–2 years). Interventions have been evaluated on randomisation

(ie, intention-to-treat analyses) and for exposure–response relationships independent of randomisation.

Unlike the observational evidence, which has consistently described associations between HAP exposure and health outcomes, interventions evaluated in trials have either insufficiently reduced or not reduced exposures and thus have not improved health. In this Series paper, we focus on trials with both exposure and health outcome data collection, excluding those that did not measure air pollution exposure,^{118,119} that did not focus on rigorous health outcome assessment,^{120–122} or have not yet published one or the other.

The evolution of HAP intervention trials mirrors development of clean cooking interventions. The Randomised Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) trial, the first of its kind, provided a locally made chimney-stove intervention. Although the trial found reductions in CO kitchen concentrations (~80% lower in intervention homes) and personal exposures (~50% lower),⁹² it saw no effect on physician-diagnosed pneumonia (the primary outcome). However, the trial found significant reductions in physician-diagnosed severe pneumonia and a positive, supralinear relationship between exposure and pneumonia.⁹³

Subsequent trials have focused on improved stoves and cleaner fuels. The Nepal Cookstove Intervention Project⁹⁴ was a two-phase randomised controlled trial. The first phase evaluated a biomass stove with a chimney in a cluster-randomised, stepped-wedge trial; the second phase added a household-level trial in which participants were randomly assigned to receive LPG and a 12 month fuel supply or a biomass stove with chimney. Primary outcomes were gestational age at birth, birthweight, and acute lower respiratory infection in children younger than 36 months. Personal exposures were not assessed, but 24-hour kitchen concentrations of PM_{2.5} and CO were evaluated. Both randomised controlled trial phases resulted in kitchen concentrations of PM_{2.5} between 10 times and 20 times the WHO interim target 1 (WHI IT-1) values.¹²³ Neither stove affected birth outcomes.⁹⁵ No exposure–response relationship was evident, but when combined with other observational evidence from Nepal, a positive, supralinear relationship between exposure and pneumonia⁹⁶ was identified.

The Cooking and Pneumonia Study (CAPS) in Malawi⁹⁷ was a community-level cluster randomised controlled trial (150 communities; 8626 households; 10 750 children) evaluating an intervention package of two fan-assisted stoves and a solar panel to charge them. The trial found no effect of the stoves on exposures to CO potentially because cooking occurred outdoors.⁹⁸ It found no effect of the intervention on pneumonia, nor any relationship between exposure and pneumonia.⁹⁷

The Household Air Pollution and Pregnancy Outcome⁹⁹ study was a randomised controlled trial enrolling

	Location	N	Intervention	Primary outcome	Findings on intention-to-treat analysis	Findings in terms of exposures and exposure-response relationships
Randomised Exposure Study of Pollution Indoors and Respiratory Effects ^{92,93}	Guatemala	534 households with presence of a pregnant woman or an infant aged <4 months	Chimney stove	Pneumonia in children aged <5 years	No significant difference	~80% indoor reduction in CO concentrations; ~50% CO personal exposure reduction; exposure reduction associated with physician-diagnosed severe pneumonia (RR 0.82, 95% CI 0.70 to 0.98)
The Nepal Cookstove Intervention Project ⁹⁴⁻⁹⁶	Nepal	For ALRI there were 5254 children (age at recruitment for phase 1 was <36 months and for phase 2 was <24 months); for birthweight there were 2379 liveborn infants during phase 1 and 549 liveborn infants during phase 2	Two trials: biomass chimney cookstove; LPG stove and fuel or biomass stove	Co-primary outcomes were ALRI incidence in children <36 months, gestational age at birth (measured by the start of the last menstrual period), and birthweight	No significant difference	No differences in indoor CO concentrations between groups; indoor PM _{2.5} reductions, but above WHO IT-1; little evidence of an exposure-response relationship for ALRI
Cooking and Pneumonia Study ^{97,98}	Malawi	10 750 children aged <5 years	Fan-assisted biomass cookstove	Pneumonia	No significant difference	No difference in CO exposure; no difference in pneumonia risk; no exposure-response relationships
Household Air Pollution and Pregnancy Outcome ^{99,100}	Nigeria	324 pregnant women	Ethanol stove	Co-primary outcomes were birthweight, preterm delivery, IUGR, and miscarriage or stillbirth	No significant difference in co-primary outcomes; higher diastolic blood pressure in control group (secondary outcome)	No differences in CO or PM _{2.5} exposure between groups; no exposure-response relationships
Ghana Randomized Air Pollution and Health Study ^{65,101-105}	Ghana	1414 pregnant women	Fan-assisted biomass cookstove; LPG stove and fuel	Co-primary outcomes were birthweight and physician-assessed severe pneumonia	No significant difference	CO reduced 47% and PM _{2.5} reduced 32% in LPG intervention group relative to control; 1 ppm increase in prenatal CO increased pneumonia risk by 10% and severe pneumonia by 15%; 1 ppm increase in prenatal CO was associated with -53.4 g (95% CI -84.8 to -21.9) change in birthweight, -0.3 cm (-0.6 to -0.1) change in birth length, 1.0 days (-1.8 to -0.2) earlier gestational age, and with weight-for-age Z score among participants without placental malaria; suggestive evidence that prenatal CO exposure was associated with increased odds of low birthweight and small for gestational age; prenatal CO was associated with reduced time to peak tidal expiratory flow to expiratory time and increased respiratory rate and minute ventilation
Cardiopulmonary Outcomes and Household Air Pollution Trial ^{29,106}	Peru	181 women	LPG stove and fuel	Co-primary outcomes were cardiovascular and respiratory health	No significant difference	Kitchen concentrations reduced by 95% for PM _{2.5} , 97% for black carbon, 87% for CO, and 49% for NO ₂ in the intervention group; exposures reduced by 69% for PM _{2.5} , 87% for black carbon, 64% for CO, and 65% for NO ₂ in the intervention group; no exposure-response relationships
Household Air Pollution Intervention Network ^{27,62,63,107-109,110-116}	Guatemala, India, Peru, and Rwanda	3200 pregnant women	LPG stove and fuel	Co-primary outcomes were birthweight; pneumonia; infant growth; blood pressure among older women (aged 40-79 years) living in the same home as the pregnant woman	No significant difference	Median exposures were lower by 66% for PM _{2.5} , 70% for black carbon, and 82% for CO in the intervention group for pregnant women; median exposures were lower by 62% for PM _{2.5} , 73% for black carbon, and 57% for CO in the intervention group for older adult women; an interquartile increase in prenatal PM _{2.5} exposures (increased by 74.5 µg/m ³) was associated with a reduction in birthweight of 14.8 g (95% CI 0.8 to 28.7); an interquartile increase in black carbon (increased by 7.3 µg/m ³) with a reduction in birthweight of 21.9 g (6.1 to 37.7); other exposure-response findings forthcoming
\$100Kitchen and Low-birth-weight Study in Rural Bangladesh ¹¹⁷	Bangladesh	1267 pregnant women	Improved stove and kitchen	Low birthweight; maternal blood CO	Adjusted risk ratio 0.63 (95% CI 0.45 to 0.89)	Reduction in spCO in the intervention group from 10.4% in the second trimester to 8.9% in the third trimester; no change in the control group

Adapted from Lai and colleagues.⁹¹ WHO IT-1 is the annual average WHO interim target guideline value for PM_{2.5} of 35 µg/m³. ALRI=acute lower respiratory infection. IUGR=intrauterine growth restriction. LPG=liquefied petroleum gas. LRI=lower respiratory infection. RR=relative risk. spCO=carboxyhaemoglobin saturation. WHO IT-1=WHO interim target 1.

Table: Health and exposure-focused randomised controlled trials of clean cooking interventions

324 pregnant women in Ibadan, Nigeria. Half of the participants were randomised to an ethanol stove intervention (intervention group), and the remaining enrolees continued to cook with solid fuels or kerosene (control group). Primary outcomes were birthweight, preterm delivery, intrauterine growth restriction, and occurrence of miscarriage or stillbirth. Blood pressure was also evaluated. Exposures to CO and PM_{2.5} were not different between control and intervention groups, and exposure assessment was complicated by missing data, large seasonal differences in pollution (eg, lower concentrations in both groups during rainy season compared with the dry season), and high background concentrations of ambient air pollution. A non-significant, suggestive protective effect for birthweight was identified. Gestational age at delivery was higher for those in the ethanol group by approximately 1 week. Diastolic blood pressure at endline was higher in the control group than the intervention group.¹⁰⁰

The Ghana Randomized Air Pollution and Health Study (GRAPHHS) was a cluster randomised controlled trial in 35 communities that evaluated LPG and a fan-assisted cookstove on birthweight and incidence of pneumonia.¹⁰¹ 1414 pregnant women were enrolled: 361 in the LPG group, 527 in the biomass cookstove group, and 526 in the control group. Neither intervention improved birthweight nor reduced severe pneumonia risk.¹⁰² Exposures to PM_{2.5} and CO were lower in the LPG group compared with the control group, but not in the biomass group.⁶⁵

GRAPHHS explored numerous exposure–response relationships. Each 1 ppm increase in prenatal CO exposure increased pneumonia risk in the first year of life by 10% and severe pneumonia by 15%.¹²⁴ In adjusted models seeking to identify particular windows of vulnerability, prenatal CO exposure at 15–20 weeks of gestation was inversely associated with birthweight and prenatal CO exposure at 34–39 weeks was associated with severe pneumonia risk for female children who were born during the trial.¹²⁵ Similarly, prenatal CO exposure was associated with reduced birthweight, birth length, gestational age, weight-for-age Z score, among those without placental malaria and there was suggestive evidence with increased odds of low birthweight and small for gestational age for all infants.¹⁰³ In a substudy of 384 infants, prenatal CO exposure was negatively associated with infant lung function.¹⁰⁴ Finally, in work done during the baseline assessments for GRAPHHS, a significant positive association between CO exposure and diastolic blood pressure was found for the expecting mothers.¹⁰⁵

The Cardiopulmonary Outcomes and Household Air Pollution (CHAP)¹⁰⁶ trial took place in Department of Puno, Peru and enrolled 181 women, with 90 assigned to a free LPG fuel intervention and 91 assigned to the control group, who continued to follow their standard cooking practices. The intervention package included an LPG stove, home fuel delivery, and behavioural

messaging and reinforcement. Co-primary outcomes included clinical markers of cardiovascular and respiratory disease, such as blood pressure, peak expiratory flow, and St George's Respiratory Questionnaire total scores. The intervention reduced all pollutant (ie, PM_{2.5}, black carbon, CO, and NO₂) concentrations and exposures significantly, including average PM_{2.5} personal exposures to 30 µg/m³.²⁹ Despite reductions in exposure, no difference in outcomes was found in the intention-to-treat analysis. In a pragmatic crossover trial after the randomised controlled trial—when control participants received the CHAP intervention package, without home delivery of fuel, and intervention households no longer had free fuel delivery—reduced kitchen concentrations of and exposure to PM_{2.5} and CO persisted.¹²⁶

The HAPIN randomised controlled trial took place in four countries where reliance on solid fuels persists: Guatemala, India, Peru, and Rwanda.^{107–109} In each of the four countries, 800 women in early pregnancy (ie, 9 weeks' to <20 weeks' gestation as confirmed on ultrasonography) were recruited and randomised 1:1 to either an LPG intervention or standard cooking practices. The intervention consisted of an LPG stove, free fuel delivered to the home, and behavioural reinforcement. Primary outcomes were birthweight, infant growth, severe pneumonia among infants, and blood pressure of older adult women living in the same households as the pregnant participants. PM_{2.5}, CO, and black carbon exposures were significantly reduced for intervention group women, children, and other adult women in the households.^{27,62,63} PM_{2.5} exposures were below WHO IT-1; reductions of all pollutants were stable over time. Intention-to-treat analyses of the effect of intervention on birthweight, infant growth, and pneumonia did not find evidence of effect.^{110,111,116} Birthweight findings were suggestive of an effect, in particular in subgroup analysis, where mothers who received the intervention in early pregnancy had heavier babies, but these findings were not statistically significant. In adjusted models examining the relationship between HAP exposures and birthweight, an interquartile increase in the prenatal PM_{2.5} or black carbon exposure was associated with a reduction in birthweight and gestational age Z scores.¹¹²

The \$100Kitchen and Low-birth-weight Study in Rural Bangladesh enrolled 1267 pregnant women¹¹⁷ and assigned women 1:1 to an improved cookstove with chimney in a prefabricated kitchen intervention (628 women in the intervention group and 639 women in the control group). Outcomes were the proportion of neonates with low birthweight and maternal blood carbon monoxide saturation (carboxyhaemoglobin saturation [spCO]) during the second and third trimester. The study found a reduced risk of low birthweight prevalence in the intervention group (adjusted risk ratio 0.63, 95% CI 0.45–0.89) and decreases in maternal spCO.

Trials and tribulations: attempting to reconcile evidence streams

The randomised trial evidence, which largely finds no effects of cleaner cooking interventions on health, stands at odds with decades of observational evidence that cleaner cooking technologies reduce air pollution exposures and improve health. Reconciling these evidence streams poses major questions for researchers and policy makers: are all observational studies severely confounded by poverty and co-exposure to a variety of other risks, such as nutrition, infection, and inadequate water and sanitation? Can settings that have undergone transitions serve as real-world evidence of potential benefits, as seen in accountability studies?

The review by Lee and colleagues⁷³—which used standard meta-analytical techniques to estimate the burden of HAP exposure on health—addressed some of these concerns by assessing risk of bias across two axes: the quality of outcome assessment (eg, clinically dictated or physician-assigned) and how and what adjustments occurred to account for confounding. For confounding, they considered any study that adjusted only for age and sex as having a high risk of bias; whereas those that adjusted for age, sex, and two other relevant covariates were of low risk of bias. They acknowledged that such an approach leaves the possibility of residual confounding, including the likelihood that houses that rely on solid fuel might have less access to or ability to use health-care services than households that use clean fuels.

Exposure–response analyses of clean cooking trials—highlighted previously—suggest that exposures to PM_{2.5} or CO are associated with health benefits, especially for birthweight and pneumonia. These analyses control for a variety of confounders, including markers of socio-economic status, alternative exposures, and proxies of nutritional status. Because the precise causal pathway from clean energy to better health remains uncertain, researchers should explore several hypotheses to explain differences between these findings and randomised controlled trial evidence. We point to potential questions that might begin to reconcile some of these discrepancies.

The first hypothesis is temporal in nature: the timing of intervention, particularly for child health outcomes, might need to target earlier stages of pregnancy, or even the periconception period, so that the intervention covers sensitive windows. For chronic outcomes, it might take longer than a short-term intervention to ensure durable health benefits. Long-term follow-up of existing cohorts is one way to evaluate some of these hypotheses. The second hypothesis relates to the HAP exposure heterogeneity. Observed reductions in PM_{2.5} or CO might be too small to deliver health benefits. They might also be undermined by exposure to other harmful pollutants such as ultrafine particles, NO₂, and air toxics.^{127,128} Finally, other risk factors for adverse health outcomes, such as malnutrition and infection, are still present when clean energy is provided and might negate any benefits of HAP exposure

reductions. Combining different interventions (eg, clean cooking, nutrition, and water and sanitation) might offer a path forward.

Importantly, both randomised trials and observational studies agree on a key point: clean fuels such as electricity or gas can reduce HAP much more than improved biomass stoves. When these clean fuels are made free or very low cost, people tend to use them almost exclusively. In both types of studies, this use has led to pollution concentrations and exposures that meet or fall below WHO IT-1.^{29,113–115}

We invite the clean cooking community to question whether we should wait for results from randomised controlled trials before supporting these interventions. Indeed, randomised controlled trials are often very controlled and thus might not reflect real-world situations. Consider outdoor air pollution: we have not had to rely on randomised controlled trials to set air quality policies, as such trials would be unethical or impractical. Instead, for the case of ambient air pollution, we focus on whether emission-reducing actions are cost-effective, technically feasible, and enforceable.

Beyond burden: where do we go from here?

Cleaning up after cleaning up cooking

Despite progress on cleaner household energy transitions, HAP remains an important exposure and contributor to ill-health. Non-cooking emissions—for instance from heating, animal food preparation, waste burning, and diesel generator use—have been less well explored than emissions from cooking. In areas where space heating is common—such as Mongolia and parts of China—heating-related emissions can be a substantial contributor to the total exposure burden from health-damaging emissions. These emissions also exist in regions where cooking transitions have already occurred, such as eastern Europe.

Because air pollution concentrations vary—from households, to neighbourhoods, to regions—cleaning up households' energy sources might be a necessary but insufficient action to decrease exposures. For many places where solid fuel use is prevalent, reducing HAP is necessary for decreasing overall exposure; where other strong sources of pollution exist, a multi-pronged approach towards regional air pollution control might be required. Such a strategy should not ignore emissions that start at home, exposing poor and vulnerable populations while also degrading air quality as smoke leaves the home.

Evaluating electric cooking

In some higher-income settings, a transition from gas to electricity for cooking is underway.^{129–131} A similar transition might be possible in specific LMIC settings. Such a transition is commendable, especially when powered by renewably produced electricity, but, without massive grid upgrades, is likely out of reach for many households using biomass fuels, who have unreliable,

low-quality electricity. In contexts where electricity is reliable and sufficient—or where there are realisable plans for its expansion—leap-frogging LPG might be possible. In the meantime, as has been done for LPG, implementation research should evaluate barriers to and enablers of electricity for cooking and develop a prioritisation of locations where an electric cooking transition might be possible.

Assessing effects on gender equity and wellbeing

Transitions from biomass to modern household energy might also advance gender equity and overall wellbeing by reducing burdens beyond health.^{132,133} Modern fuels free individuals, mostly women and girls, from the physical and time demands of fuel collection, processing, and cooking, which could also lower risks of violence during firewood collection and reduce school absenteeism. For example, a randomised controlled trial in Peru found that women in an LPG intervention group spent 3·2 fewer hours cooking and 1·9 fewer hours collecting fuel per week compared with women in the control group who were using biomass fuels, even though they cooked on average 1·0 more meals per day.¹³⁴ A systematic review found that adopting modern fuels saves time by reducing needs for fuel collection, decreasing fuel consumption, and lowering meal preparation time.¹³⁵ The review found that time savings were used for additional income generation, learning skills, and leisure activities, among others. Strengthening evidence on how modern cooking affects the lives of women and girls could help generate support from policy makers.

There is also evidence that the transition to modern fuels increases women's subjective satisfaction and wellbeing. A large cross-sectional study in China found that fully adopting clean fuels significantly improves individuals' happiness and life satisfaction.¹³⁶ By contrast, incomplete transition did not significantly affect individuals' subjective wellbeing. Notably, a mediation analysis of the results found that between a third and half of the beneficial effects were due to perceptions of improved family health. These results are consistent with a qualitative study in India, in which women who used firewood believed their cooking fuel supported their sense of wellbeing and saw no enabling relationship between LPG use and wellbeing. By contrast, firewood users who switched to LPG claimed it enhanced wellbeing.¹³⁷ Similar to our assessments of exposure and health effects, there is a need for improved methods to rigorously evaluate and establish the economic value of clean energy transitions on the lives of those in low-income settings.

Economic and policy research

Reliable evidence on the effects of clean household energy interventions on exposures and health is crucial but is only one piece of the puzzle. Policy makers, donors, and

implementers should allocate increasingly scarce resources across competing health and development needs. Economic analyses, including cost-effectiveness and cost-benefit analyses, can clarify the value of household energy investments and help to target these interventions where they will yield the largest benefits. These analyses should assess both who stands to benefit from any cost savings (such as reduced health-care expenditures) or broader economic gains, but also who bears the costs. Willingness-to-pay and ability-to-pay research can help establish the need for tariff and tax relief and subsidies to improve equity of access, and ensure the nearly exclusive use necessary to reach health gains. At a more macroeconomic level, analyses can help establish how governments should invest in expanding LPG and whether market forces are sufficient to drive diffusion, or whether supplementary measures are needed, especially in remote areas and at the end of supply chains. These strands of research are especially important since LPG for cooking is largely a private (ie, household) expenditure, whereas electricity infrastructure is often a public (ie, government) investment, perhaps likely to deliver lower overall household expenditures on energy and yield other monetisable benefits. Comprehensive economic analyses can also help establish the most appropriate mix of investments in LPG versus electrification and the extent to which there is genuinely a trade-off between household energy transition strategies. Finally, evaluation of ongoing or completed energy transitions—such as the kerosene to LPG transition in Indonesia¹³⁸ and the biomass fuel to LPG transition in Ecuador^{130,131}—can shed vital light on how to leverage administrative data to estimate effects at the population scale. Such evidence can motivate future transitions and provide key guidance on the parameters that should be captured for full evaluation.

Household energy for health

Access to energy enables much of what is taken for granted in modern life, from telecommunications to transportation. Wide disparities in access to energy result in inequity in terms of quantities of pollution emitted and experienced, reliability and quality of energy services available, and effects on health and welfare. Although recent decades have seen progress in access to cleaner fuels, transitions are incomplete for about 3 billion people globally. For some, a partial transition results in continued reliance on polluting energy sources perceived as affordable and accessible. For others, cleaner energy sources have not yet reached their doorstep. Regardless, potential health gains for this large population remain unrealised.

One way to think of the required shift is from a framing of household energy and health to one of household energy for health for all. Over half of the global population lives in homes, buildings, and cities that provide consistent and reliable access to sufficient clean energy

at home to meet basic needs—an improvement that has happened in about 100 years. We have not succeeded in sharing knowledge or finding political will and investment to empower the rest of the world with similar energy access. Doing so would reduce exposures and lift the health status for those who stand to benefit most.

Contributors

AP, TC, and DMK were responsible for the conceptualisation. AP, MD, AKA, KB, AG-W, CFG, and DMK wrote the original draft and contributed to review and editing.

Declaration of interests

We declare no competing interests.

Acknowledgments

AP would like to thank the IHME GBD HAP Collaborators, and WHO's Air Quality, Energy, and Health Unit for their thoughtful insights and suggestions. AG-W acknowledges funding from a US National Institutes of Health T32 training grant (T32ES007322). DMK was funded by the Karsten Family Foundation and the Zaffaroni Family Foundation.

References

- Smil V. Energy and civilization: a history. Cambridge: The MIT Press, 2017.
- Hall C, Tharakan P, Hallock J, Cleveland C, Jefferson M. Hydrocarbons and the evolution of human culture. *Nature* 2003; **426**: 318–22.
- United Nations. Secretary-General to Global Development Center: 'Energy is the golden thread' connecting economic growth, social equity, environmental sustainability. April 20, 2012. <https://press.un.org/en/2012/sgsm14242.doc.htm> (accessed March 1, 2025).
- Health Effects Institute. State of Global Air 2024. 2024. <https://www.stateofglobalair.org/resources/archived/state-global-air-report-2024> (accessed March 1, 2025).
- Health Effects Institute. State of Global Air 2025. 2025. <https://www.stateofglobalair.org/resources/report/state-global-air-report-2025> (accessed March 1, 2025).
- International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, WHO. Tracking SDG 7: The Energy Progress Report. Aug 13, 2025. <https://openknowledge.worldbank.org/entities/publication/94cda685-2495-4b1d-926a-147424f98f5d> (accessed Sept 1, 2025).
- Romanello M, Walawender M, Hsu S-C, et al. The 2024 report of the Lancet Countdown on health and climate change: facing record-breaking threats from delayed action. *Lancet* 2024; **404**: 1847–96.
- Gill-Wiehl A, Gould CF, Jeuland M, et al. Beyond access: clean energy use in low-income and middle-income countries. *Lancet Glob Health* 2026; **14**: e598–611.
- GBD 2021 Risk Factors Collaborators. Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024; **403**: 2162–203.
- Njenga M, Gitau JK, Mendum R. Women's work is never done: lifting the gendered burden of firewood collection and household energy use in Kenya. *Energy Res Soc Sci* 2021; **77**: 102071.
- Chandrasekaran M, Krishnapriya PP, Jeuland M, Pattanayak SK. Gender empowerment and energy access: evidence from seven countries. *Environ Res Lett* 2023; **18**: 045003.
- Krishnapriya PP, Chandrasekaran M, Jeuland M, Pattanayak SK. Do improved cookstoves save time and improve gender outcomes? Evidence from six developing countries. *Energy Econ* 2021; **102**: 105456.
- The World Bank, Institute for Health Metrics and Evaluation. The cost of air pollution: strengthening the economic case for action. 2016. <https://documents1.worldbank.org/curated/en/781521473177013155/pdf/108141-REVISED-Cost-of-PollutionWebCORRECTEDfile.pdf> (accessed March 1, 2025).
- Chowdhury S, Pillarisetti A, Oberholzer A, et al. A global review of the state of the evidence of household air pollution's contribution to ambient fine particulate matter and their related health impacts. *Environ Int* 2023; **173**: 107835.
- Bilsback KR, Dahlke J, Fedak KM, et al. A laboratory assessment of 120 air pollutant emissions from biomass and fossil fuel cookstoves. *Environ Sci Technol* 2019; **53**: 7114–25.
- Saliba G, Subramanian R, Bilsback K, et al. Aerosol optical properties and climate implications of emissions from traditional and improved cookstoves. *Environ Sci Technol* 2018; **52**: 13647–56.
- Floess E, Grieshop A, Puzzolo E, et al. Scaling up gas and electric cooking in low- and middle-income countries: climate threat or mitigation strategy with co-benefits? *Environ Res Lett* 2023; **18**: 034010.
- Bailis R, Drigo R, Ghilardi A, Masera O. The carbon footprint of traditional woodfuels. *Nat Clim Chang* 2015; **5**: 266–72.
- Naeher LP, Brauer M, Lipsett M, et al. Woodsmoke health effects: a review. *Inhal Toxicol* 2007; **19**: 67–106.
- Ezzati M, Lopez AD, Rodgers A, Vander Hoorn S, Murray CJ, Comparative Risk Assessment Collaborating Group. Selected major risk factors and global and regional burden of disease. *Lancet* 2002; **360**: 1347–60.
- Smith KR, Mehta S. The burden of disease from indoor air pollution in developing countries: comparison of estimates. *Int J Hyg Environ Health* 2003; **206**: 279–89.
- Desai MA, Mehta S, Smith KR, WHO. Indoor smoke from solid fuels: assessing the environmental burden of disease at national and local levels. 2004. <https://iris.who.int/handle/10665/42885> (accessed March 1, 2025).
- Ferrari AJ, Santomauro DF, Aali A, et al, and the GBD 2021 Diseases and Injuries Collaborators. Global incidence, prevalence, years lived with disability (YLDs), disability-adjusted life-years (DALYs), and healthy life expectancy (HALE) for 371 diseases and injuries in 204 countries and territories and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024; **403**: 2133–61.
- Naghavi M, Ong KL, Aali A, et al, and the GBD 2021 Causes of Death Collaborators. Global burden of 288 causes of death and life expectancy decomposition in 204 countries and territories and 811 subnational locations, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet* 2024; **403**: 2100–32.
- Zheng P, Afshin A, Biryukov S, et al. The burden of proof studies: assessing the evidence of risk. *Nat Med* 2022; **28**: 2038–44.
- Northcross AL, Katharine Hammond S, Canuz E, Smith KR. Dioxin inhalation doses from wood combustion in indoor cookfires. *Atmos Environ* 2012; **49**: 415–18.
- Johnson M, Pillarisetti A, Piedrahita R, et al, and the Household Air Pollution Intervention Network (HAPIN) Trial Investigators. Exposure contrasts of pregnant women during the household air pollution intervention network randomized controlled trial. *Environ Health Perspect* 2022; **130**: 97005.
- Luo Z, Zhang L, Li G, et al. Evaluating co-emissions into indoor and outdoor air of EC, OC, and BC from in-home biomass burning. *Atmos Res* 2021; **248**: 105247.
- Checkley W, Williams KN, Kephart JL, et al, and the CHAP Trial Investigators. Effects of a household air pollution intervention with liquefied petroleum gas on cardiopulmonary outcomes in Peru. A randomized controlled trial. *Am J Respir Crit Care Med* 2021; **203**: 1386–97.
- Campbell DA, Johnson M, Piedrahita R, et al. Factors determining black carbon exposures among pregnant women enrolled in the HAPIN trial. *Environ Sci Technol* 2024; **58**: 10162–74.
- GBD 2019 Risk Factors Collaborators. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet* 2020; **396**: 1223–49.
- Pillarisetti A, Vaswani M, Jack D, et al. Patterns of stove usage after introduction of an advanced cookstove: the long-term application of household sensors. *Environ Sci Technol* 2014; **48**: 14525–33.
- Ruiz-Mercado I, Masera O, Zamora H, Smith KR. Adoption and sustained use of improved cookstoves. *Energy Policy* 2011; **39**: 7557–66.
- Ruiz-Mercado I, Canuz E, Walker JL, Smith KR. Quantitative metrics of stove adoption using stove use monitors (SUMs). *Biomass Bioenergy* 2013; **57**: 136–48.
- Ruiz-Mercado I, Canuz E, Smith KR. Temperature dataloggers as stove use monitors (SUMs): field methods and signal analysis. *Biomass Bioenergy* 2012; **47**: 459–68.

- 36 Shankar AV, Quinn A, Dickinson KL, et al. Everybody stacks: lessons from household energy case studies to inform design principles for clean energy transitions. *Energy Policy* 2020; **141**: 111468.
- 37 Kar A, Tawiah T, Graham L, et al. Factors associated with the use of liquefied petroleum gas in Ghana vary at different stages of transition. *Nat Energy* 2024; **9**: 434–45.
- 38 Gould CF, Schlesinger SB, Molina E, Lorena Bejarano M, Valarezo A, Jack DW. Long-standing LPG subsidies, cooking fuel stacking, and personal exposure to air pollution in rural and peri-urban Ecuador. *J Expo Sci Environ Epidemiol* 2020; **30**: 707–20.
- 39 GBD 2023 Disease and Injury and Risk Factor Collaborators. Burden of 375 diseases and injuries, risk-attributable burden of 88 risk factors, and healthy life expectancy in 204 countries and territories, including 660 subnational locations, 1990–2023: a systematic analysis for the Global Burden of Disease Study 2023. *Lancet* 2025; **406**: 1873–1922.
- 40 Cleary GJ, Blackburn RB. Air pollution in native huts in the highlands of New Guinea. *Arch Environ Health* 1968; **17**: 785–94.
- 41 Sofoluwe GO. Smoke pollution in dwellings of infants with bronchopneumonia. *Arch Environ Health* 1968; **16**: 670–72.
- 42 Fandiño-Del-Rio M, Kephart JL, Williams KN, et al, and the Cardiopulmonary outcomes and Household Air Pollution trial (CHAP) Trial Investigators. Household air pollution exposure and associations with household characteristics among biomass cookstove users in Puno, Peru. *Environ Res* 2020; **191**: 110028.
- 43 Shupler M, Hystad P, Birch A, et al, and the PURE-AIR study. Household and personal air pollution exposure measurements from 120 communities in eight countries: results from the PURE-AIR study. *Lancet Planet Health* 2020; **4**: e451–62.
- 44 Commodore AA, Hartinger SM, Lanata CF, et al. Carbon monoxide exposures and kitchen concentrations from cookstove-related woodsmoke in San Marcos, Peru. *Int J Occup Environ Health* 2013; **19**: 43–54.
- 45 Liao J, McCracken JP, Piedrahita R, et al, and the HAPIN Investigators. The use of bluetooth low energy Beacon systems to estimate indirect personal exposure to household air pollution. *J Expo Sci Environ Epidemiol* 2020; **30**: 990–1000.
- 46 Piedrahita R, Coffey ER, Hagar Y, et al. Attributing air pollutant exposure to emission sources with proximity sensing. *Atmosphere (Basel)* 2019; **10**: 395.
- 47 Balakrishnan K, Sambandam S, Ramaswamy P, Mehta S, Smith KR. Exposure assessment for respirable particulates associated with household fuel use in rural districts of Andhra Pradesh, India. *J Expo Anal Environ Epidemiol* 2004; **14** (suppl 1): S14–25.
- 48 Smith KR, Aggarwal AL, Dave RM. Air pollution and rural biomass fuels in developing countries: a pilot village study in India and implications for research and policy. *Atmos Environ* 1967; **1983**: 2343–62.
- 49 Smith KR. Biofuels, air pollution, and health: a global review. Boston, MA: Springer, 1988.
- 50 Lim S, Bassey E, Bos B, et al. Comparing human exposure to fine particulate matter in low and high-income countries: a systematic review of studies measuring personal PM_{2.5} exposure. *Sci Total Environ* 2022; **833**: 155207.
- 51 Volckens J, Quinn C, Leith D, Mehaffy J, Henry CS, Miller-Lionberg D. Development and evaluation of an ultrasonic personal aerosol sampler. *Indoor Air* 2017; **27**: 409–16.
- 52 Pillarisetti A, Allen T, Ruiz-Mercado I, et al. Small, smart, fast, and cheap: microchip-based sensors to estimate air pollution exposures in rural households. *Sensors (Basel)* 2017; **17**: 1879.
- 53 Pillarisetti A, Carter E, Rajkumar S, et al. Measuring personal exposure to fine particulate matter (PM_{2.5}) among rural Honduran women: a field evaluation of the ultrasonic personal aerosol sampler (UPAS). *Environ Int* 2019; **123**: 50–53.
- 54 Keller JP, Clark ML. Estimating long-term average household air pollution concentrations from repeated short-term measurements in the presence of seasonal trends and crossover. *Environ Epidemiol* 2021; **6**: e188.
- 55 Steenland K, Pillarisetti A, Johnson M, et al. Optimizing exposure measures in large-scale household air pollution studies: results from the multicountry HAPIN trial. *Environ Sci Technol* 2025; **59**: 1693–99.
- 56 Pillarisetti A, Alnes LWH, Ye W, McCracken JP, Canuz E, Smith KR. Repeated assessment of PM_{2.5} in Guatemalan kitchens cooking with wood: Implications for measurement strategies. *Atmos Environ* 2023; **295**: 119533.
- 57 WHO. Global database of household air pollution measurements. <https://www.who.int/data/gho/data/themes/air-pollution/hap-measurement-db> (accessed Nov 1, 2025).
- 58 Shupler M, Godwin W, Frostad J, Gustafson P, Arku RE, Brauer M. Global estimation of exposure to fine particulate matter (PM_{2.5}) from household air pollution. *Environ Int* 2018; **120**: 354–63.
- 59 Shupler M, Balakrishnan K, Ghosh S, et al. Global household air pollution database: kitchen concentrations and personal exposures of particulate matter and carbon monoxide. *Data Brief* 2018; **21**: 1292–95.
- 60 Frostad JJ, Nguyen QP, Baumann MM, et al, and the Local Burden of Disease Household Air Pollution Collaborators. Mapping development and health effects of cooking with solid fuels in low-income and middle-income countries, 2000–18: a geospatial modelling study. *Lancet Glob Health* 2022; **10**: e1395–411.
- 61 Shupler M, Hystad P, Birch A, et al, and the PURE-AIR study investigators. Multinational prediction of household and personal exposure to fine particulate matter (PM_{2.5}) in the PURE cohort study. *Environ Int* 2022; **159**: 107021.
- 62 Ye W, Campbell D, Johnson M, et al. Exposure contrasts of women aged 40–79 years during the household air pollution intervention network randomized controlled trial. *Environ Sci Technol* 2025; **59**: 69–81.
- 63 Pillarisetti A, Ye W, Balakrishnan K, et al. Post-birth exposure contrasts for children during the Household Air Pollution Intervention Network randomized controlled trial. *medRxiv* 2023; published online July 6. <https://doi.org/10.1101/2023.07.04.23292226> (preprint).
- 64 McCracken JP, McCollum ED, Steenland K, et al, and the Household Air Pollution Intervention Network (HAPIN) Investigators. Exposure to household air pollution from biomass cooking and severe pneumonia in infants. *JAMA Netw Open* 2025; **8**: e2538721.
- 65 Chillrud SN, Ae-Ngibise KA, Gould CF, et al. The effect of clean cooking interventions on mother and child personal exposure to air pollution: results from the Ghana Randomized Air Pollution and Health Study (GRAPHHS). *J Expo Sci Environ Epidemiol* 2021; **31**: 683–98.
- 66 Shahriar MH, Chowdhury MAH, Ahmed S, et al. Exposure to household air pollutants and endothelial dysfunction in rural Bangladesh: a cross-sectional study. *Environ Epidemiol* 2021; **5**: e132.
- 67 Chafe ZA, Brauer M, Klimont Z, et al. Household cooking with solid fuels contributes to ambient PM_{2.5} air pollution and the burden of disease. *Environ Health Perspect* 2014; **122**: 1314–20.
- 68 McDuffee EE, Martin RV, Spadaro JV, et al. Source sector and fuel contributions to ambient PM_{2.5} and attributable mortality across multiple spatial scales. *Nat Commun* 2021; **12**: 3594.
- 69 Smith KR, Bruce N, Balakrishnan K, et al, and the HAP CRA Risk Expert Group. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. *Annu Rev Public Health* 2014; **35**: 185–206.
- 70 Burnett RT, Spadaro JV, Garcia GR, Pope CA. Designing health impact functions to assess marginal changes in outdoor fine particulate matter. *Environ Res* 2022; **204**: 112245.
- 71 Dherani M, Pope D, Mascarenhas M, Smith KR, Weber M, Bruce N. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. *Bull World Health Organ* 2008; **86**: 390–398C.
- 72 Amegah AK, Quansah R, Jaakkola JJK. Household air pollution from solid fuel use and risk of adverse pregnancy outcomes: a systematic review and meta-analysis of the empirical evidence. *PLoS One* 2014; **9**: e113920.
- 73 Lee KK, Bing R, Kiang J, et al. Adverse health effects associated with household air pollution: a systematic review, meta-analysis, and burden estimation study. *Lancet Glob Health* 2020; **8**: e1427–34.
- 74 Chen T, Zou C, Yuan Y, et al. Indoor air pollution from solid fuel on children pneumonia in low- and middle-income countries: a systematic review and meta-analysis. *Environ Sci Pollut Res Int* 2022; **29**: 24574–88.

- 75 Younger A, Alkon A, Harknett K, Jean Louis R, Thompson LM. Adverse birth outcomes associated with household air pollution from unclean cooking fuels in low- and middle-income countries: a systematic review. *Environ Res* 2022; **204**: 112274.
- 76 Onakomaiya D, Gyamfi J, Iwelunmor J, et al. Implementation of clean cookstove interventions and its effects on blood pressure in low-income and middle-income countries: systematic review. *BMJ Open* 2019; **9**: e026517.
- 77 Raju SP. Smokeless kitchens for the millions. Colombo: Christian Literature Society, 1954.
- 78 Clean Cooking Alliance. 2023 annual report. <https://cleancooking.org/wp-content/uploads/2024/03/CCA-2023-Annual-Report.pdf> (accessed March 1, 2025).
- 79 WHO. WHO guidelines for indoor air quality: household fuel combustion. Jan 21, 2014. <https://www.who.int/publications/i/item/9789241548885> (accessed March 1, 2025).
- 80 Shen H, Luo Z, Xiong R, et al. A critical review of pollutant emission factors from fuel combustion in home stoves. *Environ Int* 2021; **157**: 106841.
- 81 Shen G, Gaddam CK, Ebersviller SM, et al. A laboratory comparison of emission factors, number size distributions, and morphology of ultrafine particles from 11 different household cookstove-fuel systems. *Environ Sci Technol* 2017; **51**: 6522–32.
- 82 Jetter J, Zhao Y, Smith KR, et al. Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environ Sci Technol* 2012; **46**: 10827–34.
- 83 Roden CA, Bond TC, Conway S, Osoto Pinel AB, MacCarty N, Still D. Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. *Atmos Environ* 2009; **43**: 1170–81.
- 84 Du W, Zhu X, Chen Y, et al. Field-based emission measurements of biomass burning in typical Chinese built-in-place stoves. *Environ Pollut* 2018; **242**: 1587–97.
- 85 Pope D, Bruce N, Dherani M, Jagoe K, Rehfuess E. Real-life effectiveness of 'improved' stoves and clean fuels in reducing PM_{2.5} and CO: systematic review and meta-analysis. *Environ Int* 2017; **101**: 7–18.
- 86 Pope D, Johnson M, Fleeman N, et al. Are cleaner cooking solutions clean enough? A systematic review and meta-analysis of particulate and carbon monoxide concentrations and exposures. *Environ Res Lett* 2021; **16**: 083002.
- 87 Sambandam S, Balakrishnan K, Ghosh S, et al. Can currently available advanced combustion biomass cook-stoves provide health relevant exposure reductions? Results from initial assessment of select commercial models in India. *EcoHealth* 2015; **12**: 25–41.
- 88 Quansah R, Semple S, Ochieng CA, et al. Effectiveness of interventions to reduce household air pollution and/or improve health in homes using solid fuel in low-and-middle income countries: a systematic review and meta-analysis. *Environ Int* 2017; **103**: 73–90.
- 89 Kumar N, Phillip E, Cooper H, et al. Do improved biomass cookstove interventions improve indoor air quality and blood pressure? A systematic review and meta-analysis. *Environ Pollut* 2021; **290**: 117997.
- 90 Phillip E, Langevin J, Davis M, et al. Improved cookstoves to reduce household air pollution exposure in sub-Saharan Africa: a scoping review of intervention studies. *PLoS One* 2023; **18**: e0284908.
- 91 Lai PS, Lam NL, Gallery B, et al. Household air pollution interventions to improve health in low- and middle-income countries: an official American Thoracic Society research statement. *Am J Respir Crit Care Med* 2024; **209**: 909–27.
- 92 Smith KR, McCracken JP, Thompson L, et al. Personal child and mother carbon monoxide exposures and kitchen levels: methods and results from a randomized trial of woodfired chimney cookstoves in Guatemala (RESPIRE). *J Expo Sci Environ Epidemiol* 2010; **20**: 406–16.
- 93 Smith KR, McCracken JP, Weber MW, et al. Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *Lancet* 2011; **378**: 1717–26.
- 94 Tielsch JM, Katz J, Zeger SL, et al. Designs of two randomized, community-based trials to assess the impact of alternative cookstove installation on respiratory illness among young children and reproductive outcomes in rural Nepal. *BMC Public Health* 2014; **14**: 1271.
- 95 Katz J, Tielsch JM, Khatry SK, et al. Impact of improved biomass and liquid petroleum gas stoves on birth outcomes in rural Nepal: results of 2 randomized trials. *Glob Health Sci Pract* 2020; **8**: 372–82.
- 96 Keller JP, Katz J, Pokhrel AK, Bates MN, Tielsch J, Zeger SL. A hierarchical model for estimating the exposure–response curve by combining multiple studies of acute lower respiratory infections in children and household fine particulate matter air pollution. *Environ Epidemiol* 2020; **4**: e119.
- 97 Mortimer K, Ndamala CB, Naunje AW, et al. A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): a cluster randomised controlled trial. *Lancet* 2017; **389**: 167–75.
- 98 Mortimer K, Lesosky M, Semple S, et al. Pneumonia and exposure to household air pollution in children under the age of 5 years in rural Malawi: findings from the Cooking and Pneumonia Study. *Chest* 2020; **158**: 501–11.
- 99 Alexander DA, Northcross A, Karrison T, et al. Pregnancy outcomes and ethanol cook stove intervention: a randomized-controlled trial in Ibadan, Nigeria. *Environ Int* 2018; **111**: 152–63.
- 100 Alexander D, Northcross A, Wilson N, et al. Randomized controlled ethanol cookstove intervention and blood pressure in pregnant Nigerian women. *Am J Respir Crit Care Med* 2017; **195**: 1629–39.
- 101 Jack DW, Asante KP, Wylie BJ, et al. Ghana Randomized Air Pollution and Health Study (GRAPHS): study protocol for a randomized controlled trial. *Trials* 2015; **16**: 420.
- 102 Jack DW, Ae-Ngibise KA, Gould CF, et al. A cluster randomised trial of cookstove interventions to improve infant health in Ghana. *BMJ Glob Health* 2021; **6**: e005599.
- 103 Quinn AK, Adjei IA, Ae-Ngibise KA, et al. Prenatal household air pollutant exposure is associated with reduced size and gestational age at birth among a cohort of Ghanaian infants. *Environ Int* 2021; **155**: 106659.
- 104 Lee AG, Kaali S, Quinn A, et al. Prenatal household air pollution is associated with impaired infant lung function with sex-specific effects. Evidence from GRAPHS, a cluster randomized cookstove intervention trial. *Am J Respir Crit Care Med* 2019; **199**: 738–46.
- 105 Quinn AK, Ae-Ngibise KA, Jack DW, et al. Association of carbon monoxide exposure with blood pressure among pregnant women in rural Ghana: evidence from GRAPHS. *Int J Hyg Environ Health* 2016; **219**: 176–83.
- 106 Fandiño-Del-Rio M, Goodman D, Kephart JL, et al, and the Cardiopulmonary outcomes and Household Air Pollution trial (CHAP) Trial Investigators. Effects of a liquefied petroleum gas stove intervention on pollutant exposure and adult cardiopulmonary outcomes (CHAP): study protocol for a randomized controlled trial. *Trials* 2017; **18**: 518.
- 107 Barr DB, Puttaswamy N, Jaacks LM, et al, and the HAPIN Investigative Team. Design and rationale of the biomarker center of the Household Air Pollution Intervention Network (HAPIN) trial. *Environ Health Perspect* 2020; **128**: 47010.
- 108 Johnson MA, Steenland K, Piedrahita R, et al, and the HAPIN Investigators. Air pollutant exposure and stove use assessment methods for the Household Air Pollution Intervention Network (HAPIN) trial. *Environ Health Perspect* 2020; **128**: 47009.
- 109 Clasen T, Checkley W, Peel JL, et al, and the HAPIN Investigators. Design and rationale of the HAPIN study: a multicountry randomized controlled trial to assess the effect of liquefied petroleum gas stove and continuous fuel distribution. *Environ Health Perspect* 2020; **128**: 47008.
- 110 Checkley W, Thompson LM, Sinharoy SS, et al, and the HAPIN Investigators. Effects of cooking with liquefied petroleum gas or biomass on stunting in infants. *N Engl J Med* 2024; **390**: 44–54.
- 111 McCollum ED, McCracken JP, Kirby MA, et al, and the HAPIN Investigators. Liquefied petroleum gas or biomass cooking and severe infant pneumonia. *N Engl J Med* 2024; **390**: 32–43.
- 112 Balakrishnan K, Steenland K, Clasen T, et al, and the HAPIN Investigators. Exposure–response relationships for personal exposure to fine particulate matter (PM_{2.5}), carbon monoxide, and black carbon and birthweight: an observational analysis of the multicountry Household Air Pollution Intervention Network (HAPIN) trial. *Lancet Planet Health* 2023; **7**: e387–96.

- 113 Williams KN, Quinn A, North H, et al, and the HAPIN Investigators. Fidelity and adherence to a liquefied petroleum gas stove and fuel intervention: the multi-country Household Air Pollution Intervention Network (HAPIN) trial. *Environ Int* 2023; **179**: 108160.
- 114 Quinn AK, Williams KN, Thompson LM, et al. Fidelity and adherence to a liquefied petroleum gas stove and fuel intervention during gestation: the multi-country Household Air Pollution Intervention Network (HAPIN) randomized controlled trial. *Int J Environ Res Public Health* 2021; **18**: 12592.
- 115 Pillarisetti A, Ghorpade M, Madhav S, et al. Promoting LPG usage during pregnancy: a pilot study in rural Maharashtra, India. *Environ Int* 2019; **127**: 540–49.
- 116 Clasen TF, Chang HH, Thompson LM, et al, and the HAPIN Investigators. Liquefied petroleum gas or biomass for cooking and effects on birth weight. *N Engl J Med* 2022; **387**: 1735–46.
- 117 Ahmed A, Rahman AE, Ahmed S, et al. Effect of low-cost kitchen with improved cookstove on birthweight of neonates in Shahjapur, Bangladesh: a cluster-randomised controlled trial. *Lancet Reg Health Southeast Asia* 2024; **25**: 100342.
- 118 Hartinger SM, Lanata CF, Hattendorf J, et al. Improving household air, drinking water and hygiene in rural Peru: a community-randomized-controlled trial of an integrated environmental home-based intervention package to improve child health. *Int J Epidemiol* 2016; **45**: 2089–99.
- 119 Romieu I, Riojas-Rodríguez H, Marrón-Mares AT, Schilman A, Perez-Padilla R, Masera O. Improved biomass stove intervention in rural Mexico: impact on the respiratory health of women. *Am J Respir Crit Care Med* 2009; **180**: 649–56.
- 120 Hanna R, Duflo E, Greenstone M. Up in smoke: the influence of household behavior on the long-run impact of improved cooking stoves. *Am Econ J Econ Policy* 2016; **8**: 80–114.
- 121 Bensch G, Peters J. The intensive margin of technology adoption—experimental evidence on improved cooking stoves in rural Senegal. *J Health Econ* 2015; **42**: 44–63.
- 122 Berkouwer S, Dean J. Private actions in the presence of externalities: the health impacts of reducing air pollution peaks but not ambient exposure. *SSRN* 2023; published online Sept 26. <http://dx.doi.org/10.2139/ssrn.4579074>.
- 123 WHO. WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide 7. Sept 22, 2021. <https://www.who.int/publications/i/item/9789240034228> (accessed Nov 1, 2025).
- 124 Kinney PL, Asante K-P, Lee AG, et al. Prenatal and postnatal household air pollution exposures and pneumonia risk: evidence from the Ghana Randomized Air Pollution and Health Study. *Chest* 2021; **160**: 1634–44.
- 125 Kaali S, Jack DW, Mujtaba MN, et al. Identifying sensitive windows of prenatal household air pollution on birth weight and infant pneumonia risk to inform future interventions. *Environ Int* 2023; **178**: 108062.
- 126 Fandiño-Del-Rio M, Kephart JL, Williams KN, et al, and the Cardiopulmonary outcomes and Household Air Pollution (CHAP) Trial Investigators. Household air pollution concentrations after liquefied petroleum gas interventions in rural Peru: findings from a one-year randomized controlled trial followed by a one-year pragmatic crossover trial. *Environ Health Perspect* 2022; **130**: 57007.
- 127 Gould CF, Davila L, Bejarano ML, et al. Exposure to nitrogen dioxide and fine particulate matter when cooking with electricity compared to gas, a randomized crossover study in Quito, Ecuador. *Environ Health Perspect* 2024; **132**: 17702.
- 128 Paulin LM, Diette GB, Scott M, et al. Home interventions are effective at decreasing indoor nitrogen dioxide concentrations. *Indoor Air* 2014; **24**: 416–24.
- 129 Hakam DF, Nugraha H, Wicaksono A, Rahadi RA, Kanugrahan SP. Mega conversion from LPG to induction stove to achieve Indonesia's clean energy transition. *Energy Strategy Reviews* 2022; **41**: 100856.
- 130 Gould CF, Schlesinger S, Toasa AO, et al. Government policy, clean fuel access, and persistent fuel stacking in Ecuador. *Energy Sustain Dev* 2018; **46**: 111–22.
- 131 Gould CF, Bejarano ML, De La Cuesta B, et al. Climate and health benefits of a transition from gas to electric cooking. *Proc Natl Acad Sci USA* 2023; **120**: e2301061120.
- 132 Thompson LM, Diaz-Artiga A, Weinstein JR, Handley MA. Designing a behavioral intervention using the COM-B model and the theoretical domains framework to promote gas stove use in rural Guatemala: a formative research study. *BMC Public Health* 2018; **18**: 253.
- 133 Simkovich SM, Williams KN, Pollard S, et al. A systematic review to evaluate the association between clean cooking technologies and time use in low- and middle-income countries. *Int J Environ Res Public Health* 2019; **16**: 2277.
- 134 Williams KN, Kephart JL, Fandiño-Del-Rio M, et al, and the CHAP trial Investigators. Exploring the impact of a liquefied petroleum gas intervention on time use in rural Peru: a mixed methods study on perceptions, use, and implications of time savings. *Environ Int* 2020; **145**: 105932.
- 135 Petrokofsky G, Harvey WJ, Petrokofsky L, Ochieng CA. The importance of time-saving as a factor in transitioning from woodfuel to modern cooking energy services: a systematic map. *Forests* 2021; **12**: 1149.
- 136 Ma W, Vatsa P, Zheng H. Cooking fuel choices and subjective well-being in rural China: implications for a complete energy transition. *Energy Policy* 2022; **165**: 112992.
- 137 Malakar Y, Day R. Differences in firewood users' and LPG users' perceived relationships between cooking fuels and women's multidimensional well-being in rural India. *Nat Energy* 2020; **5**: 1022–31.
- 138 Imelda. Cooking that kills: cleaner energy access, indoor air pollution, and health. *J Dev Econ* 2020; **147**: 102548.

Copyright © 2026 The Author(s). Published by Elsevier Ltd. This is an Open Access article under the CC BY-NC-ND 4.0 license.