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Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals☆,☆☆

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ABSTRACT

Development and implementation of clean cooking technology for households in low and middle income countries (LMICs) offer enormous promise to advance at least five Sustainable Development Goals (SDGs): 3. Good health and well-being; 5. Gender equality; 7. Affordable and clean energy; 13. Climate action; 15. Life on land. Programs are being implemented around the world to introduce alternative cooking technologies, and we are well on the way to achieving the goal set by the Global Alliance for Clean Cookstoves to reach 100 million homes with cleaner and more efficient cooking methods by 2020. Despite evidence that household air pollution (HAP) from solid fuel combustion is responsible for 3–4 million early deaths per year, many cookstove programs are motivated and/or financed by climate change mitigation schemes and deploy alternative stoves that use solid fuels such as wood and charcoal. However, recent studies have demonstrated that improved biomass-burning stoves typically only incrementally improve air quality and yield modest or minimal health benefits. Likewise, their contributions to climate change mitigation and other SDGs may be limited. Evidence indicates that cleaner fuels, such as liquefied petroleum gas (LPG), ethanol and biogas, offer greater potential benefits not only to health, but also greater progress towards climate goals and other relevant SDGs. We present a modeled estimate of these potential gains for a diverse group of 40 LMICs. Our model suggests that cookstove programs using LPG stoves and fuel will yield greater reductions in both Disability Adjusted Life Years and Global Warming Commitment in these countries than those using improved biomass stoves. Cost and infrastructure requirements for clean fuels such as LPG are widely recognized constraints. In view of these constraints we present an analytical method to simultaneously consider health and climate needs at the national level for the same 40 countries in the context of estimated LPG expansion potentials. Comparative analyses integrating priorities across SDGs at the national and regional levels may guide more practical and effective household energy development choices going forward.

Introduction

Cooking with solid fuels is a major source of one of the world's biggest killers – household air pollution (HAP) – while also causing major environmental burdens (Chafe et al., 2013; Lacey, Henze, Lee, van Donkelaar, & Martin, 2017) and impeding the empowerment of women and girls. Widespread introduction of improved cooking technology to the poorest third of the planet has been heralded as an affordable intervention with potential to make enormous progress to mitigate these burdens (Anenberg et al., 2013; Smith & Haigler, 2008). If done properly – that is, by ensuring use of clean cooking technologies that offset use of traditional, polluting stoves and fuels – and sustainably, the introduction of clean cooking technology can drive progress towards at least five of the 2030 Sustainable Development Agenda's Sustainable Development Goals (SDGs) (see Box 1).

SDG 3 calls for major reductions in illness and early deaths due to air pollution. HAP is estimated to cause 3–4 million early deaths per year (GBD 2013 Risk Factors Collaborators, 2015; GBD 2015 Risk Factors Collaborators, 2016), and to account for 18% of all ischemic heart disease and 33% of lower respiratory infections globally (World Health

☆ One sentence summary: The global development community has taken up the challenge of improving cooking technology, but achieving health and climate benefits will require greater focus on clean fuels and broader use of analytical tools that integrate across goals to make strategic energy investment choices.

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Box 1
Sustainable Development Goals (SDGs) of particular relevance to clean cooking programs. Adapted from http://www.un.org/sustainabledevelopment/sustainable-development-goals.

SDG	Development goal	Relevant targets
3	Health and well-being	Reduce under-5 deaths. Reduce illness and early death due to air pollution
5	Empowering women and girls	Improved access to enabling technologies
7	Access to reliable, efficient modern energy	Affordable, reliable modern energy
13	Combat climate change	Implement climate measures into national policies
15	Sustainably manage forests and halt land degradation	Reduced deforestation. Reduced land degradation and desertification

Organization, 2016b). While health gains are often cited as an important benefit from clean cooking programs, many initiatives are oriented towards climate change mitigation, improving fuel efficiency, business development and/or reducing hazards and drudgery for women in impoverished settings. Carbon credits have particularly proven to be an attractive source of financing for cookstove programs: the Global Alliance for Clean Cookstoves reported in 2014 that carbon finance was the largest source of financing for cookstoves (UNFCC, 2014). Even in the currently depressed carbon markets, cookstove distribution remains one of the top transaction types (Hamrick & Gallant, 2017).

Cookstove models distributed through development projects are generally more energy-efficient than traditional open fires, and so should burn less wood and thus yield reductions in deforestation and the emissions associated with climate change (Simon, Bailis, Baumgartner, Hyman, & Laurent, 2014). However, to date they have not been shown to radically reduce emissions of fine particulate matter ($PM_{2.5}$) (Pope, Bruce, Dherani, Jagoe, & Rehfuess, 2017; Sambandam et al., 2014) that constitutes the principal exposure of concern from burning biomass and is associated with a wide range of illnesses, including pneumonia, cardiovascular disease, stroke and lung cancer (GBD 2013 Risk Factors Collaborators, 2015; World Health Organization, 2014). Pneumonia is of particular concern for the SDGs, because it is a leading cause of under-five mortality in low- and middle-income countries (LMICs). However, recent estimates of the impact of HAP on early death and disability point to its role in non-communicable diseases (NCDs), including stroke, heart disease, COPD and Lung Cancer (GBD 2013 Risk Factors Collaborators, 2015), and assuming these estimates are accurate, HAP reductions will be an important part of NCD reduction strategies.

Evaluation of existing programs with improved biomass cookstoves indicates that health benefits are often smaller than anticipated (Khandelwala et al., 2017; Mortimer et al., 2016; Quansah et al., 2017). In late 2016, a large randomized control trial in Malawi found no reductions in pneumonia incidence associated with distribution of advanced biomass stoves (Mortimer et al., 2016). No exposure data has yet been reported from that trial, but the authors report that many families who adopted the new technology did not stop using traditional fires, a practice that would have diminished the exposure reduction provided by the advanced stoves (Johnson & Chiang, 2015). Other intervention studies have likewise failed to achieve recommended reductions in $PM_{2.5}$ levels (Aung et al., 2016; Smith et al., 2011).

The challenges that trials have confronted include relatively poor performance of biomass stoves in the field compared to laboratory standards (Wathore, Mortimer, & Grieshop, 2017), incomplete replacement of traditional fires in households (fuel stacking) (Ruiz-Mercado & Masera, 2015), and potential contributions from other ambient pollution from surrounding sources (Ezzati & Baumgartner, 2017; Huang, Baumgartner, Zhang, Wang, & Schauer, 2015).To provide stronger evidence regarding the efficacy of clean cooking interventions for health, the NIH, in cooperation with the Bill and Melinda Gates Foundation, has recently launched a four country interventional trial, the Household Air Pollution Intervention Network (HAPIN, ClinicalTrials.gov identifier: NCT02944682) using liquefied petroleum gas (LPG). This efficacy trial is designed to focus on communities in which ambient air pollution is relatively modest compared to indoor pollution. Careful attention will be paid to socio-behavioural factors to maximize exclusive use of this cleaner fuel in every intervention household. Initial outcomes from this trial will be available in approximately three years.

In the meantime, available evidence suggests that health improvement outcomes are most likely when clean cooking programs focus on fundamentally clean fuels, such as LPG, electricity, biogas, or ethanol. Further, a recent trial in Nigeria using clean-fuel ethanol stoves achieved a significant reduction in blood pressure among pregnant women (Alexander et al., 2017). This paradigm, summarized as “making the clean available instead of trying to make the available clean” (Smith & Sagar, 2014), represents a relatively recent shift of focus for the global health research community focusing on HAP, and has been endorsed by the World Health Organization (WHO) (World Health Organization, 2016a).

The pivot of global public health researchers towards clean fuels, and LPG in particular, contrasts with the continued focus by some actors in the development community on improved biomass stoves. These stoves make some sense under the assumption that they reduce use of wood and other biomass fuels and provide net reductions towards CO_2 emissions targets, assisting with SDGs 13 and 15 (Cornwall, 2017). Wood fuels are used unsustainably in many countries in the developing world, particularly in tropical Africa and South Asia (Bailis, Drigo, Ghilardi, & Masera, 2015), and so reducing fuel use theoretically reduces net CO_2 emissions and deforestation. This may not be true in places with low deforestation rates, like the US, although net climate impacts are uncertain (Cornwall, 2017). It is also important to note that much of the net climate impact of both traditional and improved stoves in real-world operation comes from non-CO_2 emissions, like methane and black carbon particles (Anenberg et al., 2013; Bond, Venkataraman, & Masera, 2004; Wathore et al., 2017). Therefore, reliance on biomass fuels for cooking, even with more efficient stoves, may contribute more to global warming than would cooking with LPG.

An additional benefit from using clean fuels delivered to the home is the empowerment of women and girls (SDG 5), who gain time and reduce drudgery by not collecting firewood (Lewis et al., 2017). Finally, the use of clean fuels is an important step in the transition to modern, reliable sources of energy (SDG 7).

An inherent challenge to energy policy choices that integrate across these goals lies in the relative separation of the energy development and health communities and the fact that neither is particularly accustomed to addressing issues at the household level. For example, energy researchers and ministries have typically focused at a more ‘macro’ level (energy grids, fossil fuel supplies) and not delved into the household resources and practices that dictate cooking in both rural and urban settings. The recent Draft Energy Policy (GOI, 2017) from the Government of India articulates this challenge concisely:

“Clean cooking fuel has been the biggest casualty of lack of coordination between different energy Ministries. The clean cooking fuel policy option for rural areas has been virtually none, with a poor LPG component (1% growth per year). As if biomass is going to remain as the staple fuel, the major focus has been only on efficient cook-stoves through MNRE schemes, which owing to several reasons, did not reach the rural populace in a significant manner. On the other hand, for urban areas, LPG has been the fuel of choice. Moreover, there has been no national programme for clean cooking fuel, and no administrative Ministry responsible for this vital aspect!" (GOI, 2017, Box 2, pg. 19).

The WHO has called for development of decision support tools that integrate health and climate objectives to facilitate coordination of policy and program objectives across relevant ministries and development financing organizations (World Health Organization, 2016a). Here we offer an integrated analysis of the two most widespread cooking fuel options around the world, LPG and wood, with modeled health and climate benefits estimated for 40 priority countries, and we suggest an approach to prioritize these options at the national and international level in the context of limited access.

Estimating health and climate benefits attainable with stove/fuel programs

Benchmarking the potential of household energy options has been greatly facilitated with the development of ISO emissions standards for cookstoves and the associated development of classification tiers for safety, efficiency and emissions (https://www.iso.org/standard/61975.html), and WHO's development of indoor air quality guidelines (World Health Organization, 2014). As has been pointed out by others (Grieshop, Marshall, & Kandlikar, 2011; Shen et al., 2017; Still, Bentson, & Li, 2014), even under laboratory conditions few biomass stoves are able to achieve reductions in emissions necessary for significant health benefits, despite significant and steady progress in design. Almost all of these stoves fall short of the Tier 4 emissions standards that clean fuels such as LPG, ethanol and biogas occupy (see the Global Alliance for Clean Cookstoves – clean cooking catalog http://catalog.cleancookstoves.org/ for the most comprehensive list).

However, while laboratory-based technology assessments and standards are useful, field measurements often suggest smaller benefits than laboratory studies both in terms of emissions of health-damaging fine particles and global warming commitment. Several recent studies (Grieshop, Jain, Sethuraman, & Marshall, 2017; Guofeng et al., 2012; Johnson, Edwards, Frenk, & Masera, 2008; Roden et al., 2009; Wathore et al., 2017) conducted field assessments of several types of biomass stoves, including highly engineered models, to assess their potential emissions, exposure and climate impact reductions as compared to traditional stoves.

Here we incorporate data from these recent field-based estimates into two simulation models to consider the benefits to health and climate change mitigation at the national program level. We analyze different technology/fuel options at the national scale in 40 priority countries (see Box 2). The selection of countries was driven by the intersection of: countries with highest disease burden from HAP, countries with available data for estimated fraction of non-renewable biomass (efNRB), and countries with highest unrealized potential of LPG market expansion, as measured by a composite index.

Box 2
Countries included in analysis.

Angola	Congo	Kenya	Peru
Bangladesh	Equatorial Guinea	Madagascar	Philippines
Benin	Ethiopia	Mauritania	Solomon Islands
Bhutan	Ghana	Mozambique	Sri Lanka
Burkina Faso	Guatemala	Myanmar	Sudan
Burundi	Guinea-Bissau	Nepal	Swaziland
Cambodia	Haiti	Nicaragua	Togo
Cameroon	Honduras	Niger	Uganda
Chad	India	Nigeria	Zambia
China	Indonesia	Pakistan	Zimbabwe

Each intervention scenario assumes a 25,000 household program replacing traditional fires with different stove types, as in (Wathore et al., 2017): LPG, Advanced Fan (based on Philips HD4012LS forced-draft cookstove), and a locally made cookstove (Local ICS) (based on Chitetezo Mbaula natural-draft clay cookstove).

Averted CO_2-equivalent emissions were calculated using field emissions and fuel-use results from (Wathore et al., 2017) and national efNRB estimates by country from (Bailis et al., 2015), as the Global Warming Commitment (GWC) of emissions from wood fuel use is highly dependent on the fraction of biomass harvested from non-renewable sources (Bailis et al., 2015; Grieshop et al., 2011).

Averted DALYs were calculated based using the Household Air Pollution Intervention Tool (HAPIT) Version 3.0 (Pillarisetti, Mehta, & Smith, 2016). The following assumptions were held constant for each intervention scenario: Pre-intervention exposure: 285 μg/m^3; Counterfactual exposure: 7.3 μg/m^3; Intervention length: 3 years; Fraction using intervention: 0.6. Post-intervention exposures were calculated by scaling the 285 μg/m^3 pre-intervention value using emissions reduction factors calculated as the ratios (intervention:traditional) of field-based emission rates (Wathore et al., 2017), resulting in exposure concentration estimates of: 74 μg/m^3 (Advanced Fan), 182 μg/m^3 (Local ICS). As $PM_{2.5}$ emissions from LPG stoves are negligible relative to the ambient levels (Grieshop et al., 2011; Smith et al., 2000), we assumed that exposure to $PM_{2.5}$ following an LPG intervention will be dominated by ambient air pollution, and have used the WHO interim target of 35 μg/m^3 to represent the average post-intervention exposure in this group (World Health Organization, 2006).

The HAPIT tool utilizes these inputs along with country-level background data, including HAP burden of disease estimates from the Global Burden of Disease data (GBD 2013), to estimate the DALYs averted by each intervention in each selected country. Although reductions in personal exposure may not always track linearly with reductions in emissions because of large variability in ambient pollutant concentrations, combustion and ventilation conditions, stove usage and time-activity practices across settings(Grieshop et al., 2017), here we have calculated hypothetical health and climate benefits using emission values because this method allows direct comparison of stoves from a single study using common methods of assessment for both $PM_{2.5}$ exposure and greenhouse gases.

In Fig. 1 we present modeled estimates of average potential health gains and climate change mitigation from stove replacement programs using LPG stoves compared to improved biomass cookstoves. These results suggest that the median country would avert the loss of 4× more Disability Adjusted Life Years (DALYs) and over 100,000 more tons of CO_2 equivalents by instituting a 25,000-household LPG intervention compared to one using a basic improved biomass stove. Averted GWC will be highest for countries with high rates of non-sustainable biomass use (efNRB > 50%, Fig. 1b), but under all scenarios LPG outperforms improved biomass stoves.

Life cycle assessments that have been performed for these fuels in Africa (Gujba, Mulugetta, & Azapagic, 2015) and Asia (Cashman, Rodgers, Huff, Feraldi, & Morelli, 2016) generally confirm the reduced environmental impact for LPG as compared to solid fuel cooking (SDG 15). This analysis does not address other potentially important environmental consequences of LPG extraction, such as chemical contamination of water tables.

Making informed policy choices for clean fuel scale up

Because the international development communities increasingly need to assess energy options (e.g. LPG, wood, charcoal, ethanol, biogas, natural gas, solar, grid electricity), in the context of differing national priorities for health and climate mitigation, we suggest that explicit integration of these goals in decision support tools is necessary. While Fig. 1 shows that LPG interventions are generally preferable to improved biomass stove interventions, an important and widely cited challenge

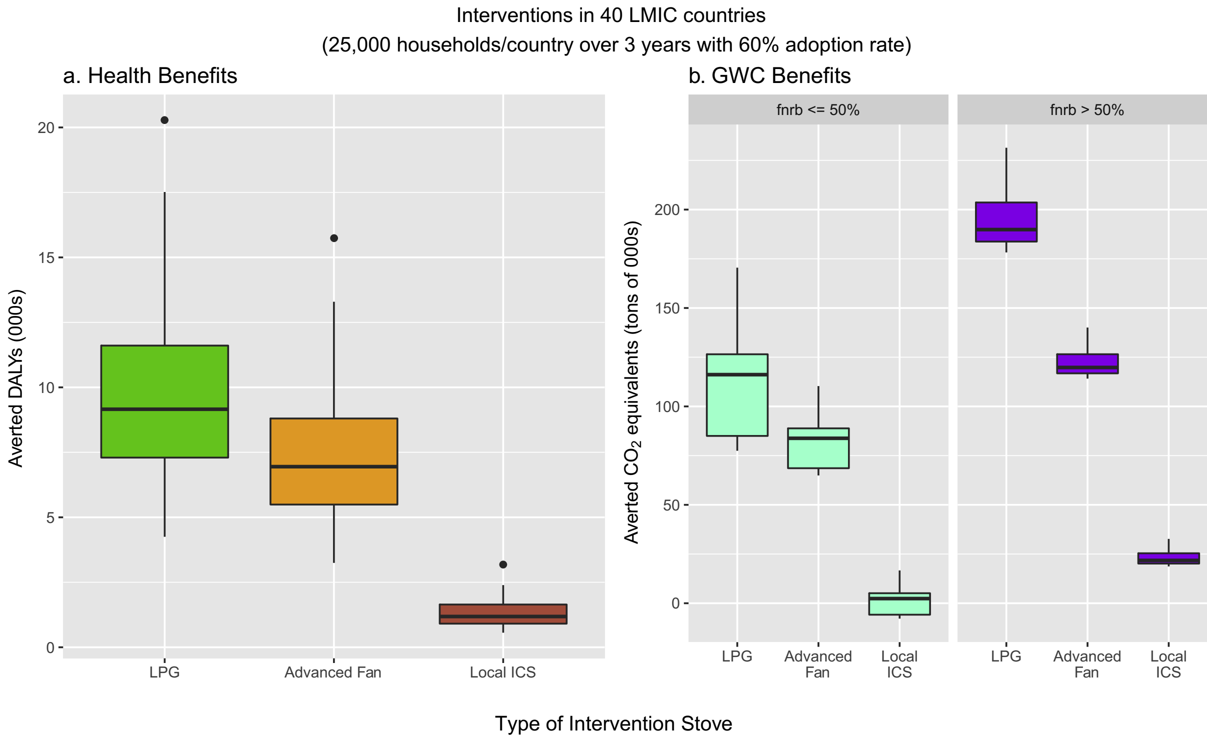

Fig. 1. Averted Disability Adjusted Life Years (DALYs) and Global Warming Commitment (GWC) in each of 40 countries for three stove intervention scenarios. a) Boxplots of averted DALYs. b) Boxplots of averted GWC for the same scenarios, stove types and countries. Upper and lower hinges of each boxplot represent the 25th and 75th percentile, respectively; whisker extent comprises values up to 1.5× the interquartile range away from each hinge; dots represent values farther than 1.5× away.

for expanded use of LPG is its availability and affordability in the poorest countries (International Energy Agency, 2016). We acknowledge this challenge but note that declining costs of LPG combined with increasing commercial distribution channels offer strong opportunities for expansion of this clean fuel in many, but not all, countries before 2030. While much of Latin America has already converted to LPG and natural gas cooking (Troncoso & Soares da Silva, 2017), much of Africa and Asia have not, and rural areas all over the developing world lag substantially in adopting these clean fuels.

LPG consumption for domestic purposes is growing rapidly, if unevenly, around the world, especially over the past five years (Fig. 2). Many countries are targeting major increases in the next decade to meet climate-related, energy modernization and other Sustainable Development Goals (IEA, 2016). This includes African nations such as Ghana and Cameroon, that have relatively modest LPG usage currently (World LPG Association, 2015).

To support an integrated analysis of fuel options we present a simple matrix (Fig. 3) for assessing the relative burden that solid fuel burning poses for health and global warming commitment at the national level in our 40 priority countries. To assess the potential role for LPG in this context we have updated and modified the GLPGP-Dalberg index for LPG expansion potential (GLPGP-Dalberg, 2012) that draws on a variety of relevant UN indicators, as well as current domestic consumption of LPG, to estimate LPG access in the near future for our 40 selected priority countries. Our version of this expansion potential index is derived by combining the following development indices: Political Stability and Regulatory Quality (Kaufmann & Kraay, 2015), Female Literacy (Central Intelligence Agency, 2015), Road Quality (World Economic Forum, 2016), Percent Urbanized (The World Bank, 2015), and per capita LPG consumption by households (United Nations Statistics Division, 2013). Missing road quality figures were imputed with the median value, each factor was rescaled to a range between 0 and 100, and the LPG Expansion potential represents an equally-weighted average of the six factors.

The resulting analysis (Fig. 3) illustrates diversity across countries in the relative burden that biomass burning poses to human health and the environment; and additionally demonstrates that the current potential for LPG expansion differs greatly by country. This information could be used at the national level both to provide a rationale for expansion of clean cooking programs (whether primarily for health, climate, or both), and to estimate the challenge facing the expansion of LPG cooking specifically.

While all 40 countries selected for this analysis rank HAP among the top 10 risk factors for nation-specific morbidity and mortality, 24 of the 40 rank HAP among the top five national risk factors (Fig. 3, quadrants A and B), indicating an urgent need for prioritization in these countries especially. Meanwhile, countries where the impact of biomass use on the environment is above the median are depicted in quadrants B and C of Fig. 3. The 12 countries depicted in Fig. 3, quadrant B, are those where clean cooking interventions have a high potential for win-win investments in health and environment.

However, expanded use of LPG for cooking has been (Fig. 2) and will likely continue to be (Fig. 3) very uneven among those nations that need clean fuel options. Our analysis suggests that LPG interventions among high HAP priority nations are most likely to be feasible in Cambodia, Equatorial Guinea, Sri Lanka, India, Ghana, Philippines and Honduras (Fig. 3, quadrants A and B, green points). Others with a very high HAP burden will likely be challenged to expand LPG in the near term (e.g. Bangladesh, Nepal, Ethiopia, Haiti, Burundi and Mozambique) and may need to allocate relatively more resources towards infrastructure, subsidies, market development, awareness, and other activities related to LPG expansion and/or to consider alternative clean fuel options such as ethanol, biogas, electricity and advanced biomass stoves.

Similarly, several countries that have high rates of unsustainable firewood use for cooking appear to have opportunities for LPG expansion (Fig. 3, quadrants B and C, e.g. India, Angola, Kenya, Mauritania, Bhutan, Peru, Indonesia, and China), while some nations with the largest fractions of non-renewable wood harvesting (Pakistan, Mauritania,

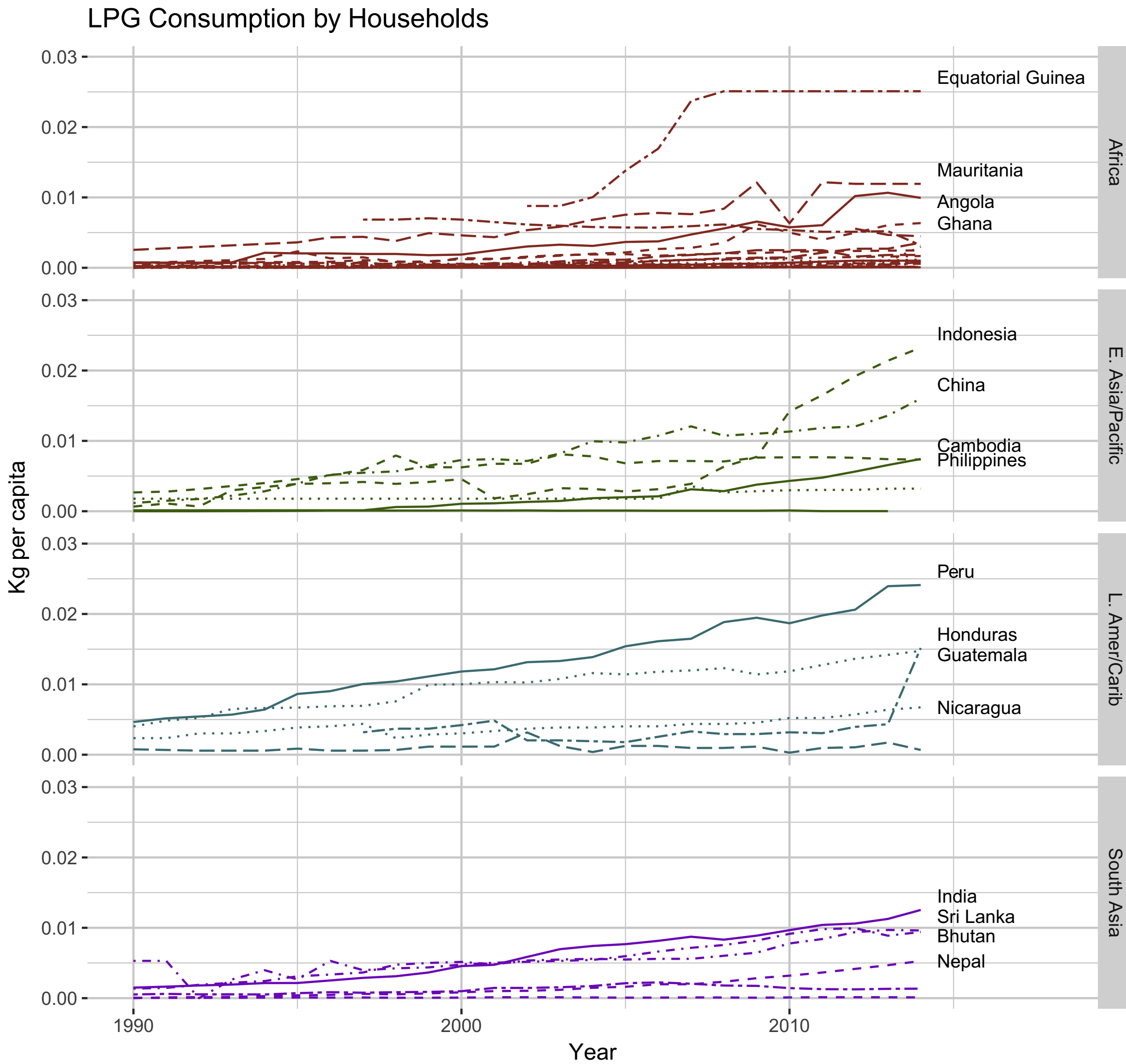

Fig. 2. Annual LPG consumption by households for the years 1990–2015, in kg per capita, for 40 countries. Source: United Nations Energy Statistics Database (United Nations Statistics Division, 2017). Countries not listed in graph, in descending order of LPG consumption in 2014, by World Bank region – Africa: Sudan, Burkina Faso, Swaziland, Kenya, Cameroon, Congo, Guinea-Bissau, Benin, Togo, Zimbabwe, Niger, Mozambique, Zambia, Madagascar, Uganda, Nigeria, Burundi, Chad, Ethiopia. South Asia: Pakistan, Bangladesh. E. Asia/Pacific: Solomon Islands, Myanmar. L. Amer/Carib: Haiti.

and Niger) may need to make more aggressive investments in LPG infrastructure or to pursue alternative clean fuels.

In this analysis of 40 nations, India stands out as the country for which growth of LPG use is likely to provide opportunities to address priority health and climate challenges (Fig. 3, quadrant B). Notably, India has recently embarked on a major national campaign to expand LPG access to poorer homes (Government of India, 2017; Smith & Sagar, 2016). This program, like many others, depends on subsidies and other significant economic incentives to ensure that LPG access is equitable and not limited to the most well-to-do households (Troncoso & Soares da Silva, 2017). Expansion for most LMICs will be easiest in urban and peri-urban areas. In rural regions governments will continue to be challenged by cost compared to that of available biomass, and by weak distribution networks, credit systems, and safety perceptions, among other concerns (World LPG Association, 2015).

Discussion

We have presented an integrated analysis of the potential health and climate benefits of clean cooking interventions across 40 priority countries in the context of each country's estimated HAP related burden of disease and fuel wood use. We have focused on comparing wood-burning stoves to LPG stoves because of the relative accessibility of these options in the near to medium term. Using field emissions results from a recent study of representative stoves, our analysis reinforces the growing consensus (Simon et al., 2014; Smith, 2015; Smith & Sagar, 2014; World Health Organization, 2014; World Health Organization, 2016a) that LPG is the superior option to reach health goals. It also suggests that LPG yields superior net benefits for climate mitigation across a range of countries. This is the first time, to our knowledge, that such an integrated analysis has been completed for a diverse group of low and middle income countries.

We have further proposed an approach to prioritize national-level investments in expanded LPG and other alternatives to fuel wood that integrates health and climate goals, and calculated a revised LPG expansion index that attempts to model general economic and structural constraints for this fuel for each of the same forty countries. Our model suggests that while LPG is technically a win-win solution for all countries, the subset of countries for which rapid expansion is likely without a major push from governments and development agencies is much smaller.

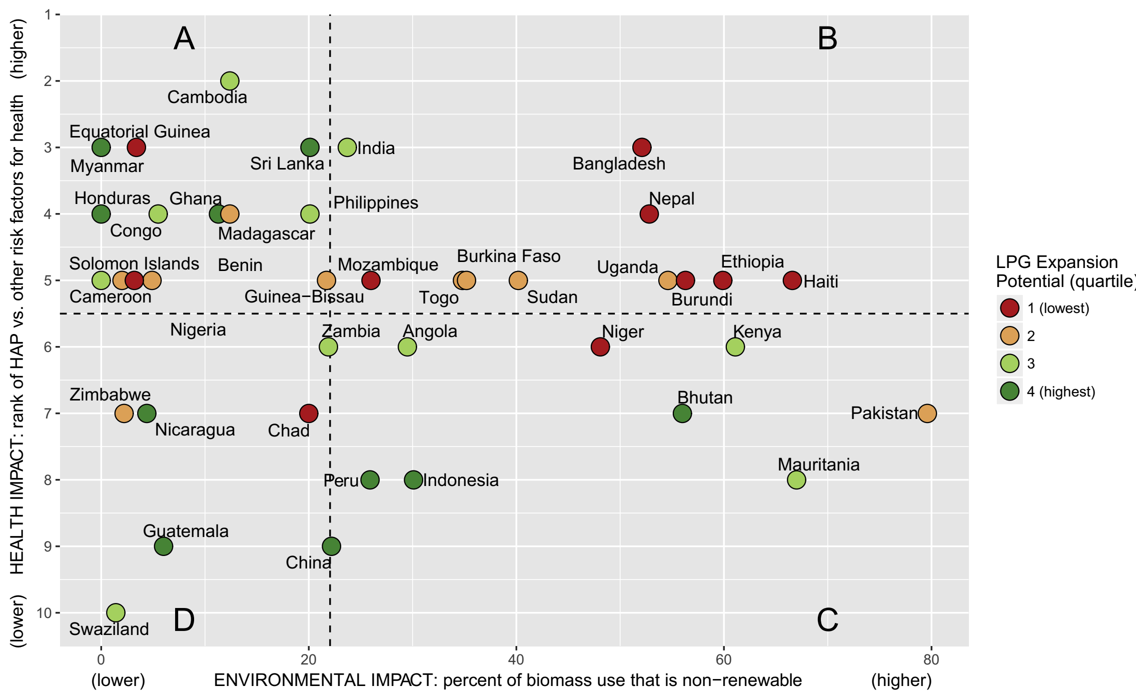

Fig. 3. Rank of HAP-related disease burden at the national scale versus efNRB for 40 countries. Health impact is the national rank of HAP relative to other risk factors (GBD 2013 Risk Factors Collaborators, 2015). efNRB is a measure of, among other things, unsustainable wood fuel use (Bailis et al., 2015). Color represents quartiles of the LPG expansion index. Lines drawn at median value for efNRB (vertical line) and below the midpoint for HAP rank (horizontal line) to separate countries for which HAP is one of the top five risk factors nationally (vs. of rank 6 to 10). Countries in the upper right quadrant (B) are those for which HAP is among the greatest risk factors for disease and have the most unsustainable supply of fuel wood for cooking.

Similar analyses for other clean fuel options (ethanol, biogas, electricity, wood pellets, etc.) will be useful. However, because these alternative fuels are likely to be more dependent on local and sub-national variables (e.g. feedstock availability and processing capacity) than on transnational pricing and distribution concerns, it may be more meaningful to perform integrated cross-fuel analyses within, rather than across, countries. The Fuel Analysis, Comparison and Integration Tool (FACIT) being developed by the Global Alliance for Clean Cooking is a hopeful beginning here (http://cleancookstoves.org/technology-and-fuels/facit/). The low emissions profiles of these alternatives are stimulating growing interest in the clean cooking sector, and they provide important opportunities to address health and environment goals, particularly in rural and remote areas where commercial supply of LPG will lag (Puzzolo, Pope, Stanistreet, Rehfuess, & Bruce, 2016; Smith, 2017).

There are a variety of important barriers that constrain the ability of clean cooking programs to reduce emissions. Continued use of open fires for cooking alongside new technology (Puzzolo et al., 2016; Stanistreet, Puzzolo, Bruce, Pope, & Rehfuess, 2014) is very common. Heating and other household energy needs, weak fuel distribution systems, high costs to households (Jeuland & Tan Soo, 2016), and specific cultural preferences also complicate switching to cleaner fuels in LMIC households, even in countries where the policy environment is favorable and market supply chains exist.

Although we do not deal substantively with these important constraints here, we have conducted our analysis of each hypothetical 25,000-household intervention under the assumption that the uptake of the intervention is 60%: that is, 60% of households adopt the intervention completely and accrue the full estimated health and climate benefit of making the switch, while 40% of the households do not adopt it at all, or adopt it at such a low level that no health or climate benefits accrue. Our calculated health and climate benefits assume successful deployment, but are more conservative than would be realized under an assumption of “complete” abandonment of the prior cooking technique in the target population.

Nonetheless, we recommend careful analytical and evaluative work before beginning any clean cooking distribution program (Rosenthal et al., 2017). For example, all cooking interventions will need to anticipate the role of community-wide cooking practices and other ambient sources of air pollution, as cumulative exposure is the final arbiter of potential health and environmental benefits. Where barriers to sustained and exclusive use of clean fuels are persistent, decision makers may need to employ or anticipate multi-fuel approaches, including continued use of solid fuels (Ruiz-Mercado & Masera, 2015). Ultimately, clean fuel programs must be assessed by how much they displace open fires in daily use as well as by how clean the technology is (Rosenthal et al., 2017). In some environments, high-performance biomass stoves, especially those with chimneys, may be the optimum technology for some years to come (Still et al., 2014). However, stronger evidence for potential health benefits from these advanced technologies is needed. It may be important to improve operability and reliability of the stoves and simplify fuel preparation for this approach to succeed (Wathore et al., 2017).

Research is critical if clean cooking is to achieve its full potential to improve health, environment and development goals (Rosenthal, 2015). This includes implementation science to address social and economic barriers to scaling up access to clean fuels and stoves, as well as stove adoption that results in complete displacement of open fires (Lewis & Pattanayak, 2012; Rosenthal et al., 2017; Ruiz-Mercado & Masera, 2015; Simon et al., 2014), technology enhancement to reduce emissions from biomass based stoves (Simon et al., 2014; Still et al., 2014), clinical and field research to build stronger evidence for health and climate benefits of all cooking technology alternatives (Ezzati & Baumgartner, 2017; Martin et al., 2013; Martin, Glass, Balbus, & Collins, 2011; Rosenthal, 2015; Sanford & Burney, 2015), and technological innovation to develop more sustainable and cost effective energy solutions for low income settings (Cashman et al., 2016). While LPG is typically less damaging to health and climate than biomass cooking, it is still a fossil fuel with multiple environmental drawbacks. In the long run, renewable clean energy sources will be increasingly important alternatives, especially as efficiency of solar capture and energy storage increase and costs for these decline.

Nonetheless, currently available clean fuels such as LPG represent important opportunities to improve lives for millions of people in LMICs and to accelerate mitigation of climate warming emissions with today's technology. They are a means to make major advances towards the SDGs by 2030. The scoping analysis presented here highlights the potential for large benefits from clean fuel interventions across diverse country settings, and serves as an example approach for integrated decision making in pursuit of SDG goals.

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