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Quantitative Guidance for Stove Usage and Performance to Achieve Health and Environmental Targets

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Abstract

Background: Displacing the use of polluting and inefficient cookstoves in developing countries is necessary to achieve the potential health and environmental benefits sought through clean cooking solutions. Yet little quantitative context has been provided on how much displacement of traditional technologies is needed to achieve targets for household air pollutant concentrations or fuel savings.

Objectives: This paper provides instructive guidance on the usage of cooking technologies required to achieve health and environmental improvements.

Methods: We evaluate different scenarios of displacement of traditional stoves with use of higher performing technologies. The air quality and fuel consumption impacts were estimated for these scenarios using a single zone box model of indoor air quality and ratios of thermal efficiency.

Results: Stove performance and usage must be considered together, as lower performing stoves can result in similar or greater fuel savings than a higher performing stove if the lower performing stove has considerably higher displacement of the baseline stove. Similarly, based on the indoor air quality model, there are multiple performance-usage scenarios for achieving modest indoor air quality improvements. To meet World Health Organization targets, three-stone-fire and basic charcoal stove usage must be nearly eliminated to achieve the particulate matter target (<1-3 hours per week), and substantially limited to meet the carbon monoxide (<7-9 hours per week).

Conclusions: Moderate health gains may be achieved with various performance-usage scenarios. The greatest benefits are estimated to be achieved by near complete displacement of traditional stoves with clean technologies, emphasizing the need to shift in the long term to near exclusive

use of clean fuels and stoves. The performance-usage scenarios are also provided as a tool to guide technology selection and prioritize behavior change opportunities to maximize impact.

Introduction

Cookstove programs and enterprises seek to achieve full adoption of high-performing technologies for the nearly 3 billion people who rely on solid biomass fuels to meet their primary household energy demands (Bonjour et al. 2013). Impacts from this solid fuel use include an estimated four million premature deaths per year from exposure to health damaging pollutants (Lim et al. 2012), and substantial climate forcing from the estimated 25% of global black carbon emissions (Bond et al. 2013). Use of inefficient stoves also results in substantial time and monetary burdens from purchasing and collecting fuel (Clancy et al. 2012; García-Frapolli et al. 2010).

Improving emissions and efficiency of cookstoves to address these impacts has long been a focus of stove designers and programs, with a variety of promising new technologies and fuels demonstrating relatively strong performance (Jetter et al. 2012). Efforts to improve cookstove emissions and fuel efficiency have been aided by recent developments in performance standards and guidelines, including the International Organization for Standardization (ISO) International Workshop Agreement (IWA) 11:2012 (IWA 11:2012): Guidelines for Evaluating Cookstove Performance (ISO 2012). IWA 11:2012 was agreed upon by a broad, international array of household energy experts and stakeholders, and provides quantitative guidance on 1) fuel efficiency, 2) total emissions, 3) indoor emissions, and 4) safety. For each of these indicators, IWA 11:2012 outlines "Tiers of Performance" that specify ranges for product performance based on laboratory testing. The tiers span from performance that is equivalent to traditional three-stone-fires (Tier 0), to interim progress (Tiers 1 – 3), and finally to aspirational performance goals (Tier 4) (see Table S1 in Supplemental Material for specific tier performance levels for

Efficiency and Indoor Emissions Tiers). For example, a stove could be measured to be Tier 3 for fuel efficiency, Tier 3 for total emissions, Tier 2 for indoor emissions, and Tier 4 for safety. Previous evaluations and comparisons often relied on difficult to define terms like "inefficient," "clean," "advanced," and "improved." The IWA Tiers address the limitations of such terminology and establish quantitative goals for technology developers, help organizations and consumers make informed decisions with technology selection, and drive technology innovation and development (Eichholtz et al. 2010; Lee et al. 2011; Noonan et al. 2012).

Similar guidance has not been provided for cookstove usage, which is also fundamental for attaining health and environmental benefits. Several studies have reported that stove stacking, the use of multiple stoves to meet daily energy demands, is common and the exclusive use of new stove technologies in homes has been rare (Lewis and Pattanayak 2012; Pine et al. 2011; Puzzolo et al. 2013; Ruiz-Mercado et al. 2011). While it is well understood that continued use of traditional, polluting technologies in homes alongside cleaner stoves and fuels limits any potential health and environmental benefits, the extent of traditional stove displacement required to meet air quality and fuel consumption targets is not clear.

To address this need, here we present a framework that extends the "Tiers of Performance" framework in IWA 11:2012 to provide quantitative guidance that integrates performance and use. Air quality and fuel consumption impacts are estimated for different usage scenarios across ranges of stove performance. The resulting performance-usage scenarios are provided as a tool to help stove designers, program implementers, policy-makers, and other stakeholders consider the most appropriate technology and behavior change pathways for achieving maximal impact.

Methods

Indoor concentrations of $PM_{2.5}$ and CO were estimated using the single zone model in IWA 11:2012 (ISO 2012). Single zone models have been applied many times for household air pollution studies (Johnson et al. 2011; Prasad et al. 1985; Smith et al. 1983), and are commonly used in air quality and climate research (Apple et al. 2010; Bond et al. 2011; Hellweg et al. 2009). The model predicts concentrations in the kitchen based on emission sources, air exchange rate, and room volume, with the assumption of constant emissions rates and perfect mixing. The model can be described mathematically as:

$$C_t = (G/[\alpha V])(1-e^{-\alpha t})+C_o(e^{-\alpha t}) \quad [1]$$

where:

C_t = Concentration of pollutant at time t (mg/m^3)
G = emission rate ($mg\ min^{-1}$)
α = first order loss rate (nominal air exchange rate) (air exchanges/min)
V = kitchen volume (m^3)
t = time (min)
C_o = concentration from preceding time unit (mg/m^3)

Fuel savings were calculated from the ratios of thermal efficiency as follows:

$$\text{Percent fuel savings} = (1 - [\eta_T/\eta_x])(\text{percent displacement of the traditional stove}) \quad [2]$$

where η_T is the traditional stove thermal efficiency and η_x is the new stove thermal efficiency. The air quality model and fuel savings calculations were applied with the emissions rates and fuel efficiencies shown in Table 1. The emission rates and thermal efficiencies for the three-stone-fire are assumed as IWA 11:2012 Tier 0 (for Indoor Emissions and Efficiency), which are based on the three-stone-fire's performance during standardized laboratory tests (Johnson et al. 2012).. Tier 4 thresholds for Indoor Emissions were derived by modeling the stove emission rates required to achieve World Health Organization (WHO) Annual Interim 1 Target for $PM_{2.5}$

(WHO 2006) and the WHO 24 hour guideline for CO (there is no annual guideline) (WHO 2010). To serve as a reference point for charcoal stoves, the assumed emission rates and thermal efficiencies for a traditional charcoal stove were derived by averaging the four traditional charcoal stoves presented in Jetter et al. (2012). The resulting rounded emission rates were 15 and 1300 mg/min for $PM_{2.5}$ and CO, respectively, and thermal efficiency was 25%. Traditional charcoal stoves were the Gyapa, ceramic jiko, metal jiko, and Kenya ceramic jiko (Jetter et al. 2012). Emission rates and thermal efficiencies used to represent Tiers 1-4 in the model are equidistant between tier boundaries (zero for the lower boundary for Indoor Emissions Tier 4). Thermal efficiency for Tier 4 was assumed as 50% by extrapolating from Tiers 1 - 3.

Stove usage was incorporated into the model by adjusting cooking times for the respective stoves. A full day of cooking was assumed to be three one-hour events, as was assumed in IWA 11:2012, and apportioned between the traditional and new stove, ranging from 0% to 100% displacement of the traditional stove with the new stove. Ventilation rates and kitchen volume were kept constant for all model runs and values were consistent with IWA 11:2012 at 15 air changes per hour and $30m^3$, respectively. The assumptions for cooking time, ventilation rate, and kitchen volume were based on a review of published sources (Bhangar 2006; Cowlin 2005; Johnson et al. 2011; Park and Lee 2003; Raiyani et al. 1993; Smith et al. 1983). To illustrate a typical simulation for predicting daily $PM_{2.5}$ concentrations with 100% three-stone-fire usage, the model run with the aforementioned ventilation rates and kitchen volumes (α and V, in Equation 1 respectively), and the Tier 0 $PM_{2.5}$ emission rate (G) from Table 1 was applied for three distinct 60 minute-periods to produce minute-by minute estimates $PM_{2.5}$ concentrations (C_t).

Results

Air quality and traditional stove usage

Estimates for use of a single stove, assuming linear relations between stove use and indoor $PM_{2.5}$ and CO, suggest that daily mean concentrations of $PM_{2.5}$ and CO increase rapidly with increased time using traditional stoves (Figure 1). Based on the model, if a three-stone-fire (Tier 0 for indoor emissions) is used more than ~10 minutes per day (equivalent to one hour per week), daily mean concentrations will exceed the WHO Interim 1 Target for $PM_{2.5}$ of 35µg/m^3 (WHO 2006) (Figure 1A), while traditional charcoal stoves could be used for up to ~25 minutes (Figure 1B). For the final $PM_{2.5}$ guideline (10µg/m^3) (WHO 2006), even 5 minutes of three-stone-fire use per day is estimated to result in exceeding the guideline. The modeled estimates suggest that meeting WHO targets for CO (7mg/m^3) (WHO 2010) may be achieved with higher traditional stove usage rates, with the three-stone-fire and charcoal stoves able to be used for approximately 75 and 50 minutes per day, respectively, before the 24-hour guideline is surpassed. Stoves that are Indoor Emissions Tier 1, 2, 3, and 4 are estimated to be able to be used for approximately 15, 30, 75, and 375 minutes per day before exceeding the WHO guideline for CO (WHO, 2006) assuming no other stoves are employed.

Air quality for new stove usage and displacement of three-stone-fire

The relationships in Figure 1 only account for the contributions of the traditional stove to indoor air quality. When new stoves are introduced into a household, the indoor air quality depends on the emissions contributions from all the stoves being used. When 24 hour mean $PM_{2.5}$ and CO concentrations were modeled across a range of three-stone-fire displacement scenarios, including combinations with stoves representing Indoor Emissions Tier 1, 2, 3, and 4, the only scenario in which WHO targets are reached for $PM_{2.5}$ (Figure 2A) and CO (Figure 2B), are with near complete displacement of the TSF with an Indoor Emissions Tier 4 stove. For $PM_{2.5}$, reaching the WHO Interim 1 Target of 35 $\mu g/m^3$ (WHO 2006), represents an estimated ~92% reduction in kitchen concentrations relative the assumed baselines scenario with three-stone-fires. However, more modest improvements in indoor air quality can be achieved through multiple performance-usage scenarios. For example, we estimated that a reduction of 50% in 24 hour mean $PM_{2.5}$ concentrations relative to exclusive three-stone-fire could be achieved by Indoor Emissions Tier 2, 3, and 4 stoves by displacing approximately 75%, 55%, and 50% of three-stone fire usage, respectively (Figure 2A). 50% relative reductions for CO concentrations compared to exclusive three-stone-fire use are estimated to be possible with approximately 90% and 60% displacement of the three-stone-fire with Indoor Emissions Tier 3, and 4 stoves. Graphs similar to those in Figure 2, are presented in Figure S1 of the Supplemental Material, which show the estimated impact on air quality for displacement of traditional charcoal stoves. Additionally, since tier levels are bound by upper and lower performance limits, we have also estimated the range of indoor $PM_{2.5}$ and CO concentrations within each respective tier for the different displacement scenarios, which can be found in Figure S2 of the Supplemental Material.

Under the different performance-usage scenarios, and again assuming linear relations between stove use and indoor pollutant concentrations, three-stone-fire is estimated to be the dominant source of air pollution for most scenarios. When used for half of the total cooking time, we estimate that the TSF contributes 98% of the $PM_{2.5}$ concentrations compared to 2% from the Indoor Emissions Tier 4 stove (Figure 2C). For the same level of displacement with the Indoor Emissions Tier 3 stove, the TSF contributes 89% of the mean 24 hour $PM_{2.5}$ concentrations. For CO, we estimate that the TSF contributes 82% and 68% of indoor concentrations for Indoor Emissions Tier 4 and 3 stove scenarios, respectively, when used for 50% of the cooking time

(Figure 2D). The disproportionate air pollutant contributions in relation to stove usage are due the exponential spacing of the Indoor Emissions Tiers in our model, which reflect the non-linear exposure-response relationships of $PM_{2.5}$ and CO with health outcomes such as acute lower respiratory infections (ALRI) (Burnett et al. 2014; Smith et al. 2011). The large estimated contributions from the three-stone-fire to indoor pollutant concentrations again underscore the importance of severely limiting their usage for achieving WHO targets.

In contrast with models that assume linear relationships between stove use and indoor concentrations, $PM_{2.5}$ exposure-response curves for health impacts such as cardiovascular disease and ALRI are exponential (Baumgartner et al. 2012; Burnett et al. 2014), which is why the greatest health benefits are accrued by achieving low exposures levels under WHO targets. Reaching these exposure levels is critical, but it is also important to recognize that more modest health gains can be achieved with various technologies and usage scenarios, such as those observed for the RESPIRE study (Ruiz-Mercado et al. 2011; Smith et al. 2011). When we apply the integrated exposure risk relationship for household air pollution from the Global Burden of Disease Study 2010 (IHME 2013) and the kitchen-child exposure ratio (0.628) from Smith et al. (2014) to the kitchen concentrations derived from our model (Figure 2A), we estimate that ALRI relative risk for children under five could be reduced from ~3 to 2 (corresponding to 75% exposure reduction relative to exclusive TSF usage) with Indoor Emissions Tier 3 and 4 stoves displacing 86% and 77% TSF usage, respectively (Figure 3). 12% lower relative risk (corresponding to 50% exposure reduction) could be achieved by displacing a three-stone-fire by 73%, 57%, and 51% with Indoor Emissions Tier 2, 3, and 4 stoves, respectively. Reaching the WHO Interim-1 $PM_{2.5}$ target of $35 \mu g/m^3$ (92% exposure reduction), could be achieved with an Indoor Emissions Tier 4 stove displacing 94% of the three-stone-fire use, but would still imply a degree of relative risk as the reference level used as a counterfactual to derive the exposure-response curve was 7μg/m^3 (IHME 2013). Even with a Tier 4 stove achieving 100% displacement, the modeled daily exposure would be ~11ug/m^3, implying a marginal relative risk (1.03) compared to the counterfactual. Aside from Indoor Emissions Tier 1 stoves, which show no substantive impacts on ALRI relative risk regardless of usage scenario, the modeled estimates indicate meaningful impacts on ALRI can be achieved for various emissions and performance and usage scenarios. ALRI was used here as the relevant health endpoint as it is the greatest contributor the health burden (measured as disability-adjusted life years) associated with household air pollution (Smith et al. 2014), and the exposure-response curve was supported with household air pollution specific data (Burnett et al. 2014; Smith et al. 2014), although similar relationships with three-stone-fire displacement could also be estimated for cardiovascular disease, lung cancer, and other health impacts.

Fuel savings and stove usage

Fuel savings were estimated using Equation 2 and the thermal efficiencies in Table 1, with the resulting linear relationships between usage and fuel savings shown in Figure 4. The highest potential savings of 70% are estimated with Thermal Efficiency Tier 4 stoves completely displacing the three-stone-fire. The greatest fuel saving scenarios, while clearly desirable, may not be realistic in many situations where exclusively transitioning to a high performing stove is difficult. A target of 50% fuel savings, however, is estimated to be achievable by displacing the three-stone-fire entirely with a Thermal Efficiency Tier 2 stove, by ~80% with a Tier 3 stove, or by ~70% with a Tier 4 stove. Figure S3 of the Supplemental Material provides ranges of fuel savings relative to three stone fires and traditional charcoal stoves for each thermal efficiency tier level, bounded by upper and lower performance limits.

Discussion

Implications for strengthening the clean cooking sector

The health and environment benefits associated with the adoption of a new stove are a function of a cooking system. In addition to stoves and fuels, the cooking system includes user behavior, physical characteristics of the home, cooking practices, and other factors. Each component of the cooking system can be influenced or altered to increase health and environmental benefits. While the performance-usage model does not account for all of these system components, it integrates many of the quantifiable factors – emissions rates, fuel efficiency, usage and displacement, room size, and ventilation – to illustrate how key parameters influence indoor pollutant concentrations and to explore multiple pathways to reduce household air pollution and fuel use.

A set of these pathways, based on various performance-usage scenarios, is provided to help organizations make informed decisions on the interventions most likely to achieve their respective goals (Figure 5). The same indoor air pollution target and reduction in ALRI relative risk can be achieved with different combinations of displacement and stove emissions performance.

In cases where full adoption of a high performing stove is difficult to achieve, the framework presented here can help programs and enterprises evaluate appropriate combinations of performance and usage. The longer term goals are to concurrently maximize new stove performance, adoption of new stoves, and displacement of old stoves. Opportunities to achieve these goals, including for program implementers, stove designers and distributors, are discussed in the following sections.

Translating health and fuel use goals into implementation

While meeting the WHO target ($PM_{2.5} < 35\ \mu g/m^3$) is the surest way to protect health, we estimate that more modest targets, such as reducing kitchen concentrations of $PM_{2.5}$ to $<166\ \mu g/m^3$ or $< 333\ \mu g/m^3$, which may be achieved through multiple performance-usage pathways, would reduce the relative risk of ARLI mortality by 33 and 12% respectively, compared with the exclusive three stone use scenario (Figure 5). Although a high performing stove with less displacement could be equivalent to a low performing stove with more displacement (Figures 2A and 2B), the largest impacts are only realized with near complete displacement of the three-stone-fire and near exclusive use of low emissions technologies (Figures 2C and 2D). These results highlight the enormous emissions contributions of a three-stone-fire relative to new stoves. Even minimal use of the three-stone-fire quickly raises concentrations to levels above WHO thresholds, where the exposure-response curves begin to level out, making health gains more difficult to achieve. The importance of exclusive or near exclusive use of a new stove is also supported by the RESPIRE study, which showed the impact of a chimney stove on reducing incidence of ALRI (Smith et al. 2011). Indoor air pollution and personal exposures were reduced by 90% and 50% respectively, but these reductions were aided by weekly field team visits to ensure that the chimney stoves were well maintained and working properly. Thus, efforts to expedite the transition to clean fuels (e.g. liquefied petroleum gas, ethanol) and technologies with the ability to fully displace traditional cookstoves should be the ultimate priority.

As is the case with meeting health goals, the best option for fuel savings is exclusive use of a high performing stove. Our model-based estimates of fuel saving (Figure 4) may be used to identify the optimal balance of fuel performance and usage for a specific context. Cookstove programs should strongly consider balancing the usability and technical performance of a stove when aiming for specific savings targets. For example, high performing stoves, in comparison to less fuel efficient stoves, can require more fuel preparation, such as drying wood and cutting into small pieces, which may limit the usage of these types of stoves. Improved designs that do not require as much fuel processing while maintaining performance are discussed in the next section. In addition, there are opportunities for fuel processing enterprises to provide an affordable fuel alternative that would eliminate the need for users to process fuel at the household level.

Behavior change strategies can also be used to increase the usage of high performance stoves and displacement of the three-stone-fire, or to mitigate the impact of emissions. The application of this quantitative guidance on household energy activities with behavior change components is explored in Johnson and Chiang (in press).

Stove designers – improving performance and usability

Usage is ultimately determined by consumers and is not typically integrated into standards frameworks. This performance-usage model, however, complements the existing performance targets in IWA 11:2012 with quantitative guidance that designers can use in their development process. Three-stone-fire displacement targets, for example, can help designers ensure their high performing technologies are well suited for the fraction of cooking tasks which corresponded to the desired indoor air pollution reduction (Figure 5) and fuel savings targets (Figure 4).

Distributors and retailers – selecting and marketing products

Distributors and retailers use information on performance and suitability of stoves to provide products which meet user needs. Ideally, independent evaluations of performance, usage, and consumer preferences are used to help identify products best suited for a given context. These evaluations can be shared through resources like the Clean Cooking Catalog (http://catalog.cleancookstoves.org), a global database of stoves and test results designed to provide clarity for evaluating stove options. Information from the catalog on stove characteristics (e.g. compatibility with different pot types) can be evaluated along with performance and user preferences to determine which technologies are likely to result in the best performance-usage scenarios.

Marketing messages about new technologies often attribute the benefits to the technology alone, rather than the use of the technology. Because any fuel savings or health benefits are only achieved if stoves are used and replace traditional technology, this message should be communicated by distributers and retailers who are interfacing with consumers. For product marketing and for broader consumer awareness campaigns, communicating this message can be challenging, especially in cases when consumers did not respond well to negative messages about current products (Pascaud and Thivillon 2014). However marketing and consumer awareness campaigns should consider ways to encourage higher levels of use of the new technology and replacing traditional technologies.

Measuring stove usage

Research and monitoring efforts often focus on the new technology or intervention, as well as factors that influence adoption of new technologies. Understanding how new technologies and interventions perform is a fundamental component to assessing air quality, health, fuel consumption and other outcomes. The analysis presented here, however, indicates that traditional stove use, even at relatively low usage rates, drive air pollutant concentrations. Thus, research and monitoring efforts should also account for use of traditional technologies and factors that influence their use and displacement.

Explicitly connecting traditional stove use with impacts and program effectiveness requires a means to measure or estimate stove usage. Measuring progress against the usage targets in Figures 4 and 5, for example, require that a quantitative stove use estimate be made. Quantitative stove use data, such as stove temperature measured over time (Ruiz-Mercado et al. 2013), support investigations into how user behavior, usage patterns, and stove performance are directly related to household air pollution, personal exposure, and fuel consumption impacts.

Recommendations for future modeling of usage and performance

Modeling the cooking system

As highlighted earlier, the system which impacts kitchen concentrations and exposures includes a variety of factors and sources that are not fully addressed in the model, such as household lighting, trash burning, and neighborhood pollution, as well as behavioral considerations such as fuel processing practices and adjusting ventilation conditions. If these other emissions sources or solid fuel use within the community are large enough, the impact of household level interventions may be limited by high ambient contributions to household air quality. Future modeling that considers multiple households in a community would provide guidance on what level of adoption is needed within a community to reach specific targets for air quality.

Ventilation is particularly important as it substantially impacts indoor air quality (Baumgartner et al. 2011; Johnson et al. 2011; Nazaroff 2008). A systematic laboratory study showed that ventilation can reduce indoor concentrations of $PM_{2.5}$ by as much as 60% (Ruth et al. 2014). In rural Rwanda, Rosa et al. (2014) reported median indoor $PM_{2.5}$ concentrations were half as much for those cooking outdoors compared to indoors (Rosa et al. 2014). Additionally, ventilation can be part of, or a primary intervention strategy based on behavioral or physical changes in the household. The implications of ventilation's impact on stove usage are more fully explored in

Johnson and Chiang (in press), which reports that in comparison to the IWA:2012 ventilation rate of 15 ACH, higher ventilation rates of 25-45 ACH would allow three-stone-fire usage for 2 – 3 times longer before WHO $PM_{2.5}$ targets are exceeded. These variations in the cooking system can be addressed through probabilistic modelling such as in Johnson et al. (2011), in which a fuller analysis of this cooking system variability is presented by applying a Monte Carlo approach to a similar single zone model.

There are other important considerations which the framework does not account for, including the availability and renewability of fuel resources. Displacing unsustainable charcoal with renewably sourced pellets, for example, has tremendous ecological and environmental benefits regardless of the efficiency of stoves that use processed fuels (Chidumayo and Gumbo 2013; Ghilardi et al. 2013).

Baseline and stacking scenarios

There are a variety of different baseline stoves and stacking scenarios that vary across regions and demographics. The use of a three-stone-fire or traditional charcoal stove as a reference point is not strictly applicable for many contexts. In terms of absolute usage of the traditional stove and its impact on air quality, however, the assumption of a three-stone-fire or traditional charcoal stove will provide a relatively conservative estimate of emissions contributions from traditional stoves.

When a new stove is introduced into a household, the total time that cooking devices are used can change or even increase. The model used here to compare scenarios held total cooking time constant at three hours, which is simplification, and total cooking time in homes can be higher and lower. Modeling other stacking scenarios in which the introduction of new cooking devices changes total cooking time could provide a more specific guidance for such cases.

Model limitations

The indoor emission rates used in the model are based on controlled laboratory tests, which are known to underestimate emissions relative to normal daily stove use in homes (Chen et al. 2012; Johnson et al. 2010). Higher emission rates would require even lower levels of three-stone-fire use to stay within WHO targets and daily cooking times longer than three hours would imply that new stoves be need to be cleaner to result in the same indoor pollutant concentrations modeled here. For example, mean cooking times in India have been estimated to range from 3.1-4.6 hours per day (Bhangar 2006; Raiyani et al. 1993; Smith et al. 1983). There are other assumptions, however, in the model which are more conservative. For example, the model assumes that all emissions enter the room and fully mix, whereas in most homes a large fraction of the emissions plume exits through windows, eaves, or other openings and never mix throughout the kitchen. As a first step towards providing straightforward and practical guidance on stove usage, however, here we have focused on only the IWA 11:2012 scenario.

Future laboratory and field studies of performance and usage could also use this framework to develop metrics and collect data that integrates emissions, fuel use, and usage. Results from these studies would provide empirical data to strengthen the model, especially when usage measurements are combined with measurements of fuel use, emissions, indoor air pollution, and kitchen parameters as was done for a case study in India (Johnson et al. 2011). Assessing model performance across a range of usage-performance scenarios in homes would be especially helpful. Perhaps most critical would be understanding how the model performs as lower emission technologies approach near exclusive use, where the predicted indoor air concentrations begin to approach WHO guidance levels as this is where the usage guidance is most relevant. Ideally, refinements of the model to account for location or specific factors such as ventilation rates, cooking times, and others would provide help provide more applicable guidance for specific contexts.

Conclusions

The importance of both performance and usage on achieving impacts has long been recognized within the household energy sector. This conclusion is reinforced by performance-usage modeling results. The quantitative framework also provides specific guidance for how performance and usage combine to influence household air pollution, which leads to practical implications for different stakeholders within the sector. While achieving high levels of both performance and adoption is a tremendous challenge, especially at a global scale, this framework can help the household energy sector prioritize efforts in the short term, and achieve continuous improvement in the long term.

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Table 1. Emission rates and thermal efficiencies used for modeling air quality and calculating fuel savings. IWA 11:2012 Tier boundaries are indicated in the smaller font.

Stove Tier	$PM_{2.5}$ Indoor emissions rate (mg/min)	$PM_{2.5}$ Indoor emissions rate (mg/min)	CO Indoor emissions rate (mg/min)	CO Indoor emissions rate (mg/min)	Thermal Efficiency (%)*	Thermal Efficiency (%)*
	Value used for model	**Range of values for tier**	**Value used for model**	**Range of values for tier**	**Value used for calculation**	**Range of values for tier**
0	40.0	>40	970	>970	15	<15
1	28.5	17 – 40	795	620 – 970	20	15 – 25
2	12.5	8 – 17	555	490 – 690	30	25 – 35
3	5.0	2 – 8	455	420 – 490	40	35 – 45
4	1.0	≤2	210	≤420	50	≥45

*Thermal efficiency is based on the high-power phase of the WBT version 4 (WBT Technical Committee 2014).

Figure legends

Figure 1. The impact of increasing traditional stove use on air pollutant concentrations in the kitchen as estimated with a single zone air quality model. Graphs A and B show the rising daily mean concentrations of $PM_{2.5}$ and CO in the kitchen as function of three-stone-fire, and traditional charcoal stove use, respectively. Notes: WHO $PM_{2.5}$ Interim Target 1 source: (WHO 2006).

Figure 2. The impact of multiple stove use on air pollutant concentrations in the kitchen as estimated with a single zone air quality model. Modeled 24 hour mean $PM_{2.5}$ and CO concentrations across a range of three-stone-fire displacement scenarios, which include three-stone-fire usage combined with stoves representing Indoor Emissions Tier 1, 2, 3, and-4. Graphs 2A and 2B show the linear relationships between three-stone-fire displacement with a new stove and indoor concentrations for $PM_{2.5}$ (A) and CO (B). Graphs 2C and 2D show the specific contributions from the three-stone-fire and Indoor Emissions Tier 1-4 stoves to 24 hour $PM_{2.5}$ and CO concentrations under the different performance-usage scenarios. Notes: TSF = three-stone-fire; WHO $PM_{2.5}$ Interim Target 1 source: (WHO 2006). WHO CO 24 hour guideline source (WHO 2010).

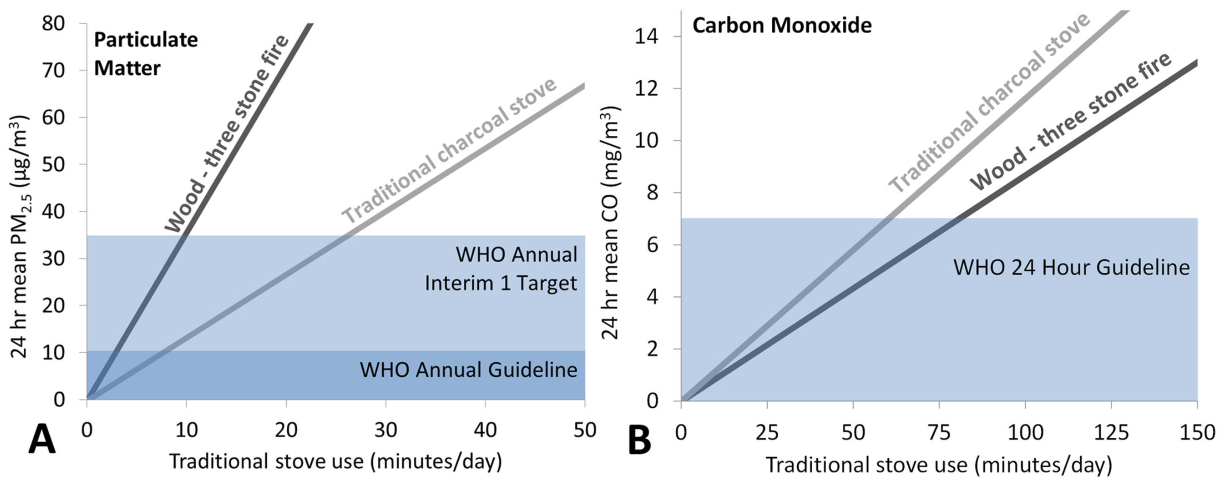
Figure 3. The modeled relative risk of children's ALRI mortality across various stove performance-usage scenarios, estimated by combining predicted exposures with an exposure-response curve. The gray dashed lines represent exposure reductions of 50 and 75%, respectively. Notes: TSF = three-stone-fire; ALRI = acute lower respiratory infection; WHO-IT1 = WHO $PM_{2.5}$ Interim Target 1, source: (WHO 2006).

Figure 4. Modeled relationships between three-stone-fire displacement and fuel savings for different performance-usage scenarios, estimated by the ratio of thermal efficiencies of the new to traditional stoves and the percent displacement of the traditional stove. Gray arrows indicate different performance-usage scenarios for which 50% fuel savings could be achieved. Notes: TSF = three-stone-fire

Figure 5. Performance-usage scenarios and associated indoor air pollution target and reduction in ALRI mortality. Given the "Percent TSF Displacement Targets" are achieved, the model

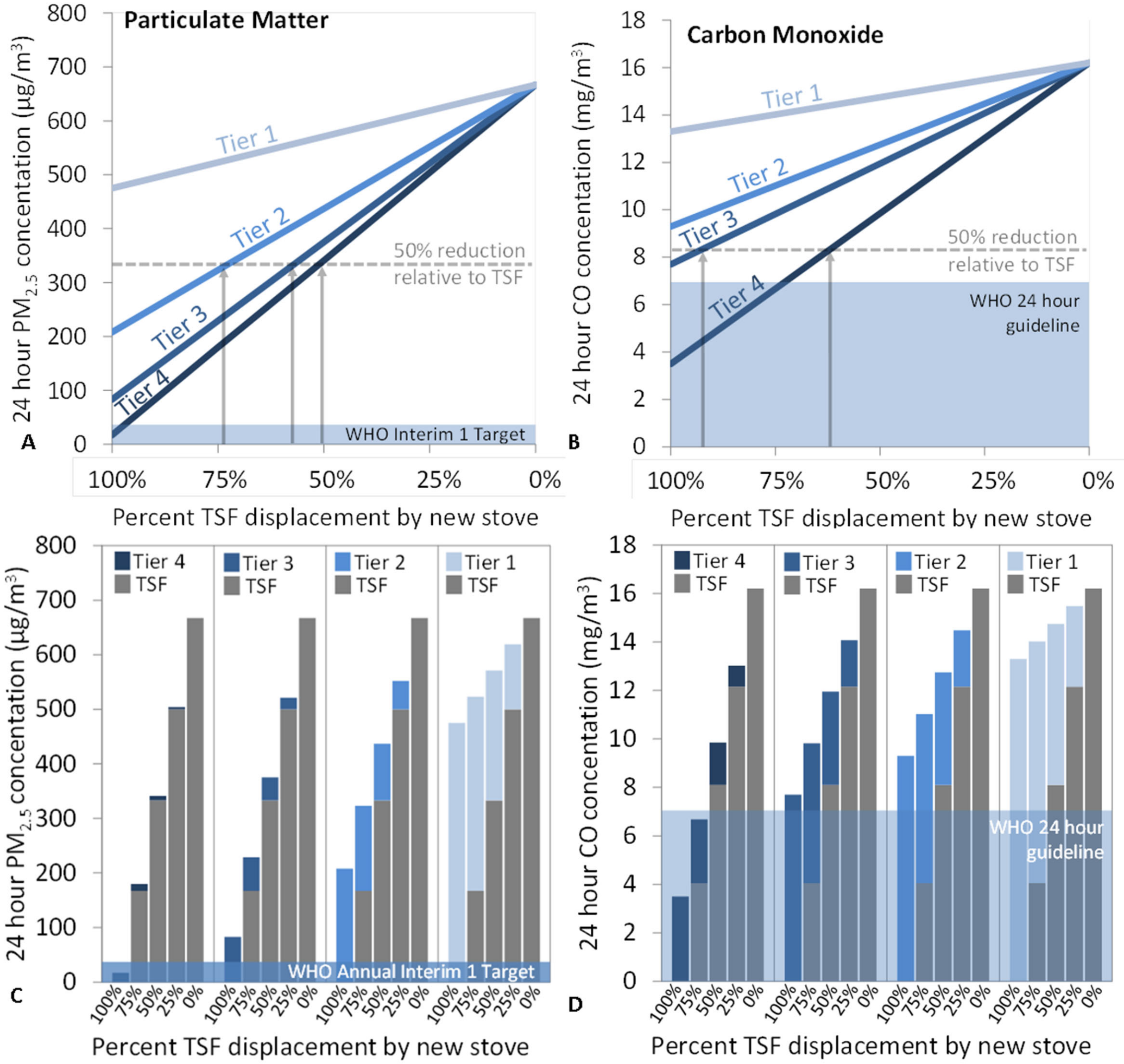
predicts that it is possible reach the associated indoor air pollution target and reduction in ALRI mortality. For example, to reach indoor air pollution levels that are less than 166 μ/m^3, a Tier 4 Indoor Emissions stove would need to be used at least 77% of the time (corresponding to 5 hours of TSF use and 16 hours of Tier 4 Indoor Emissions stove use). The same level of indoor air pollution can be also be reached with Tier 3 Indoor Emissions stove used at least 86% of the time. Notes: TSF = three-stone-fire

Figure 1.



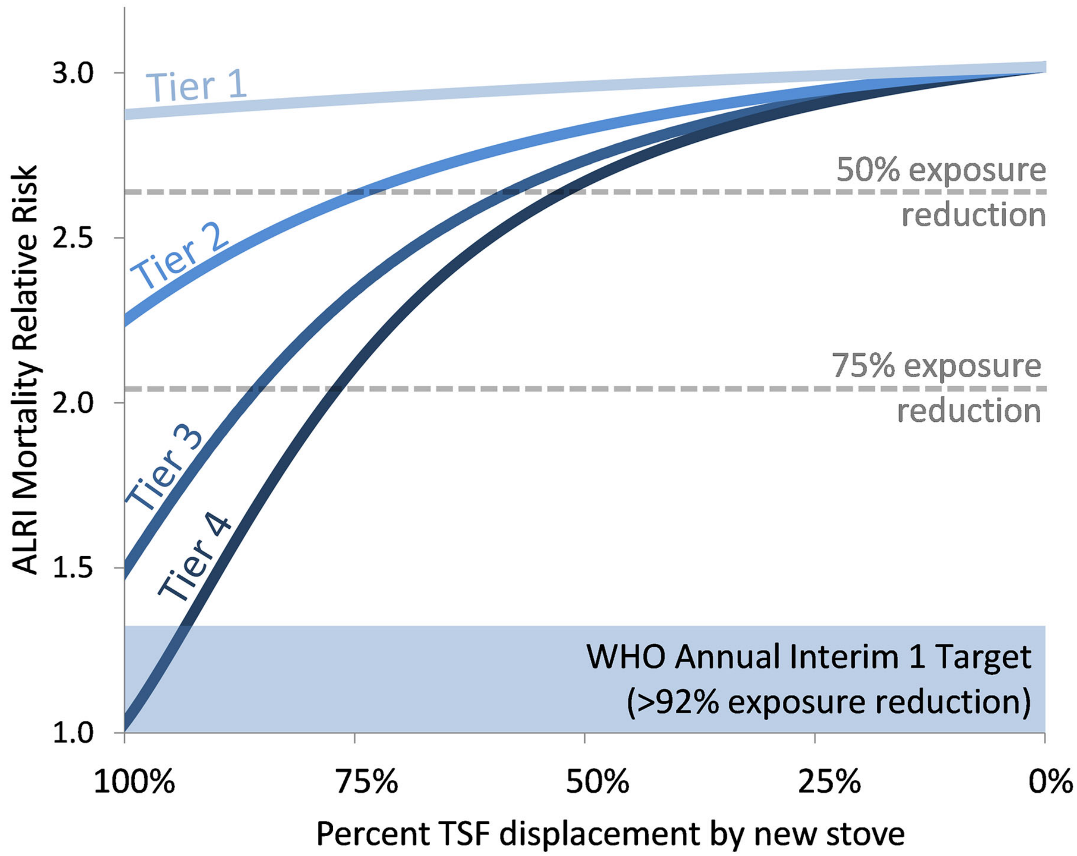
Particulate Matter
Wood - three stone fire
Traditional charcoal stove
WHO Annual Interim 1 Target
WHO Annual Guideline
24 hr mean PM2.5 (µg/m3)
Traditional stove use (minutes/day)
A
Carbon Monoxide
Traditional charcoal stove
Wood - three stone fire
WHO 24 Hour Guideline
24 hr mean CO (mg/m3)
Traditional stove use (minutes/day)
B

Figure 2.



Particulate Matter
24 hour PM2.5 concentation (µg/m3)
800
700
600
500
400
300
200
100
0
Tier 1
Tier 2
Tier 3
Tier 4
50% reduction relative to TSF
WHO Interim 1 Target
A
100%
75%
50%
25%
0%
Percent TSF displacement by new stove
Carbon Monoxide
24 hour CO concentation (mg/m3)
18
16
14
12
10
8
6
4
2
0
WHO 24 hour guideline
B
C
Tier 4
Tier 3
Tier 2
Tier 1
TSF
WHO Annual Interim 1 Target
D

Figure 3.



Tier 1
Tier 2
Tier 3
Tier 4
50% exposure reduction
75% exposure reduction
WHO Annual Interim 1 Target (>92% exposure reduction)
ALRI Mortality Relative Risk
3.0
2.5
2.0
1.5
1.0
100%
75%
50%
25%
0%
Percent TSF displacement by new stove

Figure 4.

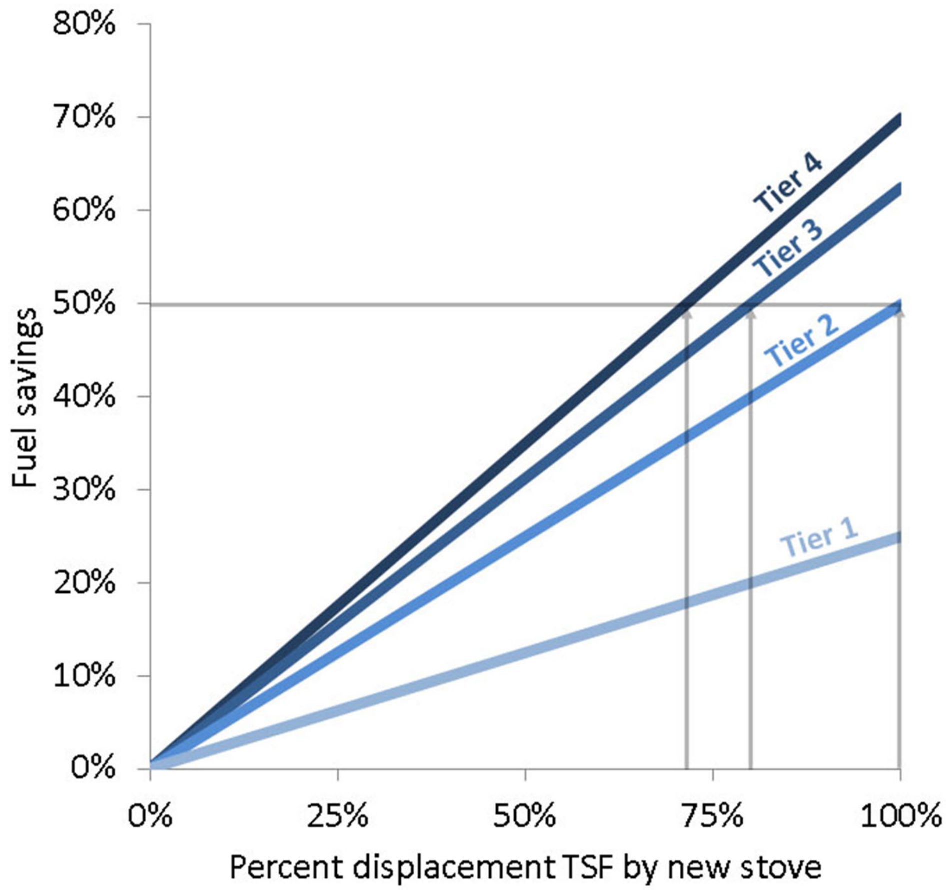

80%
70%
60%
50%
40%
30%
20%
10%
0%
Fuel savings
Tier 4
Tier 3
Tier 2
Tier 1
0%
25%
50%
75%
100%
Percent displacement TSF by new stove

Figure 5.

TSF Displacement Targets (%) Hours of TSF use/week · Hours of new stove use/week				
Tier 4 Stove	**Tier 3 Stove**	**Tier 2 stove**	**IAP $PM_{2.5}$ Target (µg/m3)**	**ALRI Mortality Relative Risk**
>97% 1 20	**NA**	**NA**	**<35 (WHO-IT1)**	**<1.14 (↓62%)**
>77% 5 16	**>86%** 3 18	**NA**	**<166 (↓75%)**	**<2.04 (↓33%)**
>49% 10 11	**>57%** 9 12	**72%** 6 15	**<333 (↓50%)**	**<2.65 (↓12%)**