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Cleaner Cooking Solutions to Achieve Health, Climate, and Economic Cobenefits

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■ INTRODUCTION

In many parts of the developing world, the simple act of cooking a meal has dire consequences for health and the environment. More than 3 billion people must rely on solid fuels such as biomass (wood, charcoal, agricultural residues, and animal dung) and coal as the primary source of household energy. These solid fuels are often burned in inefficient open fires and rudimentary stoves with inadequate ventilation, exposing families, in particular women and children, to toxic indoor smoke for hours daily over their lifetimes. Household solid fuel combustion is associated with 3.5 million and 0.5 million premature deaths annually due to indoor and outdoor air pollution

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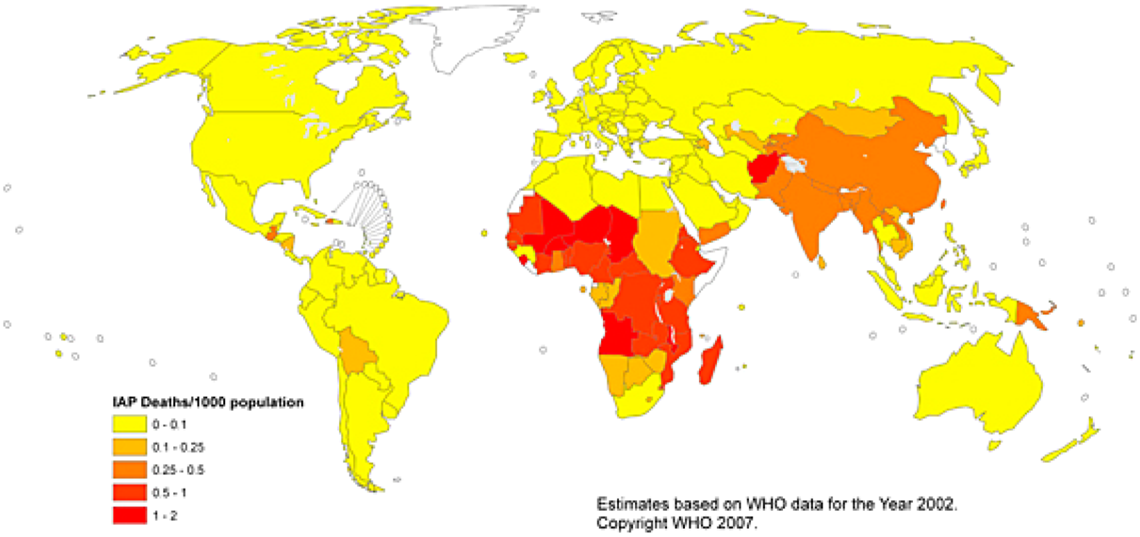

Figure 1. Premature deaths attributable to household solid fuel use occur mainly in developing countries, as shown by these national estimates for 2002 (reproduced with permission from ref 2. Copyright 2007, WHO). Globally, estimates for 2010 are approximately double these earlier estimates for 2002, mainly due to methodological improvements.[1]

Table 1. Typical Progression for Household Energy Use: Arrows Indicate Income Levels, but Other Variables Also Influence Fuel Choice, Thus Households of Varying Income May Span Different Typologies of Fuel Use[a]

Energy service	Developing countries households (← Low income →; ← Middle income →)	(← Middle income →; ← High income →)	(← High income →)	Developed countries households
Cooking	Wood (including wood chips), straw, shrubs, grasses, and bark), charcoal, agricultural residues, dung, coal, and waste	Wood, agricultural residues, charcoal, LPG, coal, kerosene, and biogas	Wood, pellets, kerosene, biogas, charcoal, LPG, natural gas, electricity	Electricity, natural gas, LPG , charcoal (barbecue)
Lighting	Open fire, candles, kerosene (sometimes none)	Kerosene, batteries, electricity	Electricity	Electricity
Space heating	Wood, agricultural residues, and dung (often none)	Wood, agricultural residues	Wood, coal, kerosene, pellets, and electricity	Wood, pellets, oil, natural gas, LPG or electricity
Other Needs (water heating, recreation)	Wood, batteries (often none)	Wood, Electricity, batteries	Wood, natural gas, LPG, electricity, batteries	Natural gas, LPG, electricity, batteries

[a]Adapted from Sovacool.[3]

exposure, respectively.[1] This burden occurs mainly in developing countries (Figure 1) and now appears to exceed the burdens of malaria, tuberculosis, and HIV combined. Millions more suffer from disabilities related to cardiovascular problems, chronic and acute respiratory conditions, and cataracts. Women and children are also burdened with time-consuming and physically demanding fuel collection that prevents them from attending school or working and puts them at risk of violence in some conflict areas. Inefficient burning of solid fuels for energy contributes to climate change, and when woodfuel is unsustainably harvested, deforestation, forest degradation, and loss of habitat and biodiversity can result.

Low-income households in developing countries are the most dependent on solid fuels for household energy needs, with developed countries and higher-income households in developing countries typically using electricity or processed fuels such as liquefied petroleum gas (LPG) and natural gas (Table 1). The share of the population relying on solid fuels for energy needs ranges from less than 25% in some developing countries to 95% in many Sub-Saharan African countries, and is nearly 100% in many rural areas.[3] As in developed countries, many homes in developing countries use multiple fuels and devices ("fuel-device stacking") for cooking, lighting, heating, and specialized cooking tasks such as making tortillas in Mexico, chapathis in India, or njera in Ethiopia, with solid fuel stoves fulfilling many of these needs (Table 1). In all countries, household energy decisions are shaped by income, tradition, social expectations, and fuel availability. For example, wood-burning heating stoves are often used in developed countries despite accessible and affordable cleaner alternatives.

Over the last decades, various national efforts have introduced millions of fuel efficient stoves (e.g., in China, India, and Kenya), with some achieving greater success than others. In the past several years, scientific advances, financial innovation, and

Table 2. Policy Priorities (Not Listed in Priority Order) for Clean Cookstoves and Fuels and Indicators for Evaluating Stove/Fuel Performance for Each Priority

policy priorities	indicator for evaluating performance
deforestation and degradation prevention, habitat and biodiversity preservation	fuel use savings (wood harvested unsustainably)
women's and girls' empowerment (social progress, gender-based violence reduction)	fuel use and time savings (collected)
economic development and poverty eradication	fuel use savings (collected or purchased), fuel expenditures savings, health-relevant emissions
reduction of health impacts of exposure to indoor and outdoor air pollution	reduction of air pollutant emissions (e.g., particulate matter, ozone-producing gases, hazardous air pollutants), exposure, and health effects
long-term climate change mitigation	reduction of emissions of long-lived greenhouse gases (e.g., carbon dioxide from unsustainably harvested biomass, methane)
near-term climate change mitigation	reduction of emissions of short-lived climate pollutants (e.g., methane, black and brown carbon, ozone producing gases)

several successful clean cookstove initiatives have begun to demonstrate the great potential for relieving the societal burden of cooking over open fires and rudimentary stoves, gaining support from influential leaders around the world. The resulting flow of resources into the sector is enabling new approaches to encourage large-scale, sustainable adoption of clean cooking solutions. However, despite significant recent progress, it remains a complex challenge to design stoves that women want to use and that reduce fuel use and emissions enough to achieve today's policy goals, in addition to making them widely accessible and affordable.

EVALUATING PERFORMANCE FOR VARIED POLICY PRIORITIES

Advanced fuels such as LPG, ethanol, and biogas are often vastly cleaner, more efficient, safer, and in many cases more appealing to users than traditional solid fuels. However, accessibility, affordability, and adaptation of local cooking devices must be improved for advanced fuels to be a viable solution for many current solid fuel users. Fortunately, clean and efficient solid fuel stoves are increasingly available around the world, and if adopted on a wide scale, could yield health, environmental, and economic cobenefits.

Over the past decade, a variety of solid fuel based cookstove models that improve combustion efficiency and reduce emissions when compared with open fires and traditional stoves have entered the market. However, policy objectives to reduce indoor and outdoor air pollution, mitigate long-term and near-term climate change, reduce deforestation, empower women and girls, and support economic development are driven by different factors, including fuel use (collected or purchased), and emissions of air pollutants that affect health and climate (Table 2). Results from recent laboratory and field testing show wide variation in stove performance for these indicators.[4−9]

Many stoves currently on the market effectively save fuel, based on data from both laboratory and field settings. Residential use of woodfuels accounts for approximately 7% of global energy use,[10] half of wood harvested worldwide annually,[11] and 6% of global deforestation,[3] mainly in specific locations or "hotspots".[12−14] Unsustainable harvesting of woodfuels degrades forests and in some locations leads to deforestation, reducing habitat, biodiversity, and uptake of atmospheric carbon dioxide. Although burning sustainably harvested woodfuels is carbon dioxide neutral, it is not climate neutral as other emitted climate pollutants like black carbon (BC), methane, and other ozone-producing gases (e.g., carbon monoxide, volatile organic compounds) are not reabsorbed.

The impact of cleaner cooking solutions on fuel use and air pollutant emissions varies by fuel type, stove design, cooking practice, and environmental conditions. Recent studies have found that many of the stoves on the market reduce fuel use by 30−60%.[4,15−18] Some advanced biomass systems, such as small-scale gasifier and biogas stoves, are even as efficient as LPG systems.[18] Less fuel use can lead to transformative benefits—less burden for women or more income for families and less risk of violence for women and girls as they collect fuel in certain insecure areas. Reduced fuel use due to increased heat transfer efficiency (with equal or greater combustion efficiency) can also mean fewer emissions of air pollutants that affect health and climate and reduced impacts on forests, habitats, and biodiversity.

But fuel savings alone are not enough—protecting public health likely requires dramatically reducing emissions from stoves.[19] Although exposure patterns vary due to individual (age, socioeconomic status, time spent in cooking area) and household differences (fuel/stove type, cookhouse ventilation, use of biomass for heating), use of solid fuels in traditional stoves results in air pollution exposure levels that can reach 50 times greater than the World Health Organization (WHO) guidelines for clean air, particularly for women and children who typically spend more time inside the home than men.[20] Exposure to indoor smoke containing toxic compounds such as fine particulate matter ($PM_{2.5}$), carbon monoxide, and hazardous air pollutants is associated with a variety of adverse health outcomes including early childhood pneumonia, chronic obstructive pulmonary disease, lung cancer, and cardiovascular disease.[21] Solid fuel users relying on open fires and traditional stoves are also at risk of severe burns and cataracts.[22]

Many solid fuel based cleaner cookstove models available on the market reduce $PM_{2.5}$ emissions, but some are much more effective than others. While laboratory studies observed 50% $PM_{2.5}$ reductions from typical natural draft stoves and over 90% reductions from some forced draft stoves, which employ a fan to increase combustion efficiency,[4,15] these reductions may be less robust in field settings.[16,23−26] Clean stoves used with chimneys can further reduce indoor $PM_{2.5}$ exposure (e.g., 27). While air pollution levels often still exceed the WHO guidelines even with use of cleaner cookstoves (particularly where background air pollution levels are high due to other emission sources or where widespread household use of traditional stoves persists in the broader community), the large reductions in exposure are likely to achieve significant health benefits.[1,28] Combined with reduced fuel use, the health benefits associated with cleaner and more efficient stoves may lead to benefit−cost ratios of 10 to 1 or more for cookstove interventions,[29]

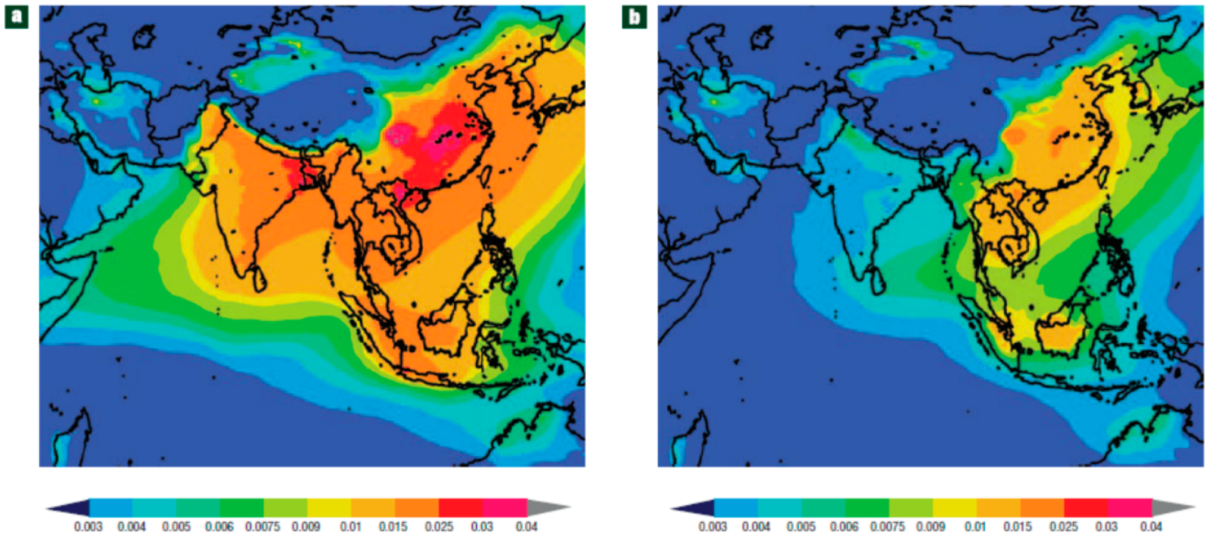

Figure 2. Effect of biofuel cooking on Asian BC loading. (a) Simulated annual mean optical depth of BC aerosols for 2004–2005 using a regional aerosol/chemical/transport model. The values include BC emissions from biofuel cooking (indoor cooking with wood/dung/crop residues), fossil fuels, and biomass burning. (b) Same as for (a), but without biofuel cooking. Reproduced with permission from ref 35. Copyright 2008, Nature Publishing Group.

although these values are likely highly variable. However, more information is needed to better understand the exposure–response relationships at very high exposure levels, as modest exposure reductions in households may have limited health benefits and large-scale emission reductions at both the household and neighborhood level may be needed to be protective of public health.[30] In addition, more efforts are needed to meet all household energy needs in a way that reduces dependence on traditional stoves and open fires; otherwise, residual use of polluting stoves and fuels can offset the exposure reductions.

Burning solid fuels in open fires and traditional stoves also releases emissions of some of the most important contributors to global climate change: carbon dioxide, methane and other ozone producing gases such as carbon monoxide, and short-lived but very efficient sunlight-absorbing particles such as BC and brown carbon.[31,32] In Asia, residential solid fuel burning contributes to atmospheric brown clouds of air pollutants that affect both outdoor air pollution exposure and climate.[10,33−38] While the mixture of emissions from cookstoves depends strongly on the stove, fuel, and user, the near-term climate impact of residential biomass and coal burning is estimated to be net warming, even when coemitted reflecting aerosols (e.g., organic carbon) are considered.[39] When methane and carbon dioxide are accounted for, the long-term climate effect of residential solid fuel use is strongly warming.

Studies show that controlling both short-lived climate pollutants such as BC and methane and long-lived greenhouse gases can increase the chances of limiting global temperature rise to below 2 °C, a long-term international goal for avoiding the most dangerous impacts of climate change.[34,40,41] In South Asia where over half of BC comes from cookstoves (Figure 2),[42] BC also disrupts the monsoon and accelerates melting of the Himalayan-Tibetan glaciers.[32,35] As a result, water availability and food security are threatened for millions of people. These problems are compounded by crop damage from ozone produced in part by cookstove emissions and from surface dimming as airborne BC intercepts sunlight. In addition, since BC is an indicator of the toxic substances in $PM_{2.5}$, reducing BC is likely to reduce harmful health effects.[43]

For the first time, a recent field study of BC emissions from stoves found that BC can be reduced substantially by forced draft stoves (by 50–90%),[5] confirming earlier laboratory-based studies.[44] Similar reductions were achieved for emissions of carbon monoxide, which is toxic and leads to the formation of ozone, a greenhouse gas and an air pollutant. The field study findings were also consistent with prior lab[18] and field studies[45] indicating that the impact of natural draft stoves on BC is highly variable—reducing BC by 33% on average, but occasionally leading to BC increases for some stoves. These findings point to an opportunity to both slow climate change and protect public health by promoting clean cooking solutions that substantially reduce both BC and total $PM_{2.5}$. Of the presently available measures to reduce BC globally, substantially reducing pollution from residential solid fuel use would have the greatest overall health benefits from a global perspective.[10,33,46]

Clean fuels must also be part of the solution. In addition to the clean gas and liquid fuels noted above, processed solid fuels (e.g., biomass pellets) used in certain types of cookstoves can burn more efficiently and cleanly than collected fuels such as wood, dung (particularly when not adequately dried), and crop residues. One prototype natural draft stove used with low-moisture pellet fuel has been shown to reduce air pollutants as much as forced draft stoves.[4] More information is needed to ensure that these processed fuels remain beneficial when accounting for upstream emissions associated with their production. Simply eliminating fuel mixing, such as mixing wood with dung, has also been found to reduce BC specifically by approximately 50%.[5]

The growing literature shows that different types of stoves and fuels vary in their health, environmental, social, and economic benefits over burning solid fuels in traditional stoves or open fires. Since the various benefits are driven by different factors, solving the problems posed by burning solid fuels in traditional stoves and open fires requires clear criteria that can be used to inform decision-makers on the suitable stove/fuel combinations that meet their specific needs. To achieve the multiple benefits simultaneously, the evidence to date indicates that the market must be driven toward stoves and fuels that are both extremely clean and efficient.[47]

■ CHALLENGES AND RESEARCH PRIORITIES

Despite the growing availability of advanced stoves and fuels that reduce fuel use, household exposures to $PM_{2.5}$, and short-lived climate pollutants (including BC), more studies are needed to quantify the benefits of different stove and fuel combinations, in both the laboratory and in the field. In addition, a major challenge is designing high-performing stoves that can be made affordable, that meet users' broader energy needs, and that women want to use. Even a high-performing stove only provides benefits if it is used frequently on a sustained basis and displaces less efficient devices. Additional research is thus needed to strengthen the evidence base and overcome challenges to achieving the many potential benefits of clean stoves worldwide (Table 3).

Strengthening the evidence base by demonstrating the magnitude of the health, environmental, and socio-economic benefits of clean cookstoves and fuels is a critical priority that will help drive investment into solving this issue. Research is needed to further define how clean stoves and fuels need to be to provide real benefits for health, climate, and the environment. More studies are needed to quantify the benefits of cleaner cooking for ambient air quality; development and child survival; reducing adult respiratory, cardiovascular, and other diseases; and reducing the incidence of severe burns and injuries. Studies on the benefits of efficient cooking solutions for refugees and other vulnerable populations specifically are also needed. In addition, many improvements can be made in stove design, monitoring, and related technologies such as stove materials and components, ventilation, and cookware. Research is needed to understand the benefits of these technological improvements, as well as of the benefits of switching from minimally processed solid fuels to cleaner gaseous, liquid, pelletized, and renewable fuels, including the impacts and efficiency of fuel production.

In addition to strengthening the evidence base, a more integrated understanding of the interplay between socio-cultural, economic, and technological factors is essential for sustaining intervention efforts. Improving access to financing, user-centered design, field testing, understanding cultural values and expectations, spreading awareness, aligning policies and regulations, and building local capacity are critical elements to advancing sustained adoption of clean stoves and fuels.[3,48] The cookstoves sector is burdened with many past examples where low-end stoves—often designed with inadequate consideration of user needs, with little or no testing—were heavily subsidized or given away without proper user training and awareness campaigns, and as a result were abandoned (e.g., 49,50). For example, some clean and efficient stoves are not designed to execute needed tasks, such as baking bread or space heating, leading to continued use of traditional cookstoves alongside the newer technology.[51−56] Since a single advanced stove is often insufficient for all the uses performed by the traditional stoves, a broader agenda to meet all household energy needs is needed to avoid residual use of traditional stoves. It is important to better understand the impact of engaging women in the clean cookstove and fuel value chain on sustained adoption rates and impacts of clean stoves and fuels on consumers' time, income, and educational and employment opportunities. Studies are also needed to determine the factors driving clean stove purchase, use, and aspirational change (e.g., attitudes about the function of the kitchen for homes and families including those factors that "pull" families to continue relying on traditional devices and those the "push" them to adopt the new stoves) and to evaluate the effectiveness of various business models, social marketing, and consumer finance strategies for achieving sustained adoption of clean stoves and fuels.

Table 3. Priorities for Future Research to Assess the Benefits of Adopting Clean Cookstoves and Fuels and to Advance Sustained Adoption of Clean Cooking Solutions Globally; Many of these Topics and Research Priorities, Shown Here in Alphabetical Order, Are Interlinked

topic	research priorities
adoption and markets	factors driving clean cookstove purchase, use, and broader aspirational change
	end-uses of traditional stoves (cooking and noncooking)
	effectiveness of business models, social marketing, and consumer finance strategies
	cost-effective monitoring protocols documenting short- and long-term stove use patterns, including stove and fuel combinations
cleaner fuels	impacts of fuel stacking and switching to gaseous, liquid, pelletized, and renewable fuels
	impacts and efficiency of fuel production
	processed biomass and biofuels, including efficient conversion of agricultural products and residues into pellets, biochar, charcoal, and gaseous or liquid fuels
climate and environment	impacts on short-lived and long-lived climate forcer emissions, global and regional radiative forcing, and nonradiative climate effects (e.g., aerosol effects on precipitation and snow/ice melt)
	impacts on deforestation, carbon dioxide uptake by forests, habitat, biodiversity
gender and livelihoods	impacts of women employed in clean cookstove and fuel value chain on adoption
	impacts on consumers (time savings, income savings, education, and employment)
	case studies and best practice analyses of women's empowerment in clean cooking project implementation
health	impacts on indoor and outdoor air quality and air pollution exposures
	impacts on development and child survival
	impacts on adult disease, including respiratory health and cardiovascular disease
	incidence of severe burns and injuries
humanitarian	impacts on refugees and other vulnerable populations in terms of meeting basic nutrition requirements, gender-based violence, livelihoods, income, and environment and health outcomes
technology	improved stove design (materials, heat transfer, design tools), monitoring (sensors, mobile tools, etc.), and related devices (electric cogeneration, fans, cookware, etc.)
testing and standards	laboratory and field testing to support voluntary industry consensus standards
	development of standards and test protocols, particularly for field testing
	research to support development of global testing infrastructure

Although progress has been made to establish interim fuel use, emissions, and safety guidelines, further development and adoption of voluntary industry consensus standards is required to provide transparency to governments, donors, investors, and others regarding the potential benefits of different solutions and to develop certification procedures, performance benchmarks, and meaningful test infrastructure for the global cookstove market.[57] Such standards can provide incentives for stove and fuel developers to rapidly innovate and improve performance. To support standard development, additional laboratory and field testing of fuel use and emissions is needed, along with laboratory tests that better reflect actual field performance. While laboratory measurements can capture performance variation across a wide range of stoves and fuels under controlled conditions, isolating the impact of the inherent qualities of the device and fuel, field measurements are needed to account for variation in users and functionality. Studies show that factors such as degree of attention given to fire tending, fuel type (as previously discussed), and proper loading of fuel dramatically affect the magnitude and composition of air pollutants that affect health and climate, often with field studies showing lower effectiveness of cleaner stoves and fuels compared with laboratory studies.[9,58,59]

Fuel use and emissions testing can be enhanced by improved methods. State-of-the-art instrumentation can provide data in real time on important aerosol characteristics such as size distribution, composition, surface area, light absorption, and light scattering. Greater use of currently available technologies and development of lower-cost instruments for use in the field could lead to a better understanding of cookstove emissions that affect health and climate. Additional metrics that may capture particle toxicity differently than does $PM_{2.5}$ mass, such as particle size distribution, particle composition, number of particles, and surface area, should also be explored further.[60−62] In addition, aerosol formation and growth models are needed to improve the design and testing of cookstoves.

■ OPPORTUNITIES FOR TRANSFORMATIONAL CHANGE

Despite these challenges, several recent and emerging international efforts are potentially game-changing opportunities to achieve simultaneous benefits for health, climate, the environment, women's empowerment, and economic development through wide-scale household adoption of clean cookstoves. Given the complexities of the problem, working toward this goal requires a multifaceted approach, including significant international investments in research, technology development, awareness raising, creative business models for manufacturers and distributors, and innovative financing mechanisms for end users.

In September 2010, U.S. Secretary of State Hillary Clinton, along with several leading international public figures and private companies, launched the Global Alliance for Clean Cookstoves, a public−private partnership to catalyze a thriving global market for clean cooking solutions (http://www.cleancookstoves.org/). Over 650 partners, including 38 countries, have joined the Alliance. In its first two years, the Alliance has raised over $30 million, directly leveraged more than $120 million in new funding from Alliance partners, increased awareness of the issue around the world, and convened over 350 global experts to help develop a forward-looking plan for overcoming the many barriers that have limited progress in the past. In its third year, the Alliance is poised to implement action plans in six priority countries (Bangladesh, China, Ghana, Kenya, Nigeria, and Uganda), catalyze private investment into the sector, and advance priority research.

An early success of the Alliance was to spearhead efforts that led to the June 2012 publication of an International Organization for Standardization (ISO) International Workshop Agreement, which serves as interim guidelines for evaluating cookstove performance,[63] the first international framework for evaluating stoves against specific indicators. The guidelines provide a rating system with tiers of performance for four performance indicators: fuel use (efficiency), total emissions (carbon monoxide and $PM_{2.5}$), indoor emissions (carbon monoxide and $PM_{2.5}$), and safety. These guidelines will not only inform governments, donors, and investors as to the stove models that can potentially achieve their intended benefits, but will drive the development of standardized fuel use and emissions testing protocols, certification procedures, and performance benchmarks for the global cookstove market. While these guidelines are beginning to provide an incentive for stove developers to innovate and improve performance, further development of formal standards and test protocols is needed.

Many countries have also expanded or begun to develop ambitious national programs to tackle this issue. Massive programs have been launched to bring clean-burning biogas to rural families in China[64] and to switch families cooking with kerosene to clean-burning LPG in Indonesia, each reaching over 40 million homes to date. In 2009, India announced a National Biomass Cookstove Initiative addressing technology, standards, testing, research, and commercial dissemination.[65] Ethiopia and Nigeria have set national goals of helping nine million and ten million households, respectively, adopt clean cooking solutions, while countries such as Ghana and Rwanda are actively weaving clean cooking into broad efforts to bring clean energy to their populations. Peru and Mexico have set national goals of helping 500,000 and 600,000 rural families, respectively, adopt clean cooking solutions. Many other countries are moving in similar directions.

Another new international initiative may provide an additional venue in which to pursue climate and health cobenefits through promoting clean cooking solutions. The Climate and Clean Air Coalition (CCAC) to Reduce Short-Lived Climate Pollutants (www.unep.org/ccac/) was launched in February 2012 by Bangladesh, Canada, Ghana, Mexico, Sweden, the United States, and the United Nations Environment Programme, with the aim of slowing the rate of climate change within the first half of this century while also protecting public health and the environment. Now with many new national and nongovernmental partners, the CCAC is working toward rapid and scaled up international actions to reduce BC, methane, and hydrofluorocarbons. The CCAC may be a new opportunity to promote clean stoves and fuels, with a particular focus on solutions that reduce BC specifically.

Several additional emerging innovations in the cookstove sector are making clean cooking solutions more affordable and promoting sustained adoption. Carbon financing, though facing an uncertain future, offers an opportunity to lower the price of clean stoves and fuels as they reduce carbon dioxide and methane emissions, but only if stoves are actually being used—verification may be facilitated by rapid developments in the real-time monitoring of stove use.[66,67] Several emerging clean stove or fuel businesses seek to leverage the growing cost of charcoal by offering less expensive and extremely clean alternative fuels such as ethanol, biomass pellets, methane, or LPG—and in some cases, these alternatives are offered to poor, rural customers through business models that allow for extremely low costs. Other innovations include manufacturing clean stoves that can charge cell phones (and thus be financed via offset phone-charging fees) and partnering with local customer support such as women's groups to increase sustained adoption.

The current literature indicates that many stoves available today provide immediate and meaningful benefits to families by reducing fuel use. Some of the more advanced stoves and fuels can also further improve health and slow the rate of climate change by significantly reducing $PM_{2.5}$ and BC emissions. While these clean and efficient technologies are nowhere near universally affordable or accessible, and while there is still much to learn on how best to meet the needs of the users, these recent and emerging efforts demonstrate that substantial progress toward wide-scale household adoption of clean stoves and fuels is possible. However, this is just the beginning. Transforming how half of the world's population cooks their food and heats their homes requires a comprehensive global approach that includes sustained investment, understanding consumer demand, technology development and supply, and research, as well as coordinated institutional support from national and international bodies and adequate policies to foster market development. The potential benefits to women, children, communities, and the world are enormous.

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REFERENCES

(1) Lim, S. S.; Vos, T.; Flaxman, A. D.; Danaei, G.; Shibuya, K.; Adair-Rohani, H.; Amann, M.; Anderson, H. R.; Andrews, K. G.; Aryee, M.; Atkinson, C.; Bacchus, L. J.; Bahalim, A. N.; Balakrishnan, K.; Balmes, J.; Barker-Collo, S.; Baxter, A.; Bell, M. L.; Blore, J. D.; Blyth, F.; Bonner, C.; Borges, G.; Bourne, R.; Boussinesq, M.; Brauer, M.; Brooks, P.; Bruce, N. G.; Brunekreef, B.; Bryan-Hancock, C.; Bucello, C.; Buchbinder, R.; Bull, F.; Burnett, R. T.; Byers, T. E.; Calabria, B.; Carapetis, J.; Carnahan, E.; Chafe, Z.; Charlson, F.; Chen, H.; Chen, J. S.; Cheng, A. T.-A.; Child, J. C.; Cohen, A.; Colson, K. E.; Cowie, B. C.; Darby, S.; Darling, S.; Davis, A.; Degenhardt, L.; Dentener, F.; Des Jarlais, D. C.; Devries, K.; Dherani, M.; Ding, E. L.; Dorsey, E. R.; Driscoll, T.; Edmond, K.; Ali, S. E.; Engell, R. E.; Erwin, P. J.; Fahimi, S.; Falder, G.; Farzadfar, F.; Ferrari, A.; Finucane, M. M.; Flaxman, S.; Fowkes, F. G. R.; Freedman, G.; Freeman, M. K.; Gakidou, E.; Ghosh, S.; Giovannucci, E.; Gmel, G.; Graham, K.; Grainger, R.; Grant, B.; Gunnell, D.; Gutierrez, H. R.; Hall, W.; Hoek, H. W.; Hogan, A.; Hosgood Iii, H. D.; Hoy, D.; Hu, H.; Hubbell, B. J.; Hutchings, S. J.; Ibeanusi, S. E.; Jacklyn, G. L.; Jasrasaria, R.; Jonas, J. B.; Kan, H.; Kanis, J. A.; Kassebaum, N.; Kawakami, N.; Khang, Y.-H.; Khatibzadeh, S.; Khoo, J.-P.; Kok, C.; Laden, F.; Lalloo, R.; Lan, Q.; Lathlean, T.; Leasher, J. L.; Leigh, J.; Li, Y.; Lin, J. K.; Lipshultz, S. E.; London, S.; Lozano, R.; Lu, Y.; Mak, J.; Malekzadeh, R.; Mallinger, L.; Marcenes, W.; March, L.; Marks, R.; Martin, R.; McGale, P.; McGrath, J.; Mehta, S.; Mensah, G. A.; Merriman, T. R.; Micha, R.; Michaud, C.; Mishra, V.; Hanafiah, K. M.; Mokdad, A. A.; Morawska, L.; Mozaffarian, D.; Murphy, T.; Naghavi, M.; Neal, B.; Nelson, P. K.; Nolla, J. M.; Norman, R.; Olives, C.; Omer, S. B.; Orchard, J.; Osborne, R.; Ostro, B.; Page, A.; Pandey, K. D.; Parry, C. D. H.; Passmore, E.; Patra, J.; Pearce, N.; Pelizzari, P. M.; Petzold, M.; Phillips, M. R.; Pope, D.; Pope Iii, C. A.; Powles, J.; Rao, M.; Razavi, H.; Rehfuess, E. A.; Rehm, J. T.; Ritz, B.; Rivara, F. P.; Roberts, T.; Robinson, C.; Rodriguez-Portales, J. A.; Romieu, I.; Room, R.; Rosenfeld, L. C.; Roy, A.; Rushton, L.; Salomon, J. A.; Sampson, U.; Sanchez-Riera, L.; Sanman, E.; Sapkota, A.; Seedat, S.; Shi, P.; Shield, K.; Shivakoti, R.; Singh, G. M.; Sleet, D. A.; Smith, E.; Smith, K. R.; Stapelberg, N. J. C.; Steenland, K.; Stöckl, H.; Stovner, L. J.; Straif, K.; Straney, L.; Thurston, G. D.; Tran, J. H.; Van Dingenen, R.; van Donkelaar, A.; Veerman, J. L.; Vijayakumar, L.; Weintraub, R.; Weissman, M. M.; White, R. A.; Whiteford, H.; Wiersma, S. T.; Wilkinson, J. D.; Williams, H. C.; Williams, W.; Wilson, N.; Woolf, A. D.; Yip, P.; Zielinski, J. M.; Lopez, A. D.; Murray, C. J. L.; Ezzati, M. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990−2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **2013**, *380* (9859), 2224−2260.

(2) World Health Organization. *Indoor Air Pollution: National Burden of Disease Estimates*; World Health Organization: Geneva, Switzerland, 2007.

(3) Sovacool, B. K. The political economy of energy poverty: A review of key challenges. *Energy Sustainable Dev.* **2012**, *16* (3), 272−282.

(4) Jetter, J.; Zhao, Y.; Smith, K. R.; Khan, B.; Yelverton, T.; DeCarlo, P.; Hays, M. D. 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* (19), 10827−10834.

(5) Kar, A.; Rehman, I. H.; Burney, J.; Puppala, S. P.; Suresh, R.; Singh, L.; Singh, V. K.; Ahmed, T.; Ramanathan, N.; Ramanathan, V. Real-Time Assessment of Black Carbon Pollution in Indian Households Due to Traditional and Improved Biomass Cookstoves. *Environ. Sci. Technol.* **2012**, *46* (5), 2993−3000.

(6) Berrueta, V. M.; Edwards, R. D.; Masera, O. R. Energy performance of wood-burning cookstoves in Michoacan, Mexico. *Renew. Energy* **2008**, *33* (5), 859−870.

(7) Johnson, M.; Edwards, R.; Alatorre Frenk, C.; Masera, O. In-field greenhouse gas emissions from cookstoves in rural Mexican households. *Atmos. Environ.* **2008**, *42* (6), 1206−1222.

(8) Johnson, M.; Edwards, R.; Berrueta, V.; Masera, O. New approaches to performance testing of improved cookstoves. *Environ. Sci. Technol.* **2009**, *44* (1), 368−374.

(9) Roden, C. A.; Bond, T. C.; Conway, S.; Osorto Pinel, A. B.; MacCarty, N.; Still, D. Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. *Atmos. Environ.* **2009**, *43* (6), 1170−1181.

(10) Chum, H.; Faaij, A.; Moreira, J.; Berndes, G.; Dhamija, P.; Dong, H.; Gabrielle, B.; Goss Eng, A.; Lucht, W.; Mapako, M.; Masera Cerutti, O.; McIntyre, T.; Minowa, T.; Pingoud, K. Bioenergy. In *IPCC Special Report on Renewable Energy Sources and Climate Change*

Mitigation; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C., Eds.; Cambridge, UK and New York, 2011.

(11) Global Bioenergy Partnership. *A Review of the Current State of Bioenergy Development in G8 + 5 Countries*; Global Bioenergy Partnership, Food and Agricultural Organization of the United Nations: Rome, 2008.

(12) Ghilardi, A.; Guerrero, G.; Masera, O. A GIS-based methodology for highlighting fuelwood supply/demand imbalances at the local level: A case study for Central Mexico. *Biomass Bioenergy* **2009**, *33* (6), 957−972.

(13) Drigo, R. *East Africa WISDOM - Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) Methodology - Spatial Woodfuel Production and Consumption Analysis of Selected African Countries*; FAO World Energy Programme: Rome, 2006.

(14) Drigo, R. *Wood-Energy Supply/Demand Scenarios in the Context of Poverty Mapping. A WISDOM Case Study in Southeast Asia for the Years 2000 and 2015*; FAO Wood Energy Programme (FOPP) and Poverty Mapping Project (SDRN): Paris, 2007.

(15) Jetter, J. J.; Kariher, P. Solid-fuel household cook stoves: Characterization of performance and emissions. *Biomass Bioenergy* **2009**, *33* (2), 294−305.

(16) Pennise, D.; Brant, S.; Agbeve, S. M.; Quaye, W.; Mengesha, F.; Tadele, W.; Wofchuck, T. Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. *Energy Sustainable Dev.* **2009**, *13* (2), 71−76.

(17) Adkins, E.; Tyler, E.; Wang, J.; Siriri, D.; Modi, V. Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. *Energy Sustainable Dev.* **2010**, *14* (3), 172−185.

(18) MacCarty, N.; Still, D.; Ogle, D. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy Sustainable Dev.* **2010**, *14* (3), 161−171.

(19) Smith, K. R.; McCracken, J. P.; Weber, M. W.; Hubbard, A.; Jenny, A.; Thompson, L. M.; Balmes, J.; Diaz, A.; Arana, B.; Bruce, N. Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): A randomised controlled trial. *Lancet* **2011**, *378* (9804), 1717−1726.

(20) World Health Organization. *Global Indoor Air Pollution Database*; World Health Organization: Geneva, 2012.

(21) World Health Organization. *Global Health Risks: Mortality and Burden of Disease Attributable to Selected Major Risks*; World Health Organization: Geneva, 2009.

(22) Smith, K. R.; Mehta, S.; Maeusezahl-Feuz, M. Indoor air pollution from household use of solid fuels. In *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Due to Selected Major Risk Factors*; Ezzati, M., Lopez, A. D., Rodgers, A., Murray, C. J. L., Eds.; World Health Organization: Geneva, 2004; pp 1435−1493.

(23) Dutta, K.; Shields, K. N.; Edwards, R.; Smith, K. R. Impact of improved biomass cookstoves on indoor air quality near Pune, India. *Energy Sustainable Dev.* **2007**, *11* (2), 19−32.

(24) Chengappa, C.; Edwards, R.; Bajpai, R.; Shields, K. N.; Smith, K. R. Impact of improved cookstoves on indoor air quality in the Bundelkhand region in India. *Energy Sustainable Dev.* **2007**, *11* (2), 33−44.

(25) Masera, O.; Edwards, R.; Arnez, C. A.; Berrueta, V.; Johnson, M.; Bracho, L. R.; Riojas-Rodríguez, H.; Smith, K. R. Impact of Patsari improved cookstoves on indoor air quality in Michoacán, Mexico. *Energy Sustainable Dev.* **2007**, *11* (2), 45−56.

(26) Balakrishnan, K., Sambandam, S., Ghosh, S., Sadasivam, A., Madhavan, S., Siva, R., Samanta, M. *Assessing Household Level Exposure Reductions Associated with the use of Market Based Improved Biomass Cook-Stoves in Rural Communities in India: Results from Field Assessments in Tamil Nadu and Uttar Pradesh*; Sri Ramachandra University: Chennai, India, 2012.

(27) Cynthia, A. A.; Edwards, R. D.; Johnson, M.; Zuk, M.; Rojas, L.; Jiménez, R. D.; Riojas-Rodriguez, H.; Masera, O. Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico. *Indoor Air* **2008**, *18* (2), 93−105.

(28) Laumbach, R. J.; Kipen, H. M. Respiratory health effects of air pollution: Update on biomass smoke and traffic pollution. *J. Allergy Clin. Immun.* **2012**, *129* (1), 3−11.

(29) García-Frapolli, E.; Schilmann, A.; Berrueta, V. M.; Riojas-Rodríguez, H.; Edwards, R. D.; Johnson, M.; Guevara-Sanginés, A.; Armendariz, C.; Masera, O. Beyond fuelwood savings: Valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico. *Ecol. Econ.* **2010**, *69* (12), 2598−2605.

(30) Pope, C. A.; Burnett, R. T.; Krewski, D.; Jerrett, M.; Shi, Y.; Calle, E. E.; Thun, M. J. Cardiovascular mortality and exposure to airborne fine particulate matter and cigarette smoke shape of the exposure-response relationship. *Circulation* **2009**, *120* (11), 941−948.

(31) Ramanathan, V.; Chung, C.; Kim, D.; Bettge, T.; Buja, L.; Kiehl, J. T.; Washington, W. M.; Fu, Q.; Sikka, D. R.; Wild, M. Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proc. Natl. Acad. Sci., U. S. A.* **2005**, *102* (15), 5326−5333.

(32) Chung, C. E.; Ramanathan, V.; Decremer, D. Observationally constrained estimates of carbonaceous aerosol radiative forcing. *Proc. Natl. Acad. Sci., U. S. A.* **2012**, *109* (29), 11624−11629.

(33) Anenberg, S. C.; Schwartz, J.; Shindell, D.; Amann, M.; Faluvegi, G.; Klimont, Z.; Janssens-Maenhout, G.; Pozzoli, L.; Van Dingenen, R.; Vignati, E.; Emberson, L.; Muller, N. Z.; West, J. J.; Williams, M.; Demkine, V.; Hicks, W. K.; Kuylenstierna, J.; Raes, F.; Ramanathan, V. Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environ. Health Perspect* **2012**, *120* (6), 831−839.

(34) United Nations Environment Programme. *Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers*; United Nations Environment Programme: Nairobi, Kenya, 2011.

(35) Ramanathan, V.; Carmichael, G. Global and regional climate changes due to black carbon. *Nat. Geosci.* **2008**, *1* (4), 221−227.

(36) Rehman, I.; Ahmed, T.; Praveen, P.; Kar, A.; Ramanathan, V. Black carbon emissions from biomass and fossil fuels in rural India. *Atmos. Chem. Phys.* **2011**, *11* (14), 7289−7299.

(37) Ramanathan, V.; Agrawal, M.; Akimoto, H.; Auffhammer, M.; Devotta, S.; Emberson, L.; Hasnain, S. I.; Iyngararasan, M.; Jayaraman, A.; Lawrence, M.; Nakajima, T.; Oki, T.; Rodhe, H.; Ruchirawat, M.; Tan, S. K.; Vincent, J.; Wang, J. Y.; Yang, D.; Zhang, Y. H.; Autrup, H.; Barregard, L.; Bonasoni, P.; Brauer, M.; Brunekreef, B.; Carmichael, G.; Chung, C. E.; Dahe, J.; Feng, Y.; Fuzzi, S.; Gordon, T.; Gosain, A. K.; Htun, N.; Kim, J.; Mourato, S.; Naeher, L.; Navasumrit, P.; Ostro, B.; Panwar, T.; Rahman, M. R.; Ramana, M. V.; Rupakheti, M.; Settachan, D.; Singh, A. K.; St. Helen, G.; Tan, P. V.; Viet, P. H.; Yinlong, J.; Yoon, S. C.; Chang, W. C.; Wang, X.; Zelikoff, J.; Zhu, A. *Atmospheric Brown Clouds: Regional Assessment Report with Focus on Asia*; United Nations Environment Programme: Nairobi, Kenya, 2008.

(38) Praveen, P.; Ahmed, T.; Kar, A.; Rehman, I.; Ramanathan, V. Link between local scale BC emissions in the Indo-Gangetic Plains and large scale atmospheric solar absorption. *Atmos. Chem. Phys.* **2012**, *12*, 1173−1187.

(39) Bond, T. C.; Doherty, S. J.; Fahey, D. W.; Forster, P. M.; Berntsen, T.; DeAngelo, B. J.; Flanner, M. G.; Ghan, S.; Kärcher, B.; Koch, D.; Kinne, S.; Knodo, Y.; Quinn, P. K.; Sarofim, M. C.; Schultz, M. G.; Schulz, M.; Venkataraman, C.; Zhang, H.; Zhang, S.; Bellouin, N.; Guttinkunda, S. K.; Hopke, P. K.; Jacobson, M. Z.; Kaiser, J. W.; Klimont, Z.; Lohmann, U.; Schwarz, J. P.; Shindell, D.; Storelvmo, T.; Warren, S. G.; Zender, C. S. Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res.* **2013**, DOI: doi: 10.1002/jgrd.50171.

(40) Shindell, D.; Kuylenstierna, J. C. I.; Vignati, E.; van Dingenen, R.; Amann, M.; Klimont, Z.; Anenberg, S. C.; Muller, N.; Janssens-Maenhout, G.; Raes, F.; Schwartz, J.; Faluvegi, G.; Pozzoli, L.; Kupiainen, K.; Hoglund-Isakkson, L.; Emberson, L.; Streets, D.; Ramanathan, V.; Hicks, K.; Oahn, N. T. K.; Milly, G.; Williams, M.; Demkine, V.; Fowler, D. Simultaneously mitigating near-term climate

change and improving human health and food security. *Science* **2012**, *335* (6065), 183−189.
(41) Ramanathan, V.; Xu, Y. The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues. *Proc. Natl. Acad. Sci., U. S. A.* **2010**, *107* (18), 8055−8062.
(42) Lamarque, J. F.; Bond, T. C.; Eyring, V.; Granier, C.; Heil, A.; Klimont, Z.; Lee, D.; Liousse, C.; Mieville, A.; Owen, B.; Schultz, M. G.; Shindell, D.; Smith, S. J.; Stehfest, E.; Van Aardenne, J. V.; Cooper, O. R.; Kainuma, M.; Mahowald, N.; McConnell, J. R.; Naik, V.; Riahi, K.; van Vuuren, D. P. Historical (1850−2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application. *Atmos. Chem. Phys.* **2010**, *10* (15), 7017−7039.
(43) Janssen, N. A. H.; Gerlofs-Nijland, M. E.; Lanki, T.; Salonen, R. O.; Cassee, F.; Hoek, G.; Fischer, P.; Brunekreef, B.; Krzyzanowski, M. *Health Effects of Black Carbon*; World Health Organization: Copenhagen, Denmark, 2011.
(44) MacCarty, N.; Ogle, D.; Still, D.; Bond, T.; Roden, C. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. *Energy Sustainable Dev.* **2008**, *12* (2), 56−65.
(45) Johnson, M., Lam, N., Pennise, D., Charron, D., Bond, T., Modi, V., Ndemere, J. A. *In-home Emissions of Greenhouse Pollutants from Rocket and Traditional Biomass Cooking Stoves in Uganda*; U.S. Agency for International Development: Washington, DC, 2011.
(46) U.S. Environmental Protection Agency. *Report to Congress on Black Carbon*; Research Triangle Park, NC, 2012.
(47) Grieshop, A. P.; Marshall, J. D.; Kandlikar, M. Health and climate benefits of cookstove replacement options. *Energy Policy* **2011**, *39* (12), 7530−7542.
(48) Hanna, R.; Duflo, E.; Greenstone, M., Up in smoke: The influence of household behavior on the long-run impact of improved cooking stoves. In *MIT Department of Economics Working Paper Series 12−10*, Cambridge, MA, 2012.
(49) Barnes, D.; Kumar, P. Success factors in improved stoves programmes: Lessons from six states in India. *J. Environ. Stud. Policy* **2002**, *5* (2), 99−112.
(50) Bailis, R.; Cowan, A.; Berrueta, V.; Masera, O. Arresting the killer in the kitchen: The promises and pitfalls of commercializing improved cookstoves. *World Dev.* **2009**, *37* (10), 1694−1705.
(51) Masera, O. R.; Navia, J. Fuel switching or multiple cooking fuels? Understanding inter-fuel substitution patterns in rural Mexican households. *Biomass Bioenergy* **1997**, *12* (5), 347−361.
(52) Joon, V.; Chandra, A.; Bhattacharya, M. Household energy consumption pattern and socio-cultural dimensions associated with it: A case study of rural Haryana, India. *Biomass Bioenergy* **2009**, *33* (11), 1509−1512.
(53) Heltberg, R. Factors determining household fuel choice in Guatemala. *Environ. Dev. Econ.* **2005**, *10* (3), 337−361.
(54) Heltberg, R. Fuel switching: Evidence from eight developing countries. *Energy Econ.* **2004**, *26* (5), 869−887.
(55) Hiemstra-van der Horst, G.; Hovorka, A. J. Reassessing the "energy ladder": Household energy use in Maun, Botswana. *Energy Policy* **2008**, *36* (9), 3333−3344.
(56) Mukhopadhyay, R.; Sambandam, S.; Pillarisetti, A.; Jack, D.; Mukhopadhyay, K.; Balakrishnan, K.; Vaswani, M.; Bates, M. N.; Kinney, P. L.; Arora, N.; Smith, K. R. Cooking practices, air quality, and the acceptability of advanced cookstoves in Haryana, India: An exploratory study to inform large-scale interventions. *Global Health Action* **2012**, *5*, 1−13.
(57) The World Bank. *Household Cookstoves, Environment, Health, and Climate Change*; Washington, DC, 2011.
(58) Bailis, R.; Berrueta, V.; Chengappa, C.; Dutta, K.; Edwards, R.; Masera, O.; Still, D.; Smith, K. R. Performance testing for monitoring improved biomass stove interventions: Experiences of the Household Energy and Health Project. *Energy Sustainable Dev.* **2007**, *11* (2), 57−70.
(59) Johnson, M.; Edwards, R.; Alatorre Frenk, C.; Masera, O. In-field greenhouse gas emissions from cookstoves in rural Mexican households. *Atmos. Environ.* **2008**, *42* (6), 1206−1222.
(60) Lam, N. L.; Smith, K. R.; Gauthier, A.; Bates, M. N. Kerosene: A Review of Household Uses and their Hazards in Low-and Middle-Income Countries. *J. Toxicol. Environ. Health, Part B* **2012**, *15* (6), 396−432.
(61) Naeher, L. P.; Brauer, M.; Lipsett, M.; Zelikoff, J. T.; Simpson, C. D.; Koenig, J. Q.; Smith, K. R. Woodsmoke health effects: A review. *Inhalat. Toxicol.* **2007**, *19* (1), 67−106.
(62) Sahu, M.; Peipert, J.; Singhal, V.; Yadama, G. N.; Biswas, P. Evaluation of mass and surface area concentration of particle emissions and development of emissions indices for cookstoves in rural India. *Environ. Sci. Technol.* **2011**, *45* (6), 2428−2434.
(63) International Standards Organization. *International Workshop Agreement 11:2012: Guidelines for Evaluating Cookstove Performance*; Geneva, Switzerland, 2012.
(64) Sinton, J. E.; Smith, K. R.; Peabody, J. W.; Yaping, L.; Xiliang, Z.; Edwards, R.; Quan, G. An assessment of programs to promote improved household stoves in China. *Energy Sustainable Dev.* **2004**, *8* (3), 33−52.
(65) Venkataraman, C.; Sagar, A.; Habib, G.; Lam, N.; Smith, K. The Indian national initiative for advanced biomass cookstoves: The benefits of clean combustion. *Energy Sustainable Dev.* **2010**, *14* (2), 63−72.
(66) Ramanathan, N.; Lukac, M.; Ahmed, T.; Kar, A.; Praveen, P.; Honles, T.; Leong, I.; Rehman, I.; Schauer, J.; Ramanathan, V. A cellphone based system for large-scale monitoring of black carbon. *Atmos. Environ.* **2011**, *45* (26), 4481−4487.
(67) Ruiz-Mercado, I.; Canuz, E.; Smith, K. R. Temperature dataloggers as stove use monitors (SUMs): Field methods and signal analysis. *Biomass Bioenergy* **2012**, *47*, 459−468.