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Household Air Pollution Interventions to Improve Health in Low- and Middle-Income Countries

An Official American Thoracic Society Research Statement

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Abstract

Background: An estimated 3 billion people, largely in low- and middle-income countries, rely on unclean fuels for cooking, heating, and lighting to meet household energy needs. The resulting exposure to household air pollution (HAP) is a leading cause of pneumonia, chronic lung disease, and other adverse health effects. In the last decade, randomized controlled trials of clean cooking interventions to reduce HAP have been conducted. We aim to provide guidance on how to interpret the findings of these trials and how they should inform policy makers and practitioners.

Methods: We assembled a multidisciplinary working group of international researchers, public health practitioners, and policymakers with expertise in household air pollution from within academia, the American Thoracic Society, funders, nongovernmental organizations, and global organizations, including the World Bank and the World Health Organization. We performed a literature search, convened four sessions via web conference, and developed consensus conclusions and recommendations via the Delphi method.

Results: The committee reached consensus on 14 conclusions and recommendations. Although some trials using cleaner-burning biomass stoves or cleaner-cooking fuels have reduced HAP exposure, the committee was divided (with 55% saying no and 45% saying yes) on whether the studied interventions improved measured health outcomes.

Conclusions: HAP is associated with adverse health effects in observational studies. However, it remains unclear which household energy interventions reduce exposure, improve health, can be scaled, and are sustainable. Researchers should engage with policy makers and practitioners working to scale cleaner energy solutions to understand and address their information needs.

Keywords: household air pollution (HAP); low- and middle-income countries (LMICs); randomized controlled trial (RCT); biomass; liquified petroleum gas (LPG)

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Overview

One of the most pressing environmental health problems affecting people living in low- and middle-income countries (LMICs) is exposure to household air pollution (HAP) generated by combustion sources used for basic energy services, such as cooking, lighting, electricity generation, and heating. In the last decade, there have been a number of intervention trials focused on strategies to reduce HAP with mixed or null health effects to date. There remains a communication gap between academic researchers and decision makers at all levels of government, multinational development organizations, on-the-ground practitioners, and financiers. A multidisciplinary group of international experts in HAP and energy access in LMIC contexts met throughout 2022 and wrote this report focused on the following key questions:

1. What have we learned from existing HAP interventions to improve health?
2. What are important secondary outcomes and design considerations for such trials?
3. How do we bridge the communication gap between academic research and decision makers that increase household energy access?
4. What are critical knowledge gaps in HAP research that require further study?

A summary of conclusions and recommendations based on expert consensus achieved through the Delphi method is outlined in Box 1.

Introduction

An estimated 3 billion people, primarily in LMICs, are exposed to HAP generated by combustion sources used for basic energy services such as cooking, heating, electricity generation, and lighting (1). HAP is generated from inefficient combustion of fuels or inefficient devices used to meet household energy needs and is composed of numerous pollutants, including fine particulate matter (particulate matter with an aerodynamic diameter of 2.5 μm or less [$PM_{2.5}$]) and black carbon. HAP is responsible for an estimated 3.2 million deaths per year (2) and is among the top five risk factors for premature mortality in LMICs (1, 3, 4). In 2014, the respiratory risks from HAP were highlighted in a Lancet Commission report (1), which summarized the evidence from largely observational studies for the association between HAP and a broad range of lung diseases, including respiratory infections, respiratory cancers, and chronic lung diseases. Furthermore, the commission highlighted HAP as a fundamental issue of health inequality, with women and children living in poverty at the highest risk of exposure (3).

Randomized controlled trials have been conducted to evaluate the effects of clean cooking interventions to mitigate HAP and improve health. These have largely focused on either more efficient biomass stoves or replacing biomass with cleaner-burning fuels such as liquefied petroleum gas (LPG) or ethanol. In 2011, a trial of vented chimney wood stoves in Guatemala (5) reported a reduction in kitchen concentrations and 48-hour personal exposures to carbon monoxide but no effect on the primary outcome of physician-diagnosed pneumonia. A large trial of improved biomass stoves in Malawi (6) reported no effects on HAP concentrations or pneumonia. Randomized trials of cookstove interventions have been performed in India (7), Nigeria (8), Peru (9), and Ghana (10), and a multicountry trial has been performed that was based in Guatemala, India, Peru, and Rwanda (11), with substantial reductions in personal exposure only achieved when traditional biomass was replaced with cleaner fuels that were used consistently. However, even where HAP was largely reduced, the trials reported little or no effects on the primary health outcomes based on intention-to-treat analyses. Most of these trials were published after the 2014 Lancet Commission report, highlighting the need to reevaluate the evidence for strategies to reduce HAP and improve health.

A further challenge is that for successful household energy interventions to be scaled, nonacademic practitioners, including policy makers, entities or organizations involved in the household energy supply chain, and end users must be engaged. There remains a science translation gap between academic researchers and country-level decision makers from local to national level governments, multinational development organization, on-the-ground practitioners, and financiers. Health-related research is only one of the many inputs into the policymaking process. It is thus critically important that researchers engage with policy makers and practitioners working to scale cleaner energy solutions to understand and address their information needs.

Methods

Committee Composition and Meetings

The project organizers invited a multidisciplinary group composed of international researchers, public health practitioners, and policymakers with expertise in air pollution, public health, and energy access. To encourage a diversity of perspectives, this group included members

Box 1: Summary of Consensus Statements

1. Observational studies demonstrate that household air pollution (HAP) is associated with adverse health outcomes.
2. Some published randomized clinical trials of household energy interventions, especially those in settings with low ambient (outdoor) air pollution, identified reduced HAP exposure.
3. Published randomized trials of household energy interventions (largely involving cooking) did not improve primary health outcomes in intention-to-treat analyses.
4. Intervention strategies for clean household energy are context dependent. The degree of exposure reduction is more important than a specific fuel or technology.
5. To investigate or explore health effects, future HAP studies should target exposures in the prenatal and early childhood periods (critical windows of exposure) and be designed with longer follow-up time (at least 5 yr).
6. Reducing exposure to HAP is an important outcome even if the intervention does not achieve a sufficiently low exposure level, such as to a "floor" of outdoor air pollution levels or World Health Organization interim targets.
7. Currently, for most practitioners (governments, nongovernmental organizations, international organizations), health is not the primary driver for scale-up decisions.
8. The largest barriers to scaling up household energy programs are affordability and availability.
9. Subsidies to increase clean energy access in resource-limited settings have both potential beneficial and harmful effects.
10. Most household energy programs require involvement of both the public (government) and private (businesses) sector to achieve a reasonable scale-up.
11. Barriers to translating research findings into decisions on policy and scale-up include the format in which academic research is communicated. Academic papers are not the optimal way to communicate with decision makers or practitioners responsible for scale-up of clean energy programs.
12. The fuel choices that result in HAP also contribute to climate change.
13. There should be more research targeting exposure to other sources of HAP beyond cooking.
14. Further research in household energy is required in several areas, including the needs and priorities of end users as well as practitioners, economic studies, the long-term impact of HAP on health, the effect of interventions on multiple pollutants, contribution of HAP to outdoor air pollution, tools that model cobenefits of clean energy programs and quantify benefits at the subnational level, and additional areas.

from within and outside academia, including those affiliated with the American Thoracic Society; the National Institutes of Health; multinational organizations, including the World Bank, International Finance Corporation, and World Health Organization (WHO); the Clean Cooking Alliance; and nongovernmental organizations (NGOs). Members were represented in both high-income settings and LMICs with research expertise that spanned observational studies, clinical trials, exposure assessment, health policy, and engineering, as well as qualitative and quantitative research, whereas household energy practitioners included those responsible for setting national or international agendas as well as those working in boundary organizations interfacing with both researchers and elected officials at the city, region, or country level on energy policy. Four separate virtual meetings were held that were based on each of the key questions. Using a "flipped classroom" approach, designated speakers for each session prerecorded a talk that was viewed by participants before each meeting. During the meeting, the talks were briefly summarized, with the majority of the time dedicated to discussion regarding key questions for that topic. Each meeting was recorded, and before the subsequent meeting, the content was summarized by the project organizers and shared with the committee. Discussions were held between meetings using DocMatter (12). On the basis of these meetings and both online and offline discussions, recommendations were proposed, and expert consensus was achieved via the Delphi method, whereby each group member voted anonymously on each recommendation. Consensus was defined as at least 80% participation in each recommendation with a minimum 70% threshold for agreement (Table 1).

Literature Search and Appraisal of Existing Evidence

Electronic searches for published literature were conducted by a medical librarian using Ovid MEDLINE (1946 to present), Embase.com (1947 to present), Web of Science (1900 to present), and the Cochrane Central Register of Controlled Trials (CENTRAL) via Ovid (1991 to present). The searches were run in March 2022.

The search strategy incorporated controlled vocabulary and free-text synonyms for the concepts of household, health, clean energy, pollutants, energy uses, LMICs, and interventions. The intervention concept was adapted from Avau et al.'s filter (13), and the concept for LMICs was developed by Cochrane Effective Practice and Organization of Care (EPOC) (14). The full database search strategies are documented in Appendix E1 in the online supplement. No restrictions on language or any other search filters were applied. All identified studies were combined and deduplicated in a single reference manager (EndNote). The citations were then uploaded into Covidence (15), a web-based collaboration software platform that streamlines the production of systematic and other literature reviews.

The 1,387 retrieved publications from the literature search returned a broad variety

Table 1. Delphi Method to Achieve Expert Consensus*

	Question	Consensus	Agreement	Comment
Q1	HAP contributes to adverse health effects.	Yes	96.60%	
Q2	Current studied interventions focused on single contributors to HAP in isolation do not improve health or save lives in LMICs.	No	55.17%	
Q3	Published randomized trials of household energy interventions (largely involving cooking) did not improve primary health outcomes in intention-to-treat analyses.	Yes	86.21%	
Q4	Some published randomized trials of household energy interventions reduced exposure to air pollution.	Yes	100.00%	
Q5	Observational studies demonstrate that HAP contributes to adverse health outcomes.	Yes	100.00%	
Q6	To investigate or explore health effects, future HAP intervention studies should target exposures in early childhood, i.e., critical windows of exposure.	Yes	100.00%	
Q7	To investigate or explore health effects, future HAP studies should be designed with longer follow-up, i.e., at least 5 yr.	Yes	96.55%	
Q8	Reducing exposure to HAP is an important outcome even if the intervention does not achieve a sufficiently low exposure level, e.g., to a floor of ambient pollution or World Health Organization interim targets.	Yes	93.10%	
Q9	Solutions for clean household energy are context dependent. The degree of exposure reduction is more important than a specific fuel or technology.	Yes	96.55%	
Q10	Important health outcomes for future HAP research should include the following:			Most important: pulmonary (33.33%), pregnancy (24.14%), cardiovascular (21.43%), neurocognitive (11.54%)
Q11	Currently, for most stakeholders (governments, NGOs, international organizations) health is not the primary driver for scale-up decisions.	Yes	92.59%	
Q12	Critical barriers to scaling up household energy programs include the following:			Most important: affordability (62.96%), accessibility (18.52%), advantage (12%)
Q13	Most household energy programs require involvement of both the public (government) and private (businesses) sectors to achieve a reasonable scale-up.	Yes	100.00%	
Q14	Barriers to translating research findings into decisions on policy and scale-up include the format in which academic research is communicated. Academic papers are not a good way to communicate with decision makers or practitioners who scale up clean energy programs.	Yes	96.30%	
Q15	Subsidies to increase clean energy access in resource-limited settings have both potential beneficial and harmful effects.	Yes	74.07%	
Q16	HAP contributes to climate change.	Yes	85.19%	
Q17	Based on the level of emissions and climate impact, widespread LPG use is recommended at scale in LMICs.	No	62.96%	
Q18	We need to do more research targeting reducing exposure to other sources of HAP beyond cooking.	Yes	88.89%	
Q19	There is a place for mechanical air filtration devices (for example, air purifiers) as an intervention to reduce exposure to HAP in LMICs.	No	44.44%	

(*Continued*)

Table 1. (*Continued*)

	Question	Consensus	Agreement	Comment
Q20	Further research in household energy is required in the following areas:			
	a. Contribution of HAP to ambient air pollution	Yes	88.89%	
	b. Long-term observational studies of HAP and health outcomes spanning decades	Yes	92.59%	
	c. Exposure–response studies on other pollutants beyond $PM_{2.5}$ and black carbon	Yes	81.48%	
	d. Mechanistic research on how HAP exposure impacts health	Yes	70.37%	
	e. Tools that can model all the cobenefits of a clean energy program (climate, health, environmental impacts, equality, gender issues) that decision makers can use for scale-up decisions	Yes	88.89%	
	f. Identifying shared language between stakeholders and academia	Yes	88.89%	
	g. Impact of subsidies and strategies to deploy them (economic studies)	Yes	96.30%	
	h. Willingness to pay (economic studies)	Yes	92.59%	
	i. Policy implications of scale-up (economic studies)	Yes	100.00%	
	j. Interventions that are designed and/or evaluated using implementation science models, theories, or frameworks	Yes	85.19%	
	k. Interventions that address multiple components of HAP	Yes	92.59%	
	l. Community-level interventions to address HAP	Yes	92.59%	
Q21	Further research in household energy should be discouraged in the following areas:			
	a. Interventions focused on short-term (<5 yr) health outcomes in healthy adults	No	55.56%	
	b. Interventions focused on improved biomass stoves and health outcomes	Yes	70.37%	
	c. Interventions that do not measure adoption and exposure reduction	Yes	74.07%	

Definition of abbreviations: HAP = household air pollution; LMIC = low- and middle-income country; NGO = nongovernmental organization.
*Consensus was defined as a minimum 80% participation and 70% agreement for each recommendation.

of publications from very different fields: biomedical, energy, policy. Reporting standards varied widely; for example, in the nonbiomedical literature, outcome definitions were sometimes not specified. Thus, it was difficult to perform a synthesis of the literature, and instead results of the literature search were used to formulate the key topics addressed in the prerecorded talks, the formulation of the Delphi questions, and manuscript preparation.

Document Development

Project organizers prepared a draft document on the basis of the discussions during and between each meeting with subsequent contributions from the writing group. These leaders collated a complete single document that was sent to all participants for review and feedback with multiple cycles of review, revision, and feedback until all participants agreed on a final version.

Topic 1: Do HAP Interventions (Addressing Cooking Services) in LMICs Improve Health?

Consensus Statement 1: Observational studies demonstrate that HAP is associated with adverse health outcomes.
Consensus Statement 2: Some published randomized clinical trials of household energy interventions, especially those in settings with low ambient (outdoor) air pollution, identified reduced HAP exposure.
Consensus Statement 3: Published randomized trials of household energy interventions (largely involving cooking) did not improve primary health outcomes in intention-to-treat analyses.

Observational studies have consistently documented worse health outcomes with higher HAP concentrations. Multiple systematic reviews with meta-analyses (16–19) have documented significant pooled associations between exposure to HAP and multiple health outcomes, including childhood pneumonia, birthweight, adverse pregnancy outcomes, and adult blood pressure. In contrast, cleaner cooking interventions have largely failed to demonstrate improvements in prespecified trial health outcomes (5, 6, 9, 10, 20–24) (*see* Table 2). These trials have tested adding chimneys to biomass stoves (5), improving the combustion efficiency of biomass stoves, and replacing biomass fuels and stoves with cleaner cooking fuels, namely LPG (6, 7, 9, 10, 20, 21, 25–33) and ethanol (8, 22). In the first trial of an HAP intervention, Smith *et al.* reported a 50% relative reduction in carbon monoxide with chimneys but no effect on physician-diagnosed pneumonia, the primary outcome (5). Subsequent trials replaced traditional three-stone cooking fires and other traditional stoves with rocket and

Table 2. Randomized Trials of Household Air Pollution Interventions Focused on Health

Citation	Countr(y/ies)	Setting	Type of Intervention	Population	Measured Exposure	Outcome(s)	Findings
Smith *et al.*, 2011 (5); Smith-Silverstein *et al.*, 2009 (35); Guarnieri *et al.*, 2015 (26); McCracken *et al.*, 2007 (27)	Guatemala	Rural	Individual RCT of an improved biomass-burning cookstove with a chimney vs. continue using an open-fire stove	534 households with a pregnant woman or infant	48-h CO using diffusion tubes (Gastec Corp.) every 3 mo for all children, fine particulate matter in a subset of participants	Primary outcome was pneumonia in children under 5 Secondary outcomes included respiratory health, blood pressure, and lung function in adult women	Reduced personal exposure to CO in intervention children when compared with control subjects and reduced fine particulate matter in the subset of intervention children when compared with control subjects. No difference in physician-diagnosed pneumonia between intervention and control children. In secondary outcomes, there was a lower risk of severe pneumonia in children. Adult women in the intervention had less wheezing, lower number of respiratory symptoms, and lower diastolic blood pressure than control subjects but no difference in lung function between intervention and control arms.
Tielsch *et al.*, 2014 (34); Katz *et al.*, 2020 (20)	Nepal	Rural	Step-wedge RCT of an improved cookstove (Envirofit International) with a chimney vs. cooking with biomass; followed by an individual RCT of an LPG stove and fuel vs. improved vented biomass cookstove	5,254 children from 3,376 households A total of 2,379 live-born infants were born during the step-wedge trial and 270 and 279 were born during the individual RCT of LPG vs. improved cookstove	24-h kitchen concentrations of particulate matter using the DataRAM pDR-1000 (Thermo Fisher Scientific) and CO using the Lascar EL-USB-CO300	Birthweight and pneumonia in children less than 3 yr of age	Particulate matter and CO kitchen concentrations were lower in the improved cookstove when compared with cooking with biomass in the step-wedge trial. Particulate matter and carbon monoxide kitchen concentrations were also reduced in participants using LPG when compared with the improved cookstove in the individual RCT. No difference in birthweight or acute respiratory infections in children.
Mortimer *et al.*, 2017 (6)	Malawi	Rural	Cluster RCT testing a cleaner-burning biomass stove (Philips fan-driven gasifier stove a solar panel, and user training) vs.	Households with a child under the age of 4.5 yr were eligible. 10,543 children (5,297 intervention vs.	48-h personal exposures to CO using the Lascar EL-USB-CO monitors at baseline and every 6 mo	Incidence of WHO Integrated Management of Childhood Illness–defined pneumonia in children under 5 yr of age	No difference in personal exposures to carbon monoxide between intervention and control participants No difference in the risk of childhood pneumonia

(*Continued*)

Table 2. (*Continued*)

Citation	Countr(y/ies)	Setting	Type of Intervention	Population	Measured Exposure	Outcome(s)	Findings
			cooking with biomass	5,246 control) in 8,470 households (4,256 intervention vs. 4,212 control) 75 clusters in both intervention and control (with ~70 participants per cluster).		diagnosed by physicians, medical officers, or other appropriately trained staff at local healthcare facilities	
Romieu *et al.*, 2009 (28); Schilmann *et al.*, 2015 (32)	Mexico	Rural	Individual RCT of an improved biomass-burning cookstove vs. open-fire stove	668 households that used an open-fire stove and had a child less than 5 yr of age. 552 women and 668 children participated in the RCT.	No	Primary outcomes include respiratory symptoms and lung function decline in women. Secondary outcomes include acute respiratory infections in children under 5.	Lower risk of respiratory symptoms, eye discomfort, headache, and back pain in intervention women compared with control subjects. Lower decline in lung function in intervention women compared with control subjects; lower duration of acute respiratory infections in children
Beltramo *et al.*, 2013 (29)	Senegal	Rural	Cluster RCT of a solar oven vs. biomass (20 study villages) HotPot, a panel solar cooker, uses a reflector to direct sunlight to a 5-L black enamel steel pot that is within a larger tempered glass bowl with a lid.	A total of 838 households ~25 households in each study village received a solar oven and 25 continued with usual cooking practices	CO using Dräger color diffusion tubes tested in a subset of 275 households	Respiratory illnesses in the last 7 d in adult women and children.	No evidence solar ovens reduced exposure to CO or self-reported respiratory symptoms such as coughs and sore throats
Bensch *et al.*, 2015 (30)	Senegal	Rural	RCT of an improved cookstove vs. biomass Portable single-pot stove with a fired clay combustion center enclosed by a metal casing.	Improved cookstove or a 5-kg bag of rice for control subjects	No	Respiratory system disease or eye problems in cooks and noncooks	A 6.9% and 5.7% reduction in respiratory system disease and eye problems in cooks but no differences in noncooks
Burwen *et al.*, 2012 (31)	Ghana	Rural	RCT of an improved cookstove vs. biomass Locally designed improved cookstove	768 participants	CO (Gastec 1DL carbon monoxide passive diffusion tubes)	Self-reported symptoms (including respiratory symptoms) in the last week	No reductions in CO; 34% of control subjects reported symptoms vs. 17% of intervention participants

(*Continued*)

Table 2. (*Continued*)

Citation	Countr(y/ies)	Setting	Type of Intervention	Population	Measured Exposure	Outcome(s)	Findings
Hanna *et al.*, 2016 (7)	India	Rural	RCT of an improved cookstove vs. cooking with biomass Gram Vikas constructed improved stove	2,575 households in 44 villages	Exhaled CO	Detailed health recall about symptoms (coughs, colds, etc.), infant outcomes, and health expenditures. Complemented height, weight, and arm circumference and spirometry	No reductions in exhaled CO, no effects on any health outcomes
Hartinger *et al.*, 2016 (35)	Peru	Rural	Cluster RCT of a multicomponent intervention vs. usual care Multicomponent intervention: an improved ventilated solid-fuel stove, a kitchen sink with in-kitchen water connection, a point-of-use water quality intervention applying solar disinfection to drinking water and a hygiene intervention focusing on handwashing with soap and kitchen hygiene	534 children in 50 communities	No	Incidence of diarrhea and acute respiratory infections in children aged 6–35 mo	No difference in the risk of diarrhea or acute respiratory infections in children
Jack *et al.*, 2021 (10)	Ghana	Urban	Cluster RCT of an LPG stove vs. improved biomass-burning cookstove vs. usual care	1,414 pregnant women in 35 clusters: 9 clusters for LPG; 13 clusters for improved biomass-burning cookstoves and 13 clusters for usual care	Personal exposures measured in a subset of participants: 72-h personal exposures to CO were measured using Lascar EL-USB-CO sensors (Lascar Electronics) in 1,224 women participants; $PM_{2.5}$ was measured using the microPEM monitors (RTI) in 879 women participants	Primary outcomes include birthweight and pneumonia in children during the first 12 mo of life	Reduced personal exposures to CO in LPG and improved biomass cookstoves when compared with control arm; reduced $PM_{2.5}$ in LPG vs. control arm but no difference between improved cookstove vs. control. No difference in birthweight or reduced severe pneumonia risk in the first 12 mo of life

(*Continued*)

Table 2. (*Continued*)

Citation	Countr(y/ies)	Setting	Type of Intervention	Population	Measured Exposure	Outcome(s)	Findings
Fandiño-Del-Rio *et al.*, 2022 (36)	Peru	Rural	Individual RCT of a multicomponent LPG intervention vs. cooking with biomass Multicomponent intervention: LPG stove, continuous fuel delivery and behavioral reinforcement.	180 participants; 90 received the intervention and 90 control women aged 25–64 yr	Four or five assessments of personal exposures over 1 yr: 48-h $PM_{2.5}$ was measured using the Enhanced Children MicroPEM monitors (ECM); 48-h personal exposures to CO using the Lascar EL-USB- CO sensors	Primary outcomes were blood pressure, peak expiratory flow, and respiratory symptoms using the St. George's Respiratory Questionnaire	Reduced personal exposures to $PM_{2.5}$ and CO in intervention participants when compared with control subjects. No difference in blood pressure, peak expiratory flow, or respiratory symptoms
Clasen *et al.*, 2022 (21); Johnson *et al.*, 2022 (25)	Guatemala, India, Peru, Rwanda	Rural	Individual RCT of a multicomponent LPG intervention vs. cooking with biomass Multicomponent intervention: LPG stove, continuous fuel delivery, and behavioral reinforcement.	3,200 households with one pregnant woman and 15% of households with an older adult woman	Three prenatal and three postnatal assessments of personal exposure: 24 h $PM_{2.5}$ was measured using the ECM; 24-h personal exposure to CO was measured using the Lascar EL-USB- CO sensors	Primary outcomes include birthweight, infant stunting and severe pneumonia, and blood pressure in older adult women	Reduced personal exposures to $PM_{2.5}$ and CO in pregnant women who belong to the intervention arm when compared with those in control arm. Reduced personal exposures to $PM_{2.5}$ and CO in intervention children when compared with control subjects. No differences in birthweight or infant stunting and pneumonia. Blood pressure findings to be published.
Alexander *et al.*, 2017 (8) and 2018 (22)	Nigeria	Rural	Individual RCT of an ethanol stove vs. cooking with biomass or kerosene	324 women who presented at any of the primary health centers for antenatal care and were less than or equal to 18 wk pregnant (determined by ultrasound biometry)	72-h personal exposure to carbon monoxide and $PM_{2.5}$. $PM_{2.5}$ was measured using the microPEM monitors. CO was monitored using Gasbadge Pro data-logging electrochemical monitors.	Primary outcome was birthweight.	No differences in personal exposures to CO or particulate matter. No difference in birthweight. No difference in blood pressure in the overall cohort.

Definition of abbreviations: CO = carbon monoxide; LPG = liquefied petroleum gas; $PM_{2.5}$ = particulate matter with an aerodynamic diameter of 2.5 μm or less; RCT = randomized controlled trial; WHO = World Health Organization.

other stoves that continued to rely on biomass fuels but were shown to improve combustion efficiency by up to 40%. When measured, trials of improved biomass stoves reported mixed effects on HAP exposure, and none achieved average reductions approaching the 2021 nor 2005 WHO interim targets or guideline values for $PM_{2.5}$ exposure (37–39). This was attributed to continued reliance on traditional stoves ("stove stacking"), continued exposure from noncooking sources, and primarily the inability of the stoves themselves to meet combustion efficiencies from any biomass fuel. Despite a lack of health effects, multilateral international agencies and NGOs set policy agendas that installed hundreds of millions of these biomass-burning stoves at considerable cost. Most of these improved stove programs were principally motivated by environmental aims, such as slowing deforestation and reducing climate pollutants, or by social objectives, such as reduced fuel wood costs or women's empowerment.

After early interventions failed to yield notable health benefits, research and some implementation programs shifted from more efficient biomass burning stoves to cleaner fuels with lower and/or more consistent emission characteristics, especially LPG (9, 10, 20, 21) and ethanol (22). The effects of these interventions on air pollution, however, have been variable. Those conducted in settings with low outdoor air pollution have reduced both kitchen concentrations and personal exposures to air pollution (25, 40) when use of the cleaner fuel was nearly exclusive. Nonetheless, even trials of cleaner fuels that were able to achieve important reductions in air pollution exposure still reported no protective effects on prespecified trial outcomes such as birthweight or pneumonia across a variety of randomized controlled trials with different designs (individual or cluster) and on different continents (10, 20, 21). An efficacious intervention strategy that both mitigates HAP exposure and achieves health benefits, as measured in these trials, is yet to be identified.

Why did some interventions reduce pollutant exposure but not improve health? There are several potential explanations. First, although reductions were achieved with cleaner improved biomass-burning stoves, these reductions were likely insufficient, with kitchen concentrations or personal exposures to air pollution remaining several-fold times higher than established air quality guidelines. Second, although cleaner fuel interventions may have reduced pollutant concentrations arising from stoves, some trials were conducted in settings where outdoor air pollution was high (10, 20). Therefore, personal exposure may not have been reduced significantly enough to achieve health benefits. Finally, even in settings where outdoor air pollution was low and reductions were achieved with cleaner fuel interventions (25, 40), it is possible that the intervention was delivered too late (in the case of maternal and pregnancy outcomes) or that the trial did not follow participants long enough (in the case of chronic pulmonary or cardiovascular outcomes) to observe health benefits. Arguments can also be made that interventions were not adequately powered, possibly because investigators were too optimistic about the effect size they expected to find, or that interventions were tested on a limited set of health outcomes. Future trials should consider testing interventions on other health outcomes, including exacerbations of underlying lung disease, medication use, and other nonrespiratory outcomes.

Exposure–response analyses conducted using data from randomized trials testing cleaner fuel interventions have found associations between higher pollutant concentrations and worse health outcomes (41, 42). These findings on exposure–response analyses indicate that although HAP may be an important risk factor for poor health across the lifespan, it does not necessarily mean that these cleaner fuel interventions improve health in the time frame or the specific health outcomes tracked by existing intervention trials. Although evidence from exposure–response analyses is informative, like other nonrandomized study designs, these analyses are susceptible to unmeasured or uncontrolled confounding by factors such as poverty, which is highly correlated with biomass use both across and within countries (43, 44). If poverty drives both solid fuel use and has a causal effect on a health outcome via pathways unrelated to HAP exposure (such as poor nutrition, lack of access to clean water and sanitation, exposure to other environmental pollutants, limited access to health care), then poverty is a threat to causal inference in most existing observational studies of HAP on health. Studies that randomly assign groups to higher or lower levels of HAP exposure via an intervention, such as randomized controlled trials or quasiexperimental approaches, may overcome this limitation, although they are not infallible. For example, poverty may lead to differential compliance with an intervention, and for health outcomes with long latencies, it is not possible to sustain a HAP intervention over decades. Furthermore, exposure reductions may not be of sufficient duration or targeted to appropriate susceptible windows via randomization.

The apparent conflict between observational studies (including exposure–response analyses) on the one hand and randomized trials on the other indicates that we should exercise caution in using observational evidence alone to drive policy decisions for household energy (45). Indeed, scientists need to be careful about how they interpret data and provide evidence-based recommendations to health departments in LMICs, all of which have limited budgets and must balance competing priorities. However, conduct of environmental health randomized controlled trials in LMICs is exceedingly complex, and other forms of evidence (following the experience in the outdoor air pollution domain) may need to be strengthened to protect the most vulnerable populations at risk from HAP exposures.

Consensus Statement 4: Intervention strategies for clean household energy are context dependent. The degree of exposure reduction is more important than a specific fuel or technology.

The cleaner we can make household energy, the better for public health, but access to the cleanest fuels depends on local contexts; thus, intervention trial results may not be directly transferable to other settings. Rural areas of LMICs face several challenges in transitioning to clean energy. The supply chain for cleaner-burning transitional fuels such as LPG may be limited or nonexistent, and access to electricity may be constrained. African countries, in particular, have the most limited access to cleaner energy fuels and technologies (46). Poverty limits the ability to pay for modern energy services. Fuel cost is one of the biggest obstacles for impoverished households to transition from solid biomass fuels to cleaner energy. Promoting policy measures that enable sustained use of a wide range of clean energy sources might be better than promoting a single fuel such as LPG.

Topic 2: What Are Important Secondary Outcomes and Design Considerations for Meaningful HAP Studies in LMICs?

Consensus Statement 5: To investigate or explore health effects, future HAP intervention studies should target exposures in the prenatal and early childhood periods (critical windows of exposure) and should be designed with longer follow-up time (at least 5 yr).

Virtually all of the randomized trials of interventions in healthy populations to reduce exposure to HAP have examined associations with short-term health outcomes, typically ascertained within 2 years or less. Longer follow-up durations would provide richer data to assess the impact of exposure to HAP on outcomes over time, especially regarding the question of whether prenatal and early childhood exposures program future lung health, cardiovascular health, somatic growth, and neurodevelopment. A few randomized clean cooking intervention studies have longitudinally evaluated health outcomes in a subset of the original intervention cohort (Table 3). Although the evidence from observational studies of the association of exposure to HAP and lung function in adults is mixed (47–49), studies of young children have tended to support a positive association between reduced HAP exposure and better growth, lung health, and cardiovascular benefits (50–53), with additional limited data on neurodevelopmental outcomes (54). The studies in children suggest that a critical window of exposure is in the prenatal period and early childhood. A longer follow-up is required to understand whether these early childhood exposure deficits are sustained and result in clinically significant effects on health across the life course.

Consensus Statement 6: Reducing exposure to HAP is an important outcome even if the intervention does not achieve a sufficiently low exposure level, such as to a "floor" of outdoor pollution levels or WHO interim targets.

Outdoor air pollution and HAP exposures overlap, especially for fine particulate matter ($PM_{2.5}$ [55–57]). Given the abundant data supporting an exposure–response relationship for $PM_{2.5}$ and cardiovascular mortality used by the Global Burden of Disease study (58), any reduction of household exposure to $PM_{2.5}$ from biomass fuel combustion by an intervention is a health-promoting outcome. In India, for example, elimination of exposure to household $PM_{2.5}$ from cooking has been modeled and would reduce population-weighted $PM_{2.5}$ exposure from all sources combined by 17%, which would have tremendous public health benefit (59).

The potential health benefits of safe household air quality can be achieved only through household-level interventions if outdoor air quality is also improved to levels that are considered safe for health (38). This may pose significant challenges in periurban and urban settings of many LMICs where outdoor air pollution levels exceed recommended WHO guidelines by several-fold. Several studies of clean energy interventions in China showed decreased effectiveness of the intervention related to higher outdoor air pollution concentrations (60, 61). The contribution of outdoor $PM_{2.5}$ to indoor concentrations should be studied in future HAP research. Personal exposure apportionment may be a way to characterize drivers of indoor exposure, including solid fuel use and outdoor pollution levels. It is important to note that although periurban and urban areas may have preexisting infrastructure or supply chains for clean household energy that could increase the sustainability of these interventions, this may not be true for rural areas of LMICs. Many variables in LMIC urban settings influence air quality, including changing fuel mix for electricity generation, industrial emissions and pollutant control technology, road dust, and city initiatives to improve public transit. As high-income countries move aggressively to increase sales of cleaner electric vehicles, there may be an acceleration of the existing pattern of dumping of older, dirty vehicles in LMICs, worsening air quality.

Topic 3: Does Academic Research Help Household Energy Interventions Get Scaled? Engaging Nonacademic Practitioners

Consensus Statement 7: Currently, for most practitioners (governments, NGOs, international organizations), health is not the primary driver for scale-up decisions.

The potential health benefits of clean residential energy transitions are often not among the leading drivers for motivating the scale-up of clean household energy in LMICs (62–64). Evidence demonstrating health burdens or potential benefits of intervention measures can be useful for opening a dialogue on the topic, but health alone is rarely enough to motivate action related to clean household energy. One important reason is that within national governments, household energy programs are implemented by ministries of environment, energy, or infrastructure, rather than the ministry of health. Cross-ministry dialogue and programmatic decision making are often not possible, and most ministries of health in LMICs lack the resources to address household energy at scale. To advance household energy through collaboration across ministries, narratives should highlight how clean energy transitions can achieve Sustainable Development Goals (4), mitigate greenhouse gas emissions, and reduce economic impacts, in addition to health gains. For social impact and business investors, the alleviation of health burden from household energy practices can help meet organizational requirements to justify work on the issue. However, sustained support from private investors will require viable business models that have been elusive, although significant business model innovation is currently underway.

Consensus Statement 8: The largest barriers to scaling up household energy programs are affordability and availability.

No single factor determines the success of household energy programs (65), but several high-priority factors were identified. Two of the highest priorities identified by the

Table 3. Household Air Pollution Studies with Long-Term Follow-Up of Health Outcomes

Citation	Country	Setting	Type of Intervention	Population	Measured Exposure	Health Outcome	Findings
Heinzerling *et al.*, 2016 (51)	Guatemala (CRECER)	Rural	Improved chimney stove	557 children ages 3–4 Three groups: 1. RESPIRE intervention 2. RESPIRE control 3. New control subjects	48-h personal CO every 6 mo during CRECER; time with improved stove	Spirometry	Decreased PEF; trend toward decreased FEV_1 in control participants
Liu *et al.*, 2022 (66)	Guatemala (CRECER)	Rural	Improved chimney stove	557 children ages 3–4 Three groups: 1. RESPIRE intervention 2. RESPIRE control 3. New control subjects		Allergic conditions (maternal report); sensitization by skin prick tests	Longer exposure to open-fire stoves was associated with higher risks of maternal reported allergic asthma and rhinitis symptoms; no association for sensitization to common allergens
Kinney *et al.*, 2021 (42)	Ghana (GRAPHS)	Rural	1. LPG 2. Improved biomass cookstove 3. Open-fire controls	1,144 live births followed for 12 mo	Personal prenatal (mother) and postnatal (infant) CO at ∼3-mo intervals	Incident pneumonia and severe pneumonia	Higher prenatal CO was associated with higher pneumonia and severe pneumonia risk over the first year of life
Boamah-Kaali *et al.*, 2021 (53)	Ghana (GRAPHS)	Rural	1. LPG 2. Improved biomass cookstove 3. Open-fire controls	1,144 live births followed for 12 mo	Personal prenatal (mother) and postnatal (infant) CO at ∼3-mo intervals; prenatal $PM_{2.5}$ in a subset	Length, weight, mid-upper arm circumference (MUAC), head circumference (HC), weight-for-age, length-for-age (LAZ), and weight-for-length (WLZ) z-scores at birth and 3, 6, 9, and 12 mo	Prenatal CO exposure increased risk for lower length and stunting; Prenatal $PM_{2.5}$ for lower LAZ *z*-score trajectories. Postnatal CO exposure increased risk for smaller HC and $PM_{2.5}$ for smaller MUAC and lower WLZ-score trajectories. Infants in the LPG arm had decreased odds of having smaller HC and MUAC trajectories as compared with those in the open-fire stove arm.
Lee *et al.*, 2019 (52)	Ghana (GRAPHS)	Rural	1. LPG 2. Improved biomass cookstove 3. Open-fire controls	384 infants with lung function data at 30 d postpartum	Average prenatal CO exposure	Infant lung function: Crs/kg = passive respiratory system compliance per kilogram; MV = minute ventilation; RR = respiratory rate; Tptef:Te = ratio of the time to peak tidal expiratory flow to expiratory time	Average prenatal CO exposure was associated with reduced Tptef:Te, RR, and increased MV; girls were more vulnerable; increased RR associated with increased risk for pneumonia
Kaali *et al.*, 2021 (67)	Ghana (GRAPHS)	Rural	1. LPG 2. Improved biomass cookstove 3. Open-fire controls	157 children aged 4 Two groups: 97 with prenatal CO data; 60 with prenatal $PM_{2.5}$ data	Average prenatal CO exposure; average prenatal PM2.5 exposure	Telomere length (TL) in cord blood mononuclear cells; blood pressure (BP) at age 4	Higher prenatal $PM_{2.5}$ exposure was associated with reduced TL; infants born to mothers randomized to LPG cookstoves had longer TL; in all children, shorter TL at birth was associated with higher systolic BP at age 4

Definition of abbreviations: CO = carbon monoxide; LPG = liquefied petroleum gas; PEF = peak expiratory flow; $PM_{2.5}$ = particulate matter with an aerodynamic diameter of 2.5 μm or less.

committee were affordability and access to cleaner energy solutions (68–70). “Affordability” refers to the capital and operational costs associated with purchasing and using a clean technology and alignment with household budgets and liquidity constraints. “Access” refers to the existence and reliability of distribution networks to provide clean technologies, related services, and the energy sources they rely on to operate. “Awareness” of the potential benefits of investing in and using clean cooking technologies was also identified as an important factor. Advantage and ability were identified as less critical factors at present. “Advantage” refers to the perceived value of the cleaner energy alternative, and “ability” is the capacity of governments to provide technical knowledge to support programs and conduct performance evaluations; this can also include the ability to sustain required funding.

Consensus Statement 9: Subsidies to increase clean energy access in resource-limited settings have both potential beneficial and harmful effects.

In multiple LMICs, subsidies have been important to support the uptake and sustained use of clean household energy technologies by the poorest, but they present inherent risks (71). Most concerns relating to the use of subsidies within the household energy sector relate to financial sustainability (72) and efficiency at reaching target populations (73, 74). Fuel subsidies create market distortions on pricing by enabling monetary transactions for which the buyer’s willingness to pay is below their opportunity cost. This creates a deadweight loss that deters commercial engagement (71). These subsidies can impose a large economic burden on governments that have constrained budgets; in 2017, government spending on fuel subsidies in Indonesia exceeded that spent on social services (75). Untargeted subsidies also can worsen inequality; in 2012, the poorest decile in Indonesia consumed less than 1% of subsidized gasoline, whereas the richest decile consumed 40%. Movement toward processed fuels needed to achieve the high combustion efficiency necessary for “clean” environments, for example, may require subsidies on both the capital cost of the cooking device and continued subsidies on fuel (which quickly exceed the cost of the device) to promote sustained use (62). Another consideration affecting the use of subsidies is the form that they will take. Past subsidies on household appliances or energy sources have taken the form of rebates for end users, relaxing of import fees and value-added tax on energy products, and incentive to manufacturers, to name a few. Although subsidies will remain an important policy tool for scaling cleaner energy solutions and reducing disparities, targeted research is needed to mitigate potential risks and define the most successful strategies. Financing models that may help address affordability are pay-as-you-go schemes for consumers, which distribute the capital and operational costs of switching to clean energy (76).

Consensus Statement 10: Most household energy programs require involvement of both the public (government) and private (business) sectors to achieve a reasonable scale-up.

Household energy programs will almost always require the involvement of both the public and private sectors to achieve scale and sustainability. Historically, many energy access programs have been government driven (68), including design of the solutions to be provided to households, heavy subsidies (up to 100%), and centralized procurements. Although this approach can sometimes reach large numbers of households, public sector agencies often face challenges in being responsive to market and consumer demand. This can lead to products that do not meet end-user needs, poor service for the products provided, and a lack of innovation in products and business models. All of this can undermine the sustainability of public sector programs that do not work through private sector partners.

The private sector is usually better positioned to serve as the delivery arm of a program, interacting directly with households. Private companies are generally more innovative, allowing them to respond to consumer needs and offer a range of products appropriate to the market. They also have an incentive to provide good service to customers, especially when payments are linked to the performance of the products provided. At the same time, the public sector is crucial to achieving the goals of household energy programs, that is, of reaching the entire underserved population. The public sector establishes policies and adopts standards that protect the quality and safety of consumers and can create a favorable environment for businesses to thrive (e.g., through import waivers or other tax incentives, clear and predictable regulations, and appropriate standards). The public sector can also employ targeted subsidies or related policy tools to incentivize companies to reach the poorest and most remote populations, which they would normally not reach through pure commercial approaches.

Consensus Statement 11: Barriers to translating research findings into decisions on policy and scale-up include the format in which academic research is communicated. Academic papers are not the optimal way to communicate with decision makers or practitioners responsible for scale-up of clean energy programs.

Academic research papers are not an effective medium to communicate research findings to most individuals and organizations working to scale clean energy. These general challenges exist beyond the HAP field in both high-income countries and LMICs. Common barriers to the use of academic research in policy or to inform implementation strategies include lack of knowledge of available research, inaccessibility of language, length of papers, and journal paywalls, as well as external factors that preclude change, such as priorities of external funders, the political environment, and competing priorities (77–80). Given the pace and insular nature of the academy and funding agencies, academic research questions are often misaligned with the barriers facing practitioners and policymakers. Policy briefs (46) that articulate key findings and, importantly, programmatic implications may be one way to reduce accessibility barriers. Short videos or infographics (Figure 1) that emphasize the key findings and recommendations of an article or report are also suggested. These resources should be posted on domains that are accessible to practitioners rather than behind journal paywalls. In addition, engagement with practitioners to inform research questions and funding opportunities that enable demonstration of academic achievement while generating highly relevant programmatic resources could help ensure that research responds to practical needs.

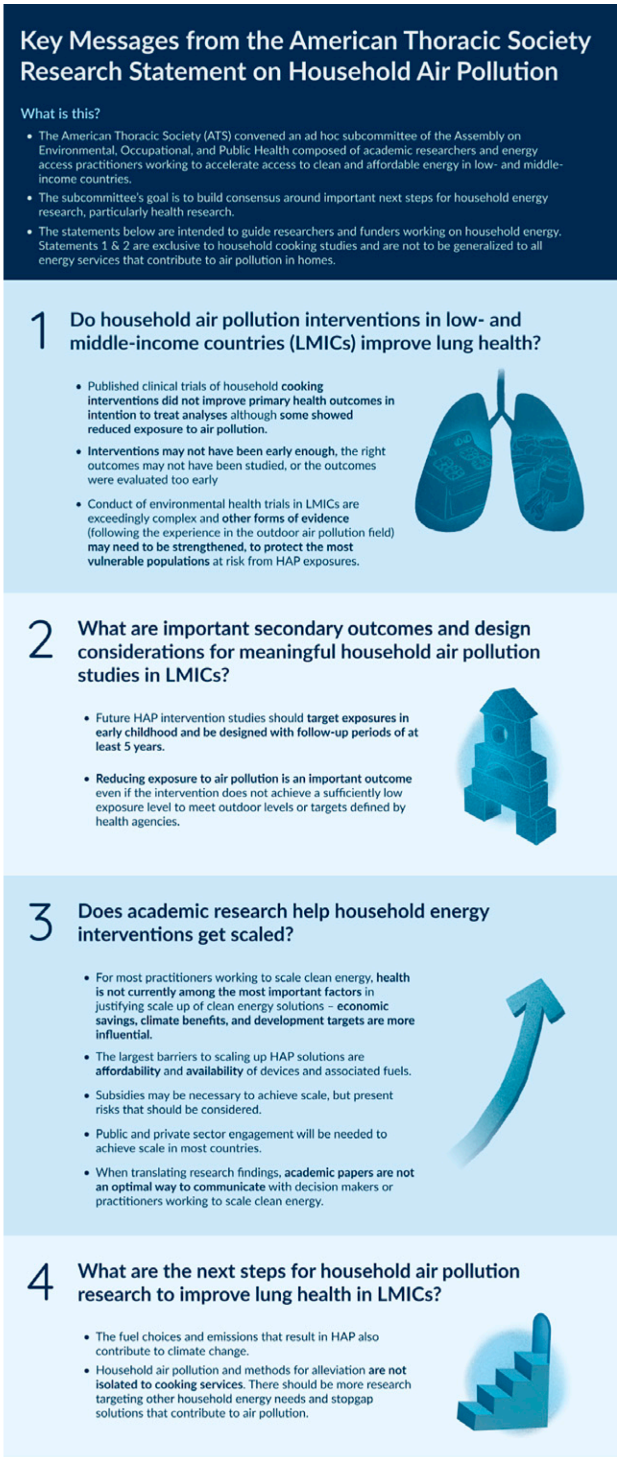

Figure 1. Example infographic used to communicate findings of academic research to household energy practitioners. This infographic summarizes the results of this research statement in a single-page document with graphics and main findings summarized using bullet points.

Topic 4: What Are the Next Steps for HAP Research to Improve Lung Health in LMICs?

Consensus Statement 12: The fuel choices that result in HAP also contribute to climate change.

Emissions from fuel extraction (especially fossil fuels and unsustainable biomass harvesting), processing (especially charcoal production), transportation, and household use all contribute to climate change. The level of emissions throughout the value chain differs across fuel types (wood, charcoal, kerosene, LPG, coal). Modeling studies suggest that transitioning from solid fuel use to full LPG use (as a cleaner transitional fuel) may have better health and climate impacts than business as usual (natural and incomplete transitioning to LPG from biomass) (81, 82); however, there are methodological limitations to these kinds of studies, including their limited ability to fully account for the climate change effects of extraction and use that typically accompanies LPG (83).

Consensus Statement 13: There should be more research targeting exposure to other sources of HAP beyond cooking.

Household energy solutions need to go beyond cooking interventions alone; there are multiple sources that contribute to HAP (84). The term "household energy" refers to the types and end uses of energy, which together satisfy various needs within the home. HAP is a result of homes lacking the fuel or technology to efficiently convert chemical energy in fuel to the forms of energy used by households (e.g., thermal, electrical). Renewable household energy sources such as solar and wind (85) may address multiple sources of HAP. For example, in some contexts, lighting needs met with fuel-based sources such as kerosene lamps can be a major source of exposure to HAP (86, 87). Clean lighting alternatives such as solar home systems or portable solar lamps are increasingly affordable with pay-as-you-go financing and can lead to significant and sustained reductions in personal exposure to both $PM_{2.5}$ and black carbon (88, 89). Replacing inefficient incandescent bulbs with light-emitting diode lights can lead to more efficient energy use (90). Backup generators, widely used in contexts with absent or unstable electrical grids, also add substantially to both household and outdoor air pollution in LMICs and may contribute to indoor air pollution (91, 92). Modeling studies suggest that the installed capacity arising from backup generators used in LMICs is equivalent to that from 900 coal-fired plants and a major source of nitrogen oxide in some regions (91). Additional examples of other HAP sources include open burning of domestic waste (93, 94) and space heating (95). Although the contribution of these noncooking sources of HAP are context dependent, future studies should take into account the contributing role of these additional sources of HAP to develop more comprehensive multicomponent interventions tailored for each setting. It is clear that the impact of standalone interventions has not achieved expected outcomes and that high outdoor air pollution has been one of the pitfalls for some failed intervention studies (6).

No consensus: There is a place for mechanical air filtration devices (for example, air purifiers) as an intervention to reduce exposure to HAP in LMICs.

The committee considered the role of air filtration devices such as high-efficiency particulate air cleaners as a strategy to reduce HAP exposure in LMICs, but no consensus was reached regarding their role. Current technologies require electricity, with access and cost posing challenges. For example, 59.5% of the population in Nigeria, the most populous African country, is connected to the electrical grid, whereas only 14.2% of the population in Malawi has grid access (96). There is no evidence that active air filtration devices are effective at addressing HAP (including both gases and particulate matter) arising from biomass fuel combustion.

Poor housing conditions have been linked to indoor air quality problems. Context-responsive, sustainable building design principles can help address these challenges in a more holistic and comprehensive manner (97). In urban slums, factors that can compound poor indoor air quality include unregulated development of substandard housing structures in unsuitable polluted areas because of weak enforcement of land use and zoning policies, overcrowding in single-room houses, inadequate ventilation due to the absence of windows, proximity to industry and roadways, reluctance of occupants to open windows due to high levels of crime, or fear of pest intrusion, thereby limiting ventilation (98). Sustainable building design based on Swahili architecture (99) exemplifies how a holistic systems thinking approach could help increase the impact of interventions that seek to address indoor pollution–related health challenges. Although such approaches demonstrate how the use of locally available materials can create healthier, naturally ventilated homes with improved indoor air quality and thermal comfort, measures must be put in place to minimize the risk of vector-borne diseases such as malaria, a problem that has been linked to the use of some traditional building materials (100, 101).

Consensus Statement 14: Further research in household energy is required in several areas, including the needs and priorities of end users as well as practitioners, economic studies, the long-term impact of HAP on health, the effect of interventions on multiple pollutants, contribution of HAP to outdoor air pollution, tools that model cobenefits of clean energy programs and quantify benefits at the subnational level, and additional areas.

Other areas of future research were recommended by the committee that will guide the development of effective HAP interventions and the translation of research findings to policy (Box 2).

The committee reached agreement that there is no longer a need for singular, narrowly focused intervention studies on improved biomass stoves and health, given the evidence suggesting that they do not sufficiently reduce HAP exposure or provide health benefits. Similarly, intervention studies that do not measure the level of adoption to new household energy technologies and that do not measure HAP exposures are not recommended.

Conclusions

HAP is associated with adverse health effects. However, it remains unclear which interventions reduce exposure, improve health, and are scalable and sustainable. Closer partnerships between academic

Box 2 Recommended future areas of HAP research

- Contribution of household air pollution to outdoor air pollution
- Long-term observational studies of household air pollution and health outcomes spanning decades
- Exposure–response studies on other pollutants beyond $PM_{2.5}$ and carbon monoxide
- Mechanistic research on the effect of HAP on health
- Development of tools that model the cobenefits of clean energy programs (climate, health, environment, equality, gender issues) and quantify benefits at the subnational level (for example, as a result of city-level programs)
- Studies responsive to the needs and priorities of households and governments, framed using language that is meaningful to both practitioners and academic researchers
- Economic studies including willingness to pay, the impact of energy subsidies and strategies to deploy them, and policy implications of scale-up
- Interventions that are designed and evaluated using implementation science models, theories, or frameworks
- Interventions that address multiple components of HAP
- Community-level interventions to address HAP

investigators and household energy practitioners will better align research agendas with policy priorities and overcome communication gaps to design and implement successful household energy interventions. ■

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