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Everybody Stacks: Lessons from household energy case studies to inform design principles for clean energy transitions

Anita V. Shankar[1],
Johns Hopkins University, Bloomberg School of Public Health, Baltimore, MD, USA

Ashlinn Quinn[1],
Fogarty International Center, National Institutes of Health, Bethesda, MD, USA[2]

Katherine L. Dickinson,
Colorado School of Public Health, Denver, CO, USA

Kendra N. Williams,
Johns Hopkins University, School of Medicine, Baltimore, MD, USA

Omar Masera,
Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Morelia, Michoacán. Mexico

Dana Charron,
Berkeley Air Monitoring Group, Berkeley, CA, USA

Darby Jack,
Columbia University, New York, NY, USA

Jasmine Hyman,
E Co Ltd, London, UK

Ajay Pillarisetti,
Gangarosa Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, GA

Rob Bailis,
Stockholm Environment Institute, Somerville, MA, USA

Praveen Kumar,
Boston College, Boston, MA, USA.

(corresponding): anita.shankar@jhu.edu.

[1]Both authors contributed equally to the paper
[2]The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the U.S. National Institutes of Health or Department of Health and Human Services.

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Ilse Ruiz-Mercado,
Escuela Nacional de Estudios Superiores Unidad Mérida, Universidad Nacional Autónoma de México (UNAM), Mérida, Yucatán, Mexico

Joshua Rosenthal
Fogarty International Center, National Institutes of Health, Bethesda, MD, USA[2]

Abstract

Stove stacking (concurrent use of multiple stoves and/or fuels) is a poorly quantified practice in regions where efforts to transition household energy to cleaner stoves/or fuels are on-going. Using biomass-burning stoves alongside clean stoves undermines health and environmental goals. This review synthesizes stove stacking data gathered from eleven case studies of clean cooking programs in low/middle-income country settings. Analyzed data are from ministry and program records, research studies, and informant interviews. Thematic analysis identify key drivers of stove stacking behavior in each setting. Significant (28%-100%) stacking with traditional cooking methods was observed in all cases. Reason for traditional fuel use includes: costs of clean fuel; mismatches between cooking technologies and household needs; and unreliable fuel supply. National household surveys often focus on 'primary' cookstoves and miss stove stacking data. Thus more attention should be paid to discontinuation of traditional stove use, not solely adoption of cleaner stoves/fuels. Future energy policies and programs should acknowledge the realities of stacking and incorporate strategies at the design stage to transition away from polluting stoves/ fuels. Seven principles for clean cooking system program design and policy are presented, focused on a shift toward "cleaner stacking" that could yield household air pollution reductions approaching WHO targets.

Keywords

adoption; clean cooking; household air pollution; cookstoves; household energy

1. Introduction

In 2016, an estimated 59% of the global population had access to clean cookstoves and fuels, a marginal increase since 2014 (IBRD/World Bank 2018). Nearly three billion people, predominantly living in Asia and Sub-Saharan Africa and overwhelmingly rural (90%) and poor, lack access to clean cooking methods (Bonjour et al 2013, IBRD/World Bank 2018; WHO 2016). The reliance on polluting fuels (primarily wood, dung, crop residues, charcoal, and kerosene) used in simple devices to meet household energy needs is a leading cause of household air pollution (HAP), which contributes to significant morbidity from respiratory and cardiovascular diseases and results in millions of deaths worldwide (GBD 2016 Risk Factor Collaborators, 2017). Data from the recent Energy Progress Report (2018) on Sustainable Development Goal 7 (SDG 7), which calls for affordable, reliable, sustainable and modern energy for all by 2030, indicates that the pace of clean household fuel transition is severely lagging. Without dramatic acceleration in the coming years, SDG 7 will be missed by a wide margin (IBRD/World Bank 2018).

A focus on improving overall living conditions to allow the sustained elimination of household sources of pollutants from cooking devices is critical from a health perspective, as considerable research has shown that HAP exposure substantially contributes to the global burden of disease (Lim et al 2012; GBD 2016 Risk Factor Collaborators 2017). This includes acute lower respiratory infections (ALRI), chronic obstructive pulmonary diseases (COPD), lung cancer, ischaemic heart diseases (IHD), diabetes, and stroke. Like other categories of air pollution, HAP affects health in a dose-dependent fashion. Integrated exposure-response (IER) models, which estimate the relative risk for a disease caused by air pollution at different $PM_{2.5}$ exposures, allow estimates not only of the current health burden of HAP, but also of the potential health benefits of reducing HAP. These models indicate that substantial reductions in HAP are needed in order to significantly reduce the burden of disease (Bruce et al 2015, Burnett et al 2014).

This implies the need for a substantial transformation in the patterns of pollutant exposure from cooking and heating practices among the rural poor. For example, the IER for child ALRI shows that reductions of 50% in exposure to HAP from exposure levels typically associated with traditional solid fuels and stoves can be expected to result in only small reductions in risks, and that much more substantial reductions (levels close to the WHO thresholds of 35 μg/m3 $PM_{2.5}$ for long-term average exposure) are needed to prevent most of the ALRI cases attributed to HAP (HEI HAP working group 2018). Based on existing data, it is nearly impossible to meet the WHO targets if households use traditional biomass fuels (Johnson & Chiang 2015). Rather, a near-complete discontinuation of the use of traditional polluting fuels would be required to achieve health goals. This process has also been termed suspension of solid fuel use (Yan et al, 2020).

In addition to the risk of premature death due to respiratory and cardiovascular disease, burn injuries associated with traditional cooking with firewood are significant. Indeed, 95% of the more than 300,000 global fire-related deaths that occur each year take place in low- and middle-income countries, where open fires and crudely constructed cookstoves play an outsized role (Gallagher et al 2016; Mock et al 2008). HAP has also been associated with visual impairment (West et al 2013) and linked with low or reduced birthweight (Epstein et al 2013; Amegah et al 2014). Moreover, there is a significant burden of time and drudgery for women and children who tend to be primarily responsible for the collection and processing of fuelwood (Ndiritu & Nyangena 2011, Nankhuni & Findeis 2004).

Many policy and program efforts designed to address these health concerns focus on transitioning households towards cleaner energy practices by encouraging adoption of the cleanest available cookstoves and fuels. Options include the promotion of clean fuels and devices such as liquid petroleum gas (LPG), biogas, natural gas, ethanol and electric stoves. Some solid fuel stoves, such as clean wood burning chimney stoves and devices that burn biomass pellets, can also reduce levels of HAP.

However, *access* to clean cooking technologies and fuels is not sufficient if the larger goal is the elimination of exposure to household pollutants. Increasing access to clean technologies and fuels rarely results in their consistent, exclusive and long-term use in poor, rural communities (Ruiz-Mercado et al 2011). Indeed, historical studies have documented that in most household energy transitions, full uptake and sustained use of non-traditional clean cooking alternatives has been low, and the transitions only partial (Mobarak, et al 2012; Hiemstra-van der Horst & Hovorka 2008; Brouwer & Falcao 2004; Malla & Timilsina 2014). Moreover, population-based surveys focused on identifying only “primary fuel use” have overlooked the heterogeneity in fuel use found at the household level. In the vast majority of clean cooking initiatives, the cleaner alternative is simply added to the traditional methods of cooking resulting in combined use. The use of multiple cooking devices and fuels is commonly referred to as stove ‘stacking’. This pattern is not unlike what typically happens in a high-income context, where the acquisition of a new cooking device (e.g., a microwave or a slow cooker) does not fully displace the original cooking apparatus but instead adds to it. In essence, given access to a portfolio of options and a diverse set of household needs, *everybody stacks*.

Assessing progress is further complicated by the fact that cookstove programs can be designed to advance multiple goals: improving health; promoting gender equity; enhancing livelihoods; reducing greenhouse gas emissions; reducing deforestation, etc. It follows that the multitude of clean cooking initiatives and programs by governments, international agencies, not-for-profit organizations and social businesses may prioritize different outcomes. For example, stove initiatives created to reduce firewood collection and deforestation or to create cookstove micro-businesses for the poor may be satisfied with marginal emission reductions and negligible improvements in HAP, if this outcome is measured at all (Rosenthal et al 2018).

The determinants of household stove and fuel choice are dynamic and multifaceted, including socio-economic and cultural factors, availability and accessibility to clean cookstoves and fuels, and socio-political and environmental influences. A primary factor is household income and the cost of devices and fuels (both initial and recurrent). However, despite evidence that households tend to adopt cleaner and more efficient fuels as price barriers decrease (either through increased income or the presence of subsidies), studies have demonstrated that woodfuel use continues despite ability to pay for alternatives (Masera 2000; Ruiz-Mercado et al 2011; Hiemstra-van der Horst and Hovorka 2008; Brouwer and Falcao 2004; Gould et al 2018).

A number of behavioral and cultural factors, such as household preferences and beliefs, food tastes, and cooking practices can also influence cooking fuel choice. For example, in certain settings, common foods are perceived as taking longer to cook and/or having a different taste when cooked using an available cleaner fuel such as LPG (Masera et al. 2000; Ouedrago 2006). In some contexts, such as rural Guatemala, firewood stoves serve as heat and light sources as well as a social gathering point and are valued for these services (Bielecki & Wingenbach 2014). Intra-household decision-making and gender roles can also influence fuel choice. In certain settings, female-headed households have opted for cleaner fuels (Malla & Timilsina 2014), although in some circumstances women may not have the decision-making authority to choose the cleanest fuel, even if they would prefer to do so (Muneer 2003, Miller & Mobarak 2013, Choumert, Combes, & Le Roux 2019).

Evidence suggests that stove use patterns and associated HAP levels also vary seasonally. For instance, in some regions in Nepal, per capita increases in fuel consumption during the winter months were found to be related to increased stove use for tasks like water heating or cooking food for animals. Only smaller increases were attributed to space heating activities, due to household heating strategies like moving metal pans with leftover charcoal to heat the home (Lam NL 2018). Understanding the seasonal dynamics of stove-fuel stacking is thus key to selecting which portfolio of options can achieve significant impacts.

Given the multiple factors affecting use of traditional cookstoves and fuels, there is a clear need for policy and program interventions to explicitly integrate stove and fuel stacking in their diagnostic, monitoring and implementation strategies to enable household energy transitions towards cleaner options (Ruiz-Mercado et al. 2015). Without such efforts, the negative impacts of residual use of biomass for cooking will remain significant. In this paper, we review evidence of stove and fuel stacking gathered in the context of a recently published series of eleven case studies of clean fuel programs across the world (Quinn, Bruce and Rosenthal (eds), 2018). We use this evidence, along with findings from additional studies, to inform design principles that acknowledge the ubiquity of stacking behavior and attempt to shift behavior towards “cleaner stacks” to effectively reduce exposure to air pollution in the home.

2. Methods

This review is a collaborative effort under the Clean Cooking Implementation Science Network (ISN) supported by the National Institutes of Health (NIH) and partners. The eleven primary case studies that are the foundation for this review have been published elsewhere (Quinn, Bruce and Rosenthal (eds), 2018), and describe a diversity of cookstove and fuel programs in Sub-Saharan Africa, Asia and Latin America. The programs were evaluated using a common framework, the RE-AIM (Reach, Effectiveness, Adoption, Implementation and Maintenance) implementation science framework (Glasgow, 1999). The application and elaboration of the widely used RE-AIM tool for this purpose is presented elsewhere (Quinn et al 2019). The eleven case studies focused on the following clean cooking solutions:

1. Liquefied petroleum gas (LPG): four programs (in Cameroon, Ghana, Indonesia and Peru) and one program that reviewed an LPG program alongside a newer program to promote electric induction cooking (Ecuador);
2. Ethanol/methanol: two programs (in Ethiopia and Nigeria);
3. Biogas: two programs (in Cambodia and East Africa (Kenya, Tanzania and Uganda)); and
4. Compressed biomass pellets and briquettes: two programs (in Rwanda and China).

The eleven programs profiled in the case studies used a wide range of dissemination strategies. Some programs were market-based, such as a small-scale effort in Rwanda to promote biomass pellet fuels and gasifier stoves (Jagger and Das 2018), a pilot in Nigeria focused on ethanol/methanol stoves and fuels (Ozier et al 2018), and efforts by Chinese industries to scale up compressed biomass fuel production (Carter et al 2018). Others were government-led and national in scope, often with a focus on subsidies: Indonesia's "Zero Kero" program (Thoday et al 2018), Ecuador's LPG and induction subsidies (Gould et al 2018), and Cameroon's LPG scale up (Bruce et al 2018). Other government-led efforts focused specifically on lower-income or rural residents, such as Ghana's rural LPG program (Asante et al 2018; Abdulai et al 2018; Agbokey et al 2019) and Peru's *Fondo de Inclusión Social Energético* (FISE, Energy for Social Inclusion Fund) (Pollard et al 2018). Dutch development agencies formed national or regional partnerships with state and private sector actors to develop the two profiled biogas programs (Hyman and Bailis 2018; Clemens et al 2018). Finally, international agencies and NGOs worked together to improve access to cooking technologies in Ethiopia's humanitarian camps, where ethanol stoves and fuels were provided to refugees (Benka-Coker et al 2018).

All eleven case studies used a combination of primary data collection on stove and fuel use patterns, interviews with program and policy officials, and compilation and analysis of locally available documentation and published background as the basis for the evaluation. While all were guided by the adapted RE-AIM framework described above, each case study utilized, by necessity, slightly different sources, locally adapted surveys and analytical methods (See original papers in Quinn, Bruce, and Rosenthal (eds.) 2018 for details.)

Using thematic analysis of the case studies combined with additional discussion with the case study developers, a number of themes and barriers related to adoption of clean cooking technologies and displacement of traditional stoves were identified. Members of the Clean Cooking Implementation Science Network then developed a set of seven design principles for implementing a "cleaner stack" of cooking technologies and behaviors. The principles were designed using an iterative process involving expert review of the thematic analyses, construction of initial principles, and incorporation of feedback from researchers, program implementers and other stakeholders. These design principles are meant to serve as high-level guidelines that anticipate stove and fuel stacking and can be used to improve prioritization and decision-making during the program design process.

3. Results

The case studies revealed substantial stove stacking with traditional stoves and fuels in every one of the reviewed clean cooking programs (Table 1). This result holds true even in the case of older, more established programs, such as in Indonesia and Ecuador, where LPG has been subsidized heavily since the early- to mid-2000s and the majority of households now report that LPG is their primary cooking fuel. In the Carchi region of Ecuador, where 93% of households are primary LPG users, only 19% of these households use LPG exclusively. The other 81% of households continue to use traditional wood fuel, with 79% of them using it at least once a week, and 27% using it daily. In the Central Jakarta and Yogyakarta regions of Indonesia, where 61% and 73% of households report primary LPG use, only 10% and 20%, respectively, are exclusive LPG users. Eighty percent of households stack with an additional fuel, and 73% of them use traditional wood stoves. Stacking was also seen in newer LPG programs, such as Peru's FISE program, where 95% of program participants reported continued use of biomass fuel, comprising 40% of all cooking. A survey conducted 9 months after participation in Ghana's rural LPG program demonstrated limited success in transitioning households away from woodfuel use, as all participants reported that wood remained their primary cooking fuel. Moreover, only 8% continued to use LPG even as a secondary fuel, while 92% had abandoned LPG fuel completely because of high cost of refills and distance to filling stations. Lastly, although the national LPG "masterplan" in Cameroon was too new to evaluate through the case study, surveys in Cameroonian provinces where LPG had been promoted on a smaller scale revealed that 90% of peri-urban and 99% of rural residents reported stacking with biomass fuels.

The case studies focused on ethanol stoves and on biomass pellet fuels and stoves also found stacking behavior. In a low-income urban setting in Ethiopia focused on market-driven promotion of the CleanCook ethanol-fueled stove, 100% of respondents reported stacking, using up to 5 stove types. Of CleanCook adopters, 98% used charcoal stoves, while 70% used firewood, 6% kerosene, and 50% electricity in addition to the ethanol stove. A separate arm of the Ethiopia ethanol project focused on a refugee settlement, and even in this context, where settlers have very limited options, ethanol fuel supply interruptions led to stacking with wood stoves. In a small sample of urban homes in Lagos, Nigeria, the CleanCook was used regularly by 65% of households, but only one third of these reported to use it exclusively, while most stacked with kerosene. In the case of Rwanda's Inyenyeri program promoting pellet fuels and stoves, exclusive use of the pellet fuels was extremely rare. Amongst Inyenyeri adopters, 65% of cooking events took place on portable charcoal stoves, fixed charcoal stoves and traditional 3-stone fires. Lastly, in a small research project in China where compressed biomass fuel and gasifier stoves were provided to households for free, 77% of homes continued to regularly use their traditional wood chimney stoves. Daily use of the gasifier stove was modest initially (40% of the days in a month) and declined over time.

Biogas systems are somewhat different than the other clean cooking options. They have high upfront costs and require daily labor inputs. However, if well maintained, they provide a consistent home-based fuel supply with minimal recurring monetary costs. The study of Cambodia's National Biodigester Program found a high degree of exclusive use of biodigesters within the household for preparing meals. One survey found just 28% of adopters stacked biogas with wood or charcoal, but a second, smaller survey carried out in a different location found that approximately 50% stacked. Those who stacked did so predominantly for high energy tasks that are performed outdoors, resulting in a somewhat "cleaner stack" (reduced indoor exposures relative to solid fuel use inside the home). Commonly reported tasks for which a three stone fire was used included preparing livestock feed and heating water for bathing. The Cambodian case combined subsidies and loans for investing in the technology alongside a warranty and repair service, which facilitated access by the rural poor and prevented interruptions in use. A review of the African Biogas Partnership Program's impacts in East Africa found a similar degree of stacking in Kenya, where 46% of adopting families continued to use wood and/or charcoal. Stacking was much higher in Uganda and Tanzania, despite a similar implementation strategy (Clemens 2018). In the Kenyan case study, respondents noted that the biogas produced was insufficient for longer cooking tasks, particularly staples like *ugali* (thick maize porridge), beans, and *matoke* (green bananas). However, some also noted a preference for the flavor of certain foods cooked with wood or charcoal.

Among the other fuel types (LPG, ethanol, pellets, and electricity), initial and/or recurrent cost was overwhelmingly reported as a primary barrier to exclusive use of clean cookstoves and fuels. The cost of fuel was noted in Ghana, Peru, Ecuador, urban Ethiopia, Indonesia, and Cameroon. After recurrent costs, ready access, temporal interruptions in supply, and volume insufficiency of clean fuels were commonly reported reasons for the continued use of polluting fuels across settings. In Ghana, Peru and Cameroon, supply chain challenges, such as LPG shortages and the distance to filling stations (which have time and cost repercussions) were reported as barriers to exclusive LPG use. In the Ethiopian refugee camp setting, periodic ethanol shortages caused refugees to return to the use of polluting kerosene stoves. As mentioned above, in the two biogas case studies (East Africa and Cambodia), insufficiency of fuel to feed the biogas digesters was reported as a barrier to exclusive use.

Many of the studied programs directly targeted cost barriers. In Peru, LPG fuel vouchers were used. However, as a result of a time-restricted and confusing exchange process, and a relatively minor offset of total LPG use costs, the case study reported nearly universal stacking with traditional solid fuels. Even in Indonesia, where the transition to LPG from kerosene is considered a success, with nearly 70% of households reporting LPG as their primary fuel, wood fuels continued to be used alongside LPG in the majority of households. In this case study, the degree of LPG adoption and usage was strongly correlated with both household income and inversely related to the age of the main cook (with more LPG use among cooks under age 35). In the case of Ecuador, the government began heavily subsidizing LPG fuel in 2001. The program was broadly successful in spurring adoption (but not exclusive use) of LPG. Partly due to this success, however, LPG subsidization has resulted in a large fiscal burden for the government. In an attempt to reduce this burden, the government launched the electric induction cooking program in 2014 to encourage a switch away from LPG. However, to date, uptake of electric induction stoves has been extremely limited.

In several cases, users reported that the clean fuel and/or clean cooking device was poorly suited for particular cooking tasks and continued use of biomass for these tasks. For example, in Ethiopia, the two-burner CleanCook ethanol stove was poorly suited to baking the staple food, *injera*. In China, users reported that certain local foods could not be prepared with clean-fuel stoves, although this was not well documented. In Ecuador, the heating benefit of biomass fuels was one reason provided for stacking behavior. In several instances, the choice of biomass for particular tasks appears to be an outcome of economizing with purchased clean fuel -- that is, that the cost of fuel was driving the choice to use cheaper biomass fuels in the preparation of slow-cooking foods such as beans and porridge, heating large pots of water, or space heating.

Finally, other factors that were cited as influences on stacking behaviors included perceptions that food might taste different when cooked with clean versus solid fuels, concerns related to the safety of clean fuels, new skills needed to cook with a clean fuel, and the need for different cookware.

4. Discussion

Everybody stacks

The eleven clean cookstove and fuel programs reviewed spanned a range of scales of interventions, primary program mechanisms (market-driven or government-driven), locations, and time periods. In all of these cases, the clean stoves and fuels studied were used alongside traditional, polluting stoves and fuels by a substantial proportion of adopters.

This evidence aligns with many other studies that have also found persistent stove stacking across a wide variety of contexts (Piedrahita et al, 2016; Mobarak et al, 2012; Pillarisetti et al, 2019; Sambandam et al 2014; Gould et al 2020; Kat et al 2020; Troncoso, et al 2020). Several recent publications provide a snapshot of a growing evidence base on the extent and nature of stacking. For example, recent evidence from northern Ghana confirms that LPG is adopted more widely in urban areas than rural (51.5% vs 7.5%) and that urban homes frequently stacked with charcoal, whereas rural homes continued to use a three-stone fire (Dalaba et al 2018). A panel data analysis of Tanzanian household energy transitions found that the public health, environmental and social benefits of the government's policy to facilitate access to modern energy (primarily electricity) were likely diminished due to significant fuel stacking (Choumert-Nkolo et al 2019). A review of LPG adoption evidence from the Indian ACCESS survey concluded that very few of the 8500 study households had stopped using firewood when they adopted LPG (Gould and Urpelainen 2018). *In short, everybody stacks*.

So why does everybody stack? The observational nature of the case studies, the fact that several factors are operating simultaneously, and differences in measurement approaches limit the ability to examine causal relationships or the relative strength of the influences in any one setting. However, we note some common patterns across cases.

Not surprisingly, purchase costs of the technology and fuels are barriers in low income settings (see for example, Puzzolo et al 2016). Our analysis offers insights about the nature of costs within various settings and with different fuels and how these affect stacking behaviors. Programs that disseminate improved biomass cookstoves for free or at reduced costs typically do so with the aim of sustained use and replacement of less efficient cooking. Most of these programs experience adoption, stacking and/or sustainability challenges for reasons less influenced by monetary fuel cost. By comparison, almost all clean fuel programs have recurrent monetary fuel and/or maintenance costs. The relative significance of costs as a barrier is influenced by public and private financing mechanisms as well as by the cost of alternatives. Seasonal cash shortages, especially for those living rural areas can contribute to seasonal stove stacking during lean periods. In communities for which traditional fuels used in polluting devices (e.g. wood, charcoal, kerosene burned in open fires or inefficient stoves) are routinely purchased, the recurring costs of clean fuels may be less of a barrier, especially if they are price-competitive with traditional fuels. Other factors, such as access or taste preference, become relatively more important. In most programs, challenges with maintaining a reliable and easily accessible supply of the clean fuel lead to stacking. Reliability is affected by central fuel production limitations, distance to resupply points, distribution inadequacies, or maintenance of the digester plant (in the case of biodigesters). A more detailed analysis of fuel supply challenges, drawing on this same set of case studies, is detailed elsewhere (Puzzolo et al 2019).

A growing body of empirical evidence also suggests that a single new technology or fuel is often insufficient to address all of the household energy needs (e.g., preparing traditional foods, feeding animals, and space heating) for which the traditional stove is often well adapted (Ruiz-Mercado & Masera 2015; Troncoso, et al 2019; Pillarisetti et al 2019). Our case studies provide some support to this argument for preparation of particular food items or for heating, and they also acknowledge other perceived benefits of traditional cooking options, which promote continued use of biomass fuels after clean fuel adoption.

The programs in the reviewed case studies were oriented primarily to mitigation of greenhouse gas emissions and deforestation, or to business generation locally, rather than to the reduction of health impacts of cooking emissions (Quinn et al 2018). As such, the programs were not well designed to completely displace traditional fuels. Nonetheless, the results provide new evidence from large and/or national programs that stacking with additional fuels and technologies is the most likely outcome of any single-technology clean cooking intervention.

In part, the historical challenge with stacking in clean cooking interventions results from important mismatches between fuel, technologies and household end-uses; and from attempts to introduce a single clean technology (such as LPG, biogas, ethanol, pellet fuels or electric induction cooking) into a complex and culturally adapted system where food preparation is intertwined with other household needs. This analysis suggests that clean cooking programs will be more likely to successfully transition homes to modern energy when we anticipate fuel stacking and consider more integrated approaches to program design.

Strive for the cleanest stack

The pervasiveness of stacking highlights the need for guiding principles that can be followed to reduce household air pollution exposures and achieve health improvements. Based on existing data and adopting a health-focused perspective, we define “cleaner stacking” as the sustained use of a portfolio of stove/fuel technologies and practices that results in 24-hour average HAP exposures that meet or approach the WHO guidelines. Recognizing the likelihood of fuel stacking and moving households toward the cleanest stack may lead to more effective outcomes with greater reach and increased sustainability than have been achieved with single-stove interventions. We posit that a cleaner stack can be achieved by promoting multi-component interventions that combine several clean-fuel appliances alongside behavioral reinforcements focused on reducing exposure to residual air pollution, while taking into account the local socio-cultural and economic ecosystem within which domestic energy is supplied and used.

The foundation of a cleaner stacking strategy must include fuels, stoves, and appliances that either in isolation or combined can comply with the WHO targets. One option is to use combinations of modern fuels, such as gas (LPG, natural gas, and biogas), electricity, alcohol fuels (ethanol and methanol), and densified wood fuels, such as pellets – all of which are low emitters of $PM_{2.5}$. Alternatively, clean woodburning stoves, for example modern biomass cookstoves with chimneys, may be promoted together with clean fuel stoves and devices to more effectively reduce the reliance and HAP associated with traditional open fires (see for example the case of Mexico, Ruiz et al. 2018).

For households with secure monetary incomes, appliances that use different clean fuels also provide a buffer against fluctuations in fuel supply and price. For example, the use of electric rice cookers alongside LPG stoves was observed in the case study in Indonesia (Thoday et al. 2018) and is common throughout much of Asia. Many electric appliances now exist to meet specific cooking needs (e.g. rice cooking, slow cooking, water boiling, reheating) that might supplement a primary stove fueled by LPG, biogas, or alcohol at a relatively low cost. Electric pressure cookers and multi-cookers are also increasingly common, have a relatively small energy footprint at the household level, and may have potential for low resource settings.

The best available evidence in the health literature suggests that, to date, the overwhelming majority of biomass stoves do not yield sufficient emissions reductions that will achieve the WHO guidelines. The newest generation of gasifier stoves burning high quality dried pellets may provide an exception (Champion & Grieshop 2019). Optimized wood stoves with chimneys may offer another option for reduced kitchen exposure (Ruiz et al 2018) especially for low density rural environments where ambient air pollution is low. In most other places around the world, a transition to clean fuels will be necessary to achieve measurable health gains (Pope et al. 2017, WHO 2016). Nonetheless, transitions to clean fuels do not occur quickly and, as shown in the previous section, evidence from the existing literature indicates that biomass stoves are used even after clean fuel cooking devices become more commonplace. With this in mind, the other aspect of the clean stack comprises a set of strategies to reduce exposure to smoke from traditional biomass stoves even as their use diminishes and they are replaced by clean cooking appliances.

Strategies that can reduce exposure to smoke from cooking with biomass fuels include 1) changing the location of the cookstove, 2) diverting the smoke away from household members, 3) reducing cooking time, and 4) increasing combustion efficiency. For example, stoves that can be operated outdoors or in a semi-enclosed space will reduce the intensity of exposure to smoke, as will well-functioning chimneys that divert smoke outdoors, either alone or in combination with exhaust fans or smoke hoods that are vented outdoors. Note, however, that smoke generated or diverted outdoors is only a partial solution as it tends to re-enter the indoor environment, potentially affecting other community members' exposure to HAP as it does so. Reduced cooking time can lessen smoke generation and could be achieved with energy-efficient cooking appliances such as pressure cookers, retained heat cookers, and insulated storage vessels/thermoses that keep food and/or water warm without the need to reheat them. Strategies such as presoaking beans will also serve to reduce cooking time. Increased combustion efficiency has been the focus of many manufacturers of improved biomass stoves, with features such as thermoelectric fans and Top-Lit Up-Draft (TLUD) designs improve the combustion of fuels and thus reduce the generation of smoke (Posner 2018, Marchese 2018). Again, to achieve substantial exposure reductions it is likely that multiple strategies from this list will need to be employed, in conjunction with a transition of as many cooking tasks as possible to stoves and appliances that use clean fuels.

Prior conceptual studies and logic models have laid the foundation for a set of design principles to develop the cleanest stack cooking program for a given context (Puzzolo et al 2016, Rosenthal et al 2017, Quinn et al 2018). Of note, the logic model proposed by Quinn et al. outlines five interlinked areas of focus that influence stacking as demonstrated in our case study review. These focus areas include: 1) enabling institutional environment, 2) industry structure and services, 3) fuel pricing and costing, 4) consumer demand and 5) user and community needs and perceptions. The design principles identified herein build upon this model as it relates to household cooking behavior. Essentially, these principles anticipate that any new cooking technology, including combined fuel interventions, will be taken up in the context of the multiple household energy service needs (e.g., food preparation and storage, space heating, animal fodder preparation, lighting). While there is no blueprint for clean cooking systems, the 11 cases suggest the following seven design principles for clean cooking system design:

The ideal clean stack design should:

1. **Minimize exposures:** Focus on minimizing exposures to hazardous pollutants and other threats to physical safety. This may require improving overall household living conditions and introducing more than one clean fuel and cooking appliance. Acknowledge that in many settings (e.g. rural), traditional biomass fuel use is unlikely to be abandoned quickly. While clean fuel appliances are the mainstay of a clean stack strategy, implementers should develop and encourage strategies to reduce the residual exposure to biomass smoke (e.g. by changing the cooking location, diverting smoke from indoor areas, reducing cooking time, and/or improving combustion efficiency of biomass stoves).

2. **Minimize capital and recurrent costs of total cooking needs:** Understanding the range and average costs consumers will bear relative to alternatives is key to displacing polluting fuel use. Efforts to design programs and related policies to influence both the clean fuel and polluting alternatives simultaneously may be required. For example, pro-poor policies that reduce costs of clean fuels to consumers could be coupled with incentives to reduce use of solid fuels through conditional cash transfers.

3. **Mitigate potential interruptions to affordability and physical access:** Plan for liquidity constraints and the probability of economic shocks to households from major events (e.g. illnesses, job losses etc.). It is also critical to minimize vulnerability to interruptions in fuel supply from distribution chain irregularities and allow for backup technologies and fuels to still meet food preparation needs while maintaining the cleanest possible stack.

4. Understand local conditions and needs, promoting local participation: Be adaptable and attuned to the local context, i.e. home architecture styles, seasonal patterns, energy supply chains, cooking practices, and other related energy needs (space heating, warm water for bathing, etc.). Promote participatory processes where local people can clearly express their needs and contribute to design solutions.

5. Support multiple appliances that respond to specific, locally-relevant household energy needs: Consider the availability of, and access to, different appliances that facilitate clean preparation of staple or traditional foods. For example, rice cookers, pressure cookers, large-capacity water heaters, and insulated containers may meet well-defined energy needs in specific settings. This includes capacity to hold larger pots, save cooking time (like pressure cookers), or allow for slow cooking.

6. Understand the customer experience over time (i.e. customer journey): Uptake of new cooking technologies and fuels requires adaptation to new cooking practices. Technologies that fail to maximize fuel and device durability, reparability and replaceability in local markets at affordable rates over time will likely not be sustained. Facilitating long term change includes anticipating and mitigating resistance to some household or community level behavior changes needed to meet total energy needs.

7. Continually monitor progress and implement improvements: Allocate sufficient budget and resources for monitoring through the whole project lifecycle. Monitor residual use of polluting stoves use, behavior and exposures, evaluate and adapt as the program implementation continues.

Conclusions and Policy Implications

Based on the eleven case studies analyzed here and supported by the existing literature, the overwhelming evidence is that everybody stacks. While multiple reasons for stacking exist, the most widely reported reasons include initial or recurring costs, the mismatch between cooking technologies and household needs, and unreliable fuel supplies. Single-focus interventions, such as LPG distribution, have yet to be shown to successfully reduce household air pollution to levels that can achieve health gains. One of the principal challenges to reducing the global burden of disease from HAP is the need to decrease or eliminate stacking with polluting fuels and/or devices. More holistic and locally informed approaches encompassing multiple fuels and devices are necessary. We offer seven design principles to frame and inform policy and programs towards cleaner stacking in light of this ubiquitous phenomenon. We emphasize that more attention should be paid to *discontinuation* of traditional stove use, rather than focusing solely on uptake or adoption of cleaner stoves and fuels. Future energy policies and programs should acknowledge the realities of stacking and incorporate strategies at the design stage to enable households to transition away from use of polluting stoves and fuels.

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Highlights

- Pervasive use of multiple stoves and fuels, or stove stacking, has been observed in numerous settings
- Eleven implementation science case studies of clean cooking programs document extensive stacking
- A cleaner stack can be achieved by promoting multi-component clean fuel interventions
- Seven evidence-based design principles informing the ideal clean cooking stack are presented
- Policy should focus on both increased uptake of clean cooking systems and discontinuation of polluting stoves and fuels

Table 1.

Program information and clean cooking adoption rates by case study

Country	Clean fuel promoted	Program Details	Population, stacking/stove use behavior	Primary reasons reported for stacking behavior			
				Recurrent Costs	Supply Challenges	Task - based requirements	Other
Ghana	LPG	Government-led program since 2014 to provide LPG access to 50% of Ghana's population by 2020. Provides a 1-burner LPG stove, 6 kg LPG cylinder, hose, and regulator; participants must pay for the initial filling of gas and for subsequent refills (~5 USD). ~150,000 households received the package as of 2017.	In rural areas almost no sustained use of LPG. 100% of surveyed respondents still used wood as their primary fuel 9 months after LpG distribution; and only 8% still used any LPG 18 months post-distribution.	Recurrent fuel costs	Distance to refill, fuel shortages, lack of spare parts		
Peru	LPG	Government-led program since 2012 supplying a voucher subsidizing half the cost of one LPG cylinder per month for eligible households (those matching "living in poverty" criteria). 928,800 active users as of 2017.	In rural areas, among households that used LPG stoves, 95% reported stacking with traditional biomass stoves; approximately 60% of cooking done with LPG and 40% with biomass. Personal PM2.5 exposure was consistently above the WHO interim targets.	Recurrent fuel costs required for exclusive use	Supply chain and logistical barriers to exchange LPG cylinders		Seasonal and taste related preferences
Ecuador	LPG	National, universal LPG subsidy, provided by Ecuadorian government with price fixed at US$1.60/15 kg cylinder since 2001 (with limits on monthly refills in some areas).	In a region where LPG has been heavily subsidized (Carchi district, Ecuador), 93% report LPG is primary fuel, but only 19% use LPG exclusively; 79% of households use wood at least once per week	Costs are still barriers for poorest families	LPG access difficult in some remote locations, leading to time and travel costs	Heating benefit of wood. Woodfuel also useful for energy intensive cooking	
	Electric/ induction cooking	The *Programs de Eficiencia Energética para la Cocción* (PEC) since 2014 includes a consumer credit for an induction stove purchase and 80 kWh of free electricity per month (projected to cover household cooking for a family of five). 670,000 households have participated.	Despite introduction of an induction-cooking program, sustained use of electricity for cooking is almost nonexistent in region studied.	Costs of induction stoves and required cooking pots. Increased electricity costs			
Indonesia	LPG	Government-led program, since 2007, to convert 42 million kerosene-using households to LPG. Provides starter package of 3 kg filled cylinder, one-burner stove, rubber hose and regulator. LPG was subsidized. Program has surpassed targets, with 57.2 million free LPG packages distributed as of 2015.	Primary LPG users: Central Jakarta (73%), Yogyakarta (63%), exclusive LPG users: Central Java subdistricts (19.5%) Yogyakarta City (9%). Some stacking with clean fuel (electricity), but 73% of stackers continue to use wood alongside LPG. Quantity of biomass use per month is similar in households with and without LPG.	Fuel cost	Distance required to obtain cylinders	Biomass preferred for larger volume cooking tasks and cooking traditional foods	Local food/ taste preferences
Cameroon	LPG	Government LPG Masterplan announced in 2016 to expand LPG use for cooking from < 20% to 58% of all Cameroonian households by 2035. Nascent program but surveys conducted in peri-urban and rural	In rural areas, 16% report primary LPG use but only 1% use it exclusively. In peri-urban population, 58% report primary LPG use but only 10% use it exclusively. Thus, 90% of peri-urban and 99% of rural LPG-using households	Recurrent fuel cost	Travel distance to obtain cylinders and refills	Large amounts of gas needed for slow-cooked staple foods	Safety concerns of LPG

Country	Clean fuel promoted	Program Details	Population, stacking/stove use behavior	Primary reasons reported for stacking behavior			
				Recurrent Costs	Supply Challenges	Task - based requirements	Other
		communities near Limbe, Cameroon in 2016-2017	reported stacking LPG with biomass; stackers only obtain about 50% of the LPG per year that would support exclusive use.				
Nigeria	Ethanol	Commercial program to put in place distribution of 2500 CleanCook (ethanol) double burner stoves in a pilot in an urban and peri-urban population around Lagos.	In an urban population, 4-5 months after receiving Clean Cook, 65% reported using it regularly. Of those, approximately 35% reported exclusive use, with the remainder stacking with kerosene. One third also reported cooking with two stoves simultaneously primarily to save time. Fuel canisters were sold at an average rate of 2.3 canisters per household/month. This rate provides approximatively one-third of the estimated amount of fuel that a typical Lagos household requires to meet all their cooking needs.	Initial costs (Willingness To Pay experiment) as well as recurring fuel costs.	Fuel purchase was difficult due to limited retail outlets.	Kerosene used for cooking beans and other slow-cooking fuels because the flame burns hotter and lasted longer than on the CleanCook.	Ethanol fuel canisters become depleted during cooking without warning.
Ethiopia: Refugee camps	Ethanol	Government program in nine refugee camps in collaboration with Gaia Association, a 2-burner Ethanol stove and fuel provided to families for free - 10,500 households have been provided the stoves.	Stacking varied across camps depending on food stuffs. For some, CleanCook stove was well adapted to cooking, others less so.		Intermittent fuel shortages	Stove not well suited to baking traditional *injera* bread	
Ethiopia: Urban program		Low-income urban intervention is a market-driven initiative in partnership with the Former Women Fuelwood Carriers' Association (FWFCA) which offers a subsidized price for the CleanCook stove. In operation since 2005, with 500 households using the stove (fuel must be purchased at retail rates).	All surveyed respondents stacked, using between 2-5 stoves; 98% report using charcoal; 70% firewood; 6% kerosene, and 50% electricity in addition to ethanol.	Recurring cost of fuel		Stove not well suited to baking traditional *injera* bread	
Rwanda	Biomass pellets	Rwandan for-profit social benefit company, Inyenyeri. Customers sign up to buy 30, 45, or 60 kg of biomass pellets per month. Customers receive 1-3 Mimi Moto gasifier stoves depending on their quantity of pellets. Since 2011 with some changes to program since rollout - 3000 households have adopted the system.	In urban areas, 65% of cooking done with traditional biomass fuels. Exclusive use of the clean technology is extremely rare.	Recurring fuel costs, and need for higher quality cookware	Pellet production by Inyenyeri is currently limited.		Peer perceptions and influence. Additional cooking skill required
China	Biomass pellets	Since 2005, national strategic plans set renewable energy targets for rural household energy programs leading to increased production of densified biomass fuels (pellets and briquettes). While case study focuses on supply-side issues at the factory level; a Sichaun-based cookstove demonstration project evaluated uptake and adoption among 113 households who	In a rural population, 77% of homes continued to regularly use their traditional wood chimney stoves. Daily use of gasifier stove was modest initially (40% of days in month) and declined over time.			Perception that certain local dishes can't be cooked on the gasifier stove	Many homes already stacked with a different type of clean fuel stove (electric or gas).

Country	Clean fuel promoted	Program Details	Population, stacking/stove use behavior	Primary reasons reported for stacking behavior			
				Recurrent Costs	Supply Challenges	Task - based requirements	Other
		received the gasifier stoves and pellet fuel at no cost.					
East Africa (Kenya, Tanzania, Uganda)	Biogas	African Biogas Partnership Program supported by donor finance and carbon credit mechanisms in three countries, targeting all rural families that own 2 or more stabled cows to support fuel production. Since 2009, local masons installed 27,000 fixed-dome household bio-digesters.	In rural areas, where nearly 93% of households rely primarily on wood or charcoal fuels - after biogas installation 46% report stacking in Kenya, 71% in Tanzania, and 89% in Uganda.		Insufficient gas produced by digester to meet all cooking needs	Woodfuels used to cook traditional staple foods or foods that require long cooking times	Perceptions of taste may also play a role
Cambodia	Biogas	Began in 2006 as joint initiative of the Dutch Development Organization (SNV) and the Cambodian government, and operating as an independent Cambodian initiative since 2015. Program objectives are to create a "self-financing" bio-digester market, with financial sustainability partially achieved through carbon finance. The program installs the Farmer's Friend bio-digester, from 4 m3 to 12 m3, with estimated gas production 0.8-~4.0 m3/day, with 26,000 bio-digesters installed.	In rural areas, surveys found between 28% and 50% of adopters stacked with wood or charcoal. Measures of wood consumption in control versus intervention households show that biogas adoption reduces wood consumption between 54–78%, but does not eliminate the use of wood fuel.		Insufficient gas produced by biodigester to provide fuel for cooking food for livestock; insufficient size of biogas burners for preparing food for livestock	Animal feed preparation	