WHO Indoor Air Quality Guidelines: household Fuel Combustion

Review 3: Model for linking household energy use with indoor air quality

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Summary

Background

This review describes how emissions from household energy devices are linked to indoor air quality – a relationship that is fundamental to providing instructive health-based guidance on how much pollution technologies can be emitted indoors. Important considerations that affect this relationship are discussed, as well as modelling approaches which can be used to predict concentrations of indoor air pollutants caused by the emissions of these devices. A model well suited for accounting for the variety of household environments and cooking demands in the developing world is used to provide quantitative guidance on what emissions performance levels are required for meeting WHO Air Quality Guidelines (AQGs).

Aim and key questions

The aim of this review was to provide guidance on the emissions performance of household combustion technologies that would be required for households to meet WHO AQGs. Key factors that have an impact on the relationship between emissions and indoor air quality and the approaches that can be used to quantify this relationship are also discussed. The following questions are addressed by this review:

1. What considerations are important for linking indoor emissions to indoor pollutant levels?
2. What are the modelling options for linking emission rates with indoor air pollutant levels?
3. Based on the model, what PM2.5 and CO emission rates will correspond to achievement of goals involving various percentages of homes meeting WHO AQGs for both unvented and vented combustion technologies?

Methods

A model is used to derive emission rate guidance for household combustion technologies. The model uses input distributions of air exchange rates, kitchen volumes, device usage times, and for ventilated technologies, and the fraction of emissions that enter the kitchen to estimate indoor pollutant concentrations. Compared with reported concentrations of $PM_{2.5}$ and CO, the modelled distributions are in general agreement. For example, 60% of the model's predicted 24 hr mean indoor $PM_{2.5}$ concentrations from emissions of traditional chulhas fall between 500-1,800 µg/m^3 (mode of 800), which compares well to the mean of 826 µg/m^3 from studies reporting kitchen concentrations in homes using traditional biomass stoves in the South East Asia Region. Similar agreement was found with indoor CO concentrations, as well as when emissions from an unvented rocket stove were considered. To determine what emission rates that would result in various percentages of homes meeting the WHO AQGs for $PM_{2.5}$ and CO, the model was run iteratively and a relationships between emission rates and the AQGs were derived.

Findings

Based on this approach, emission rate guidelines are provided which would result in an initial target of 60% of homes meeting the annual $PM_{2.5}$ Interim-1 (unvented: 1.75 mg min^{-1}; vented: 7.15 mg min^{-1}) and 24 hr CO AQGs (unvented: 0.35 g min^{-1}; vented: 1.45 g min^{-1}); and a final target of 90% of homes meeting the final annual $PM_{2.5}$ (unvented: 0.23 mg min^{-1}; vented: 0.80 mg min^{-1}) and 24 hr CO (unvented: 0.16 g min^{-1}; vented: 0.59 g min^{-1}) AQGs.

Conclusions

Emissions performance from the best currently tested solid biomass technologies indicate that while these stoves meet the initial CO targets, improvement in $PM_{2.5}$ emission rates are needed for both unvented and vented stoves to meet the first target. Meeting the final emission rate targets would require substantially greater emissions performance for solid biomass stoves, although the use of clean burning gas and liquid fuels such as LPG, natural gas, biogas, and ethanol, as well as electricity represent technologies which can provide high levels of protection immediately. Research recommendations are made for development of standardized testing or analytical approaches which better predict emissions performance of cookstoves in homes during normal use, in order that benchmarking of technologies against emissions guidelines can indicate a more realistic estimate of performance for the end user. Finally, further development of models which can be used to link indoor air quality with emissions performance are recommended, as well as tools for producing location-specific emissions rate guidance.

1. Introduction

This review addresses approaches to link indoor pollutant emissions from stoves and other sources with indoor air quality. It also suggests an approach to setting limits on indoor emissions from household combustion technologies to meet WHO AQGs.

As summarized in Review 2 (Emissions of health-damaging pollutants from household stoves), unvented stoves, particularly those using solid fuels, produce substantial emissions of health-damaging pollutants. Total exposure to these pollutants depends on a number of factors, and is a function of the pollutant levels in all the places where people spend time during normal daily activities. While the factors driving personal exposures are often complex, the guidance presented in this review supposes that people should be able to spend as much time as desired in the kitchen (or room with emissions source) without being subjected to health risks from emissions caused by cooking, heating, lighting, or other household energy devices. Therefore, the guidance presented in this review focuses explicitly on the link between emissions from household energy devices and the resulting indoor air pollutant concentrations where the source is located.

Another key consideration for linking emissions sources with indoor air quality is that even within single homes, emissions arise from a variety of sources needed to meet daily energy needs, such as multiple cookstoves, devices for heating water or air, and lamps for lighting. Similarly, they do not relate directly to emissions from non-energy sources such as mosquito coils and incense. Providing a functional set of emissions guidelines to address this level of complexity of sources would be impractical to implement as the indoor air quality and associated emissions limits for one device would then be affected by the emissions performance of any other devices, the existence of which cannot be predicted and would change over time. For the sake of clarity and provision of instructive guidance on emissions, the recommendations presented here assume a single source.

The specific guidance here is aligned with the WHO AQGs for $PM_{2.5}$ and CO. As Review 4 (Health impacts of HAP) details, the WHO AQGS include $PM_{2.5}$ and CO as well as other pollutants. Exposure to $PM_{2.5}$ has been shown to have the strongest link to most health impacts (see Review 4) and is used as a risk indicator in burden of disease studies, and as the best indicator of health risk across combustion source categories. WHO also provides CO AQGs including for chronic exposures *(1)*, and similarly is a commonly measured pollutant in household energy sector studies and may be better linked than $PM_{2.5}$ to some health outcomes, such as low birth weight (see Review 4, Health impacts of household air pollution). Given the high indoor air and exposure concentrations of $PM_{2.5}$ and CO associated with household energy use (see Review 4), these are the critical pollutants for the provision of guidance. For these reasons, particulate matter and CO have become the most commonly measured emissions species for standardized stove performance test protocols[1], which means that measurement against guidelines could be readily achieved. NO_2 is not included here as the evidence for health impacts in the household energy sector is not as strong, although it is often measured in developed-country indoor settings as an indicator of emissions from gas combustion, which produces relatively little PM and CO *(2)*.

2. Questions addressed

The key questions addressed by this review are:

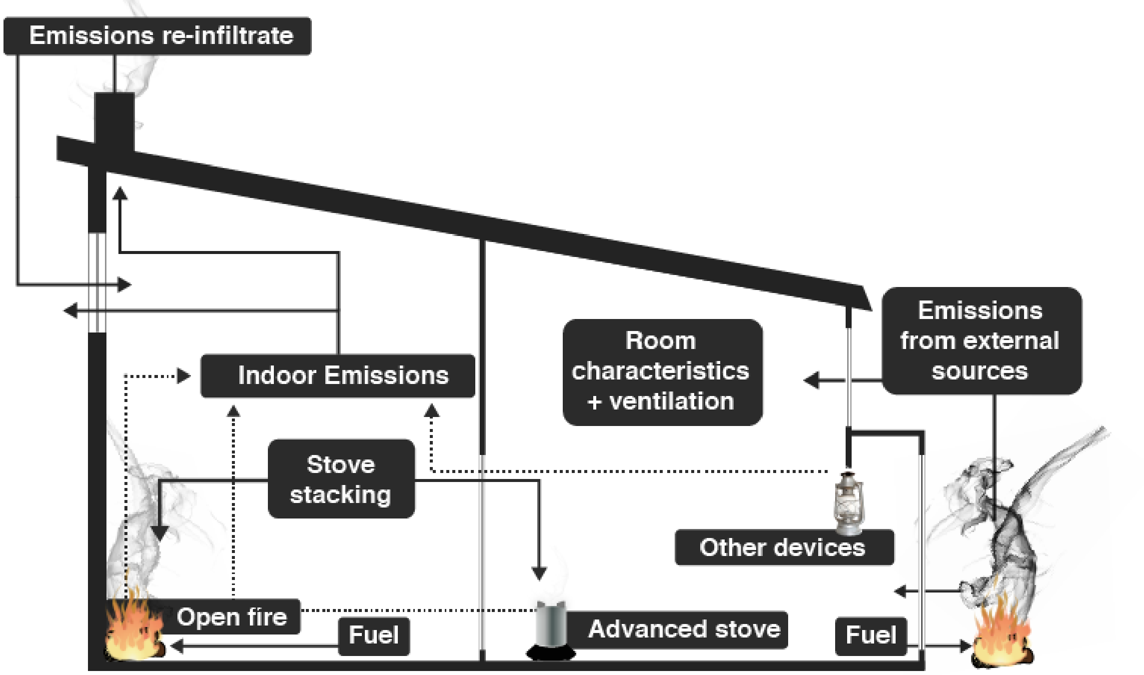
1. What considerations are important for linking indoor emissions to indoor pollutant levels?
2. What are the modelling options for linking emission rates with indoor air pollutant levels?
3. Based on the model, what PM2.5 and CO emission rates will correspond to achievement of goals involving various percentages of homes meeting WHO AQGs for both unvented and vented combustion technologies?

3. Key considerations for linking indoor emissions to indoor air concentrations

The relationship between emissions from stoves and indoor air quality involves several factors, as shown in Figure 1. Nevertheless, stove emissions are the key driver of indoor air quality. At any given ventilation rate (degree to which pollution escapes from the indoors) and room size, stoves that emit low quantities of pollutants into the indoor environment per day are likely to result in lower average indoor air pollution (IAP) levels than those that emit high amounts.

[1] Examples of standardized stove testing protocols which have measurements for PM and CO include the Water Boiling Test 4.2.2, Bureau of Indian Standards (Standard 13152), and the Beijing City Local Standard DB11/T 540-2008.

Figure 1. Schematic of factors impacting indoor air quality



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Actual emissions and IAP, however, may be influenced by use of several stoves over the day, as stacking of stove use is commonly employed to meet the variety of cooking and heating needs in a home *(3-5)*. Furthermore, the frequency and duration of stove use changes over time due to factors such as seasonal demands for heating or cooking, fuel availability and cost, as well as the condition of the stove or other device. Indoor air quality (IAQ) is also impacted by general outdoor air pollution as well as local outdoor factors, such as re-infiltration of stove emissions (especially important for chimney stoves), nearby burning of trash or crop residues, cooking outdoors, and pollution arising from nearby traffic, industry, and households. As stacking and outdoor pollution vary in different places and times and this report focuses on stove-specific guidelines; we do not address these issues further. They are, however, some of the main reasons that actual IAP levels in real households may exceed those due to emissions from a particular stove.

A stove like any other device may not perform well over time due to lack of maintenance and repair and general “wearing out.” In addition, stoves, like other devices, may not be operated as designed by the manufacturer, for example though improper loading of the fuel or even being loaded with fuel for which it was not designed (wet instead of dry, for example). The guidelines developed in this report do not attempt to deal with these issues and essentially refer to new stoves used as intended.

At the physical level, the characteristics of the room and ventilation patterns impact IAQ. Large, highly ventilated rooms will have better indoor quality than small poorly vented rooms assuming the all other factors are the same. Removal processes also affect indoor air quality, which include venting through eaves, chimneys, and windows, as well as deposition on surfaces and particle settling. Finally, the IAQ within any given room is often heterogeneous, as air pollutant concentrations within rooms are stratified especially when the main contributors are high temperature point sources such as cookstoves *(6-8)*.

We start first with description of simple models that allow estimation of the impact of household physical parameters and emission sources on IAP. We then describe ways to address the variation of these parameters across households in a population.

4. Using models to relate emissions to indoor air quality

To provide context on modelling approaches this section summarizes examples of commonly employed models. The approaches combine mass rate of pollutant emission within a room (e.g. kitchen) or home with mathematical models of pollutant transport and fate to provide indoor pollutant concentrations. These models range from simple constructs to complex computer-based simulations and all have the capacity to provide indoor concentration estimates indicative of those observed in homes due to the stove in question. These models can also provide a means to assess the direct contribution of a stove or other device independently of neighborhood pollution and other sources, which is important for linking guidelines with emissions performance of specific technologies.

4.1 Single zone model

The simplest construct is the single-zone model, with the key ideas as follows. The air in a zone, typically a room bound by walls and a ceiling in the context of indoor air quality, is perfectly mixed such that any pollutant emitted into room air is uniformly mixed throughout the space. (The dimensions of the room are typically determined with a tape measure). The room receives fresh air at a given rate through natural infiltration and/or mechanical means, and this supply is matched by an outflow of room air by exfiltration and/or mechanical means at the same rate. Non-ventilation pollutant loss mechanisms (for example, particle deposition onto room surfaces) can be included. Different pollutant emission rate functions can be considered, but the simplest is a constant rate (for example, emissions during active cooking). The duration of emissions rate can be set to reflect the time the source emits into the zone. The effect of an exhaust chimney or canopy hood, which removes emitted pollutants before they mix into the general kitchen air, can also be accounted for by applying fractional terms to the emissions rate. Based on these parameters, the concentrations in a room can be estimated over time. An example application of a single zone model is presented in Appendix 2.1 of this paper.

The single zone model approach was applied to the household energy sector in developing countries as early as the 1980s *(9)*. In this study, Smith et al. (1983) used a single zone model to predict kitchen concentrations of particulate matter and benzo(a)pyrene of resulting from cooking with solid fuels in India (see Appendix 1 for a summary of this model's development and application). A similar single zone modelling approach was employed by Prasad et al. (1985) to predict indoor CO concentrations resulting from cook stove emission *(10)*. Single-zone models have also been used in reverse to estimate emission factors for cookstoves *(11)*, and for kerosene lamps *(12, 13)*. Single zone models are also commonly employed in other contexts for air pollution and climate studies *(14-16)*, as well as tools for estimating exposure and risk such as the USEPA IAQX model *(17)*.

4.2 Three-zone model

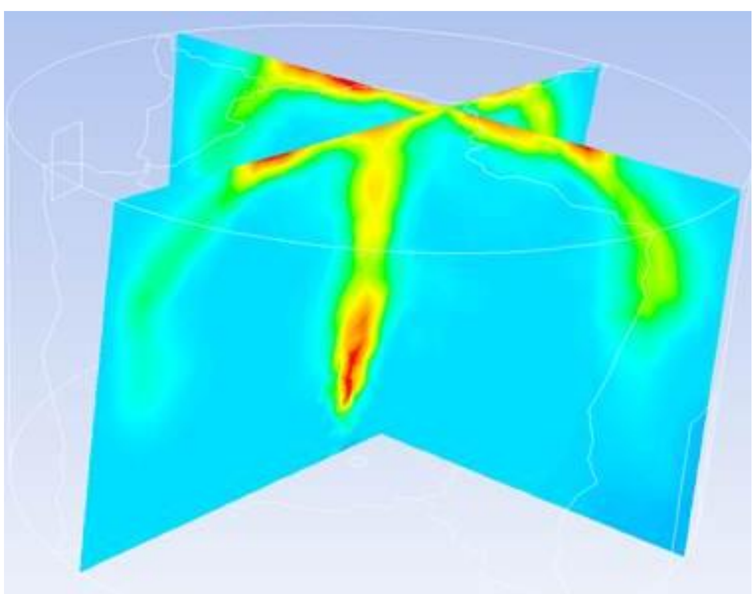
A more complicated but still tractable construct is a three-zone model, which was originally formulated for exposures due to welding *(18)*. Because perfect mixing is physically unrealistic, the pollutant concentration does vary between locations in a room, which can be addressed with a three-zone model. In a cookstove scenario as in welding, a thermal plume rises from the emission source to the ceiling without first completely mixing into the general room air. The thermal plume that rises upwards from the stove to the ceiling can be considered zone 1. The warm air within given distance to the ceiling can be considered zone 2. The rest of the kitchen which is the zone of occupancy would be zone 3. It is assumed that the air in each zone is perfectly mixed, but that there is a limited air flow between the zones.

The thermal plume from the stove creates a circulating airflow pattern in the kitchen; as the warm ceiling-level air cools, it falls into the zone of occupancy and is drawn back into the thermal plume. Similar to the single zone model, the three-zone model can account for a deposition or loss parameters in the different zones, as well as a fractional terms for the venting of emissions out of the ceiling and kitchen zones, and the duration of the emissions rate can be set to reflect the time the source emits into the zone. An example application of this model is presented in Appendix 2.2.

4.3 Computational fluid dynamic models

Computational fluid dynamic (CFD) modeling is a physics-based approach that considers the forces by which air and pollutants are transported within a room. The space is divided into thousands of smaller volumes of air by a mesh of intersecting lines. The points of intersection are termed nodes. The results of the models are strongly dependent on the resolution of nodes used. Even basic models often include 100s of thousands to millions of nodes. A system of equations is formulated at each node; the equations account for momentum, thermal energy and conservation of mass, and are solved via a computer program. One application of CFD models is the prediction of three-dimensional velocity fields that describe how air and pollutant move at thousands of positions within the room (see Figure 2).

Figure 2. Example of a 3D CFD model designed to visualize pollutant dispersion in a room from a biomass cookstove.



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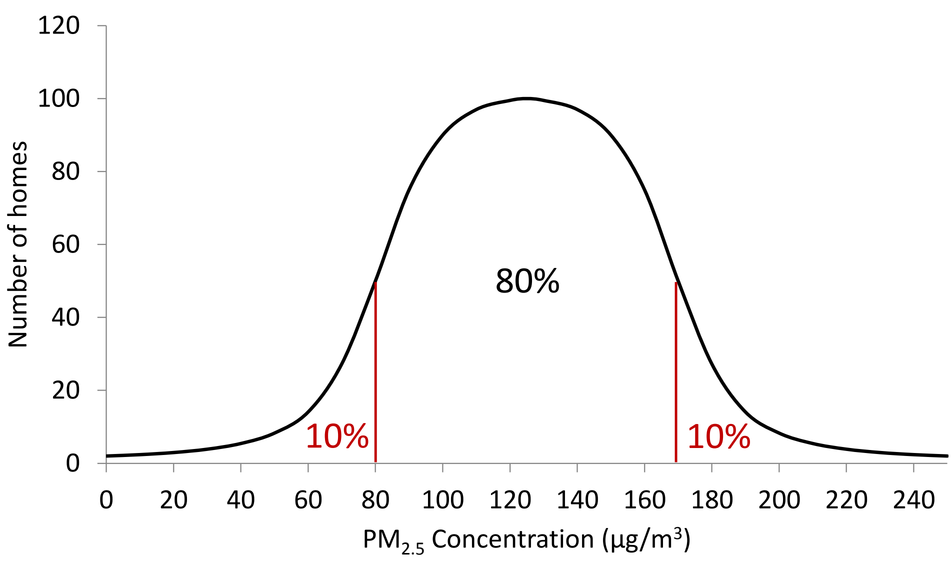
Emissions sources can be modeled which, in conjunction with the velocity field, enables estimating pollutant concentrations at these same positions. We are not aware of published work that has used CFD modeling to estimate pollutant levels in kitchens in developing countries, though CFD approaches have been presented at conferences and as part of graduate student research *(19, 20)*. CFD modeling has also been applied to designing canopy hoods for commercial kitchen ranges to improve capture of cooking emissions *(21)*, and employed for other air pollution studies *(22, 23)*.

5. Population assessments of indoor air quality

The models presented above and in Appendices 2.1 and 2.2 have been described in the context of individual households where the physical parameters (e.g. volume and ventilation rate) are understood. In a population, however, households vary in their characteristics, sometime widely. Some are bigger, some smaller. Some are well-ventilated and some not.

One way to address this large variation is to repeat the modeling procedures, varying the input parameters, such as kitchen volume, according to the variation that has been observed in a population. With the input information varied according to the population of households being considered, IAQ then can be described as a distribution or more formally a probability distribution. See Figure 3, which shows the distribution of estimated pollution levels in a hypothetical population of households. It shows that with the stove considered, 80% of the households have indoor levels between 80 µg m^{-3} and 170 µg m^{-3}, but 10% have more than 170 µg m^{-3} and another 10% have less than 80 ug m^{-3}.

Figure 3. Hypothetical distribution of estimated pollutant concentrations across a population.



A common statistical approach to probabilistic modeling is a “Monte Carlo” simulation, for which input parameters are randomly selected from predetermined distributions and run iteratively through the model to produce an output distribution of the outcome variable *(24)*. Applying a Monte Carlo simulation to the modeling approaches above, therefore, provides a more generalizable representation of the IAP levels observed across homes compared to discrete estimates, and thereby provides a means to base recommendations on the percentage of homes likely to meet a given AQG.

6. Methods

6.1 Application of a Monte Carlo single zone model

The Monte Carlo Box Model (MCBM) as described in Johnson et al. (2011), is a single zone model summarized here to illustrate how emission rates can be directly related to WHO AQGs. The MCBM requires few assumptions compared to other modeling approaches, can be applied across a range of conditions to represent a broad spectrum of households, and has been applied specifically to household energy use in developing countries *(8)*. It is important to note that other modeling approaches, such as the three-zone model could also be used with a Monte Carlo approach, but to our knowledge have not yet been applied to relate indoor air quality with stoves and other household energy devices in the developing world. CFD models, while providing spatially detailed concentration estimates for a given room, are computationally intensive and require highly detailed characteristics of the room and emission source. Although parametric CFD models can be conducted where model parameters are systematically varied, the requirements for detailed input data and extensive computation means CFD models are not suited to a simple Monte Carlo-based approach.

For the MCBM, and as described in section 4.1, IAP concentrations are modeled assuming instantaneous mixing from a single source, with zero backflow to the room, and that removal of the pollutant from the air is dominated by ventilation and competing loss mechanisms are negligible (e.g. surface reactions, particle settling).

The model used corresponds to that described in Appendix 2.1 and thus does not consider deposition or apply directly to a stove with a chimney. It does account for variation across households not only in kitchen parameters (volume and ventilation) but also in stove use, efficiency, and emission rate.

The model is described mathematically as:

Equation 1. $$C_t = \frac{Gf}{\alpha V}\left(1 - e^{-\alpha t}\right) + C_o \left(e^{-\alpha t}\right),$$

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) (min^{-1})
V = kitchen volume (m^3)
t = time (min)
C_o = concentration from preceding time unit (mg m^{-3})
f = fraction of emissions that enters the kitchen environment from the stove

For the purposes of illustrating the model's prediction of indoor pollutant concentrations, we summarize its application as presented in Johnson et al. (2011) to the Indian context. India was selected as available data for inputs were relatively comprehensive, and it represents a country with a large number of households using solid fuel stoves. The model used lognormal input distributions for air exchange rates, kitchen volumes, stove performance metrics (emissions factors, thermal efficiency, and power), and energy demands to predict resulting indoor concentrations of $PM_{2.5}$ and CO. The fuel/stove technologies applied for this exercise included the traditional Indian chulha, LPG, and a mass manufactured rocket style stove (Envirofit G3300). See Table 1 for the parameters used and the literature from which they were derived.

Table 1. MCBM inputs for India

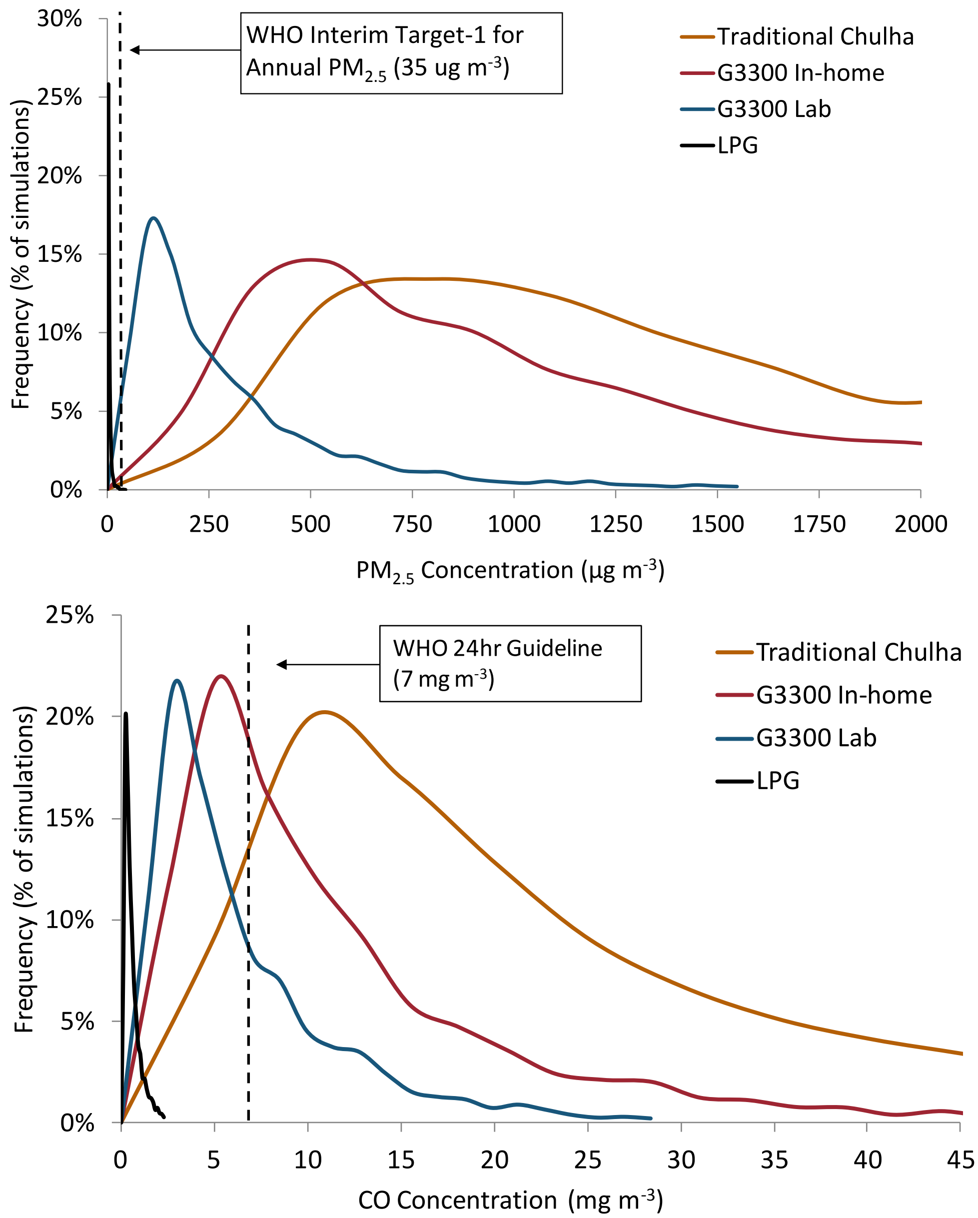
Parameter	Unit	Geo mean	Min	Max	SD	Basis
Air exchange rate (α)	hr^{-1}	25	3	60	15	*(25-27)*
Kitchen volume (V)	m^3	30	3	100	15	*(26-29)*
Fraction of emissions entering room (f)	Unitless	1	-	-	-	Only non-chimney stoves are presented in this section
Cooking energy required	MJ-delivered	11	3	30	6.5	*(30)*
Stove Power						
Traditional Chulha	KJ s^{-1}	4.9	2	15	3.4	*(27)*
G3300 In-home CCT	KJ s^{-1}	3.8	2	10	1.1	*(27)*
G3300 Lab WBT	KJ s^{-1}	3.1	2	10	0.3	*(31)*
LPG	KJ s^{-1}	1.6	0.5	5	0.2	*(32)*
Thermal Efficiency						
Traditional Chulha	%	14	5	35	1.4	*(27)*
G3300 In-home CCT	%	22	10	45	6.6	*(27)*
G3300 Lab WBT	%	29	20	45	2.9	*(31)*
LPG	%	54	40	60	5.4	*(32)*
Emission factors						
Traditional Chulha	$PM_{2.5}$ (g kg^{-1})[b]	5.2	1	10	1.0	*(27)*
	CO (g kg^{-1})	64	10	100	13	*(27)*
G3300 In-home CCT	$PM_{2.5}$ (g kg^{-1})	5.0	0.2	10	1.0	*(27)*
	CO (g kg^{-1})	47	10	90	9	*(27)*
G3300 Lab WBT	$PM_{2.5}$ (g kg^{-1})	1.6	0.5	5	0.8	*(31)*
	CO (g kg^{-1})	34	5	80	10	*(31)*
LPG	$PM_{2.5}$ (mg min^{-1})	0.175	0.02	2	0.07	*(33)**
	CO (g kg^{-1})	15	2	40	3.0	*(32)*

Adapted from: *(8)*.**We have updated the $PM_{2.5}$ emissions from LPG to an emissions rate recently measured at the USEPA, which is likely the most accurate estimate to date.

The resulting distributions are show in Figure 4 which are comprised of 5000 simulated runs of daily cooking for each stove/fuel scenario. The distributional outputs illustrate how the relationship with AQGs can be related to source emissions for the Indian context. For example, these outputs show that only the LPG scenario resulted produced distributions in which a majority of Indian homes were predicted to meet the interim-1 $PM_{2.5}$ target (over 99%) and the final AQG (94%). For CO, all LPG simulations were predicted to meet the guideline and the

G3300 resulted in 69% (laboratory-based inputs) and 46% (field-based inputs)[2] of simulations meeting the 24 hr AQG.

Figure 4. Distributions of modeled 24-hour $PM_{2.5}$ and CO concentrations for India



Source: ***(8)*** **Reproduced with permission**

[2] Laboratory inputs for stove performance were measured during variations of controlled water boiling tests. Field-based stove performance inputs were measured during controlled cooking tests in Indian homes, for which participants repeatedly prepared a pot of rice.

7. Assessment of the quality of the overall body of evidence (model validity)

Assessment of the quality of this evidence for the purpose of these guidelines (i.e. providing guidance on emission rates that will allow the AQGs to be met), is based on two main types of validation approaches, as summarized below.

7.1 Comparison of model predictions with observed kitchen concentrations

The first source of validation comes from comparison of estimated concentrations of the two pollutants ($PM_{2.5}$ and CO) derived from the model with those observed for kitchens in field studies.

Table 2 summarizes results for model predictions of $PM_{2.5}$ and CO concentrations for three types of stove/fuel (traditional solid fuel, unvented rocket-type wood stove, and gas), along with average (24 or 48-hr) concentrations measured in homes across the world. The latter data are obtained from the systematic reviews of HAP and exposure (see Review 5) and of Intervention impacts on HAP and exposure (see Review 6), as indicated in the table. Data from the SE Asian region compiled in Review 5 are also shown where available as input data for the model are derived from studies carried out in that region (India).

Table 2: Comparison of model predictions and observed concentrations of $PM_{2.5}$ and CO

Stove/fuel type	$PM_{2.5}$ (μg/m^3)		CO (mg/m^3)	
	Model	**Observed**	**Model**	**Observed**
Traditional solid fuel	>60% in range 500 – 1,800 Mode: 800	Mean: 826 (SD=1038) (SEAR); 972 (SD=876) (all regions)*	>60% in range 5 – 25 Mode: 12	Mean: 11.09 (SD=8.03) (SEAR); 9.94 (SD=7.11) (all regions)*
Unvented rocket-style stove	>60% in range 200 – 1,500 Mode: 500	Mean 410 (range 170 – 1,180)**	>60% in range 2 – 15 Mode: 5	Mean 7.56 (range 5.04 – 17.99)**
Gas	99% would meet IT-1 (35)	All clean fuel; mean: 72 (SD=41) (SEAR); 66 (SD=37) (all regions)*	All would meet the 24-hr AQG (7)	All clean fuel: mean: N/A (SEAR); 1.49 (SD=0.69) (all regions)*

*Data from systematic review of pollutants levels of HAP and exposure (see Review 4) **Data from systematic review of Intervention impacts (see Review 5)

For traditional solid fuel stoves, the predicted and observed results are very similar. For the rocket-type stove, results are also comparable for $PM_{2.5}$, although the model distribution is a little lower than that observed for CO. For gas, which is predicted by the model to meet the IT-1 for $PM_{2.5}$ in 99% of homes, it was found that in practice average concentrations in homes were approximately 70 μg/m^3. For CO, gas was predicted to meet the 24-hr AQG of 7 mg/m^3 in 100%

of homes, and this was borne out with an average concentration observed in homes of 1.49 (SD=0.69) mg/m^3. The reasons for the considerably higher values for observed $PM_{2.5}$ concentration lie with the common practice of multiple stove and fuel use in these homes, and pollutants from neighboring households and other sources entering the study kitchens.

7.2 Comparison based on simultaneous measurement of emissions and pollutants

The second source of validation derives from data obtained from India for which emission rates, ventilation, room volume and indoor concentrations of CO were simultaneously measured *(8)*. This study found that the model underestimated the observed CO concentrations in the room by 46%; several factors may be contributing to this, including spatially heterogeneous distributions in the kitchen, with measured values reflecting higher concentrations nearer the stove, rather than average concentrations for the whole room.

7.3 Summary

Overall, these validation studies suggest that for $PM_{2.5}$ concentrations, the model performs well. The high observed levels for clean fuel users do not question the validity of the model, but rather emphasize the need to control other, more polluting sources in the home and neighborhood, if AQG values are to be met. For CO concentrations, there is some evidence that the model may underestimate observed CO concentrations in some settings, but it appeared to be satisfactory for the studies of traditional stoves and clean fuel. An additional consideration for validity is that the model inputs are based solely on data from India, and better regional performance may be obtained using input data collected on a regional, if not sub-regional basis.

The overall assessment of the evidence provided by the model was assessed to be of **moderate** quality.

7.4 Emissions guidance for WHO AQGs

This section outlines the application of the MCBM to produce emission recommendations aligned with WHO AQGs. Although there are limitations to any modelling approach, and more model development and validation should be pursued, the MCBM's capacity to produce distribution estimates of indoor pollutant concentrations similar to those observed in homes, with relatively few required assumptions demonstrates the capacity to link emissions performance with WHO AQGs. The emissions guidelines are presented as $PM_{2.5}$ and CO emitted per minute, as an emissions rate provides instructive guidance for technologies and it can be readily measured using standardized protocols.

To derive the emission guidelines, the model was run using 5000 iterations of randomly selected values from distributions of air exchange rate, kitchen volume, and cooking time. The resulting output distributions of $PM_{2.5}$ and CO room concentrations were then analyzed to determine what emission rates would correspond to given percentages of modeled kitchens meeting WHO $PM_{2.5}$ and CO AQGs. The annual interim-1 (35µg m^{-3}) and final (10 µg m^{-3}) $PM_{2.5}$ guidelines are used as exposure to household air pollution is a chronic experience. The 24-hr CO AQG is used since the WHO currently does not recommend an annual CO AQG.

7.5 Inputs for MCBM

Ideally, country or region-specific inputs would be available for the model as they would provide more accurate guidance for specific contexts. At this time, however, there are not sufficient data for such an approach for each part of the world. Therefore, the input distributions used here are based on data from India, where the most comprehensive information for the input distributions was available, and where a large number of homes are using biomass cookstoves. The input distributions were assumed to be normally distributed on a logarithmic scale (log-normal), as are typical for most environmental data, and truncated at highly improbable limits for the given parameter. An air exchange rate of five changes per hour, for example, represents a very low ventilation rate for homes which use traditional open fire stoves, whereas an air exchange rates above 45 per hour is at the limit of what could be considered an indoor kitchen (e.g. a veranda or three-walled kitchen). For kitchen volumes, 5 m^3 represents the smallest of cookhouses, whereas 100 m^3 represents an extremely spacious kitchen. Daily times the stove was burning were limited to 45 minutes to eight hours, based on reported estimates from India. These limits encompass more than 95% of the distributions. The fraction of emissions entering the room (f) was conservatively set at one, assuming that no emissions escaped the room through eaves, windows, or other venting holes before mixing with the room air. The initial kitchen concentration (C_0) was set to zero so that the model concentrations accounted for only those stemming from stove emissions.

Table 3. Input distributions for air exchange rates and kitchen volumes.

Parameter	Unit	Mean	Min	Max	SD
Air exchange rate (α)	hr^{-1}	20	5	45	7.5
Kitchen volume (V)	m^3	30	5	100	15
Stove burn time	hr day^{-1}	4	0.75	8	2

The data used as the basis for the model's input distributions are presented in Table 4. Air exchange rates reported in studies of household energy projects have typically used the tracer decay, which estimates the number of air changes per hour by analyzing the rate at which a concentration of a gas such as carbon monoxide decreases after the source has been removed. In some of the studies in Table 4, exceptionally high air exchanges were observed, well beyond the maximum 45 ACH in the model. However, air exchanges above ~45 per hour are similar to those that would be observed in an outdoor environment, and thus were not included in input distribution. Kitchen volumes in these studies were obtained by directly measuring the dimensions of the room. Stove burn times in these studies were typically estimated based on participant recall, which is not the most reliable measure. Brant et al. (2011), however, reported cooking times based on direct measurement of stove temperature over several days, which at 4.3±2.2 hours is close to what was use in the model and generally in agreement with cooking times presented in the other studies.

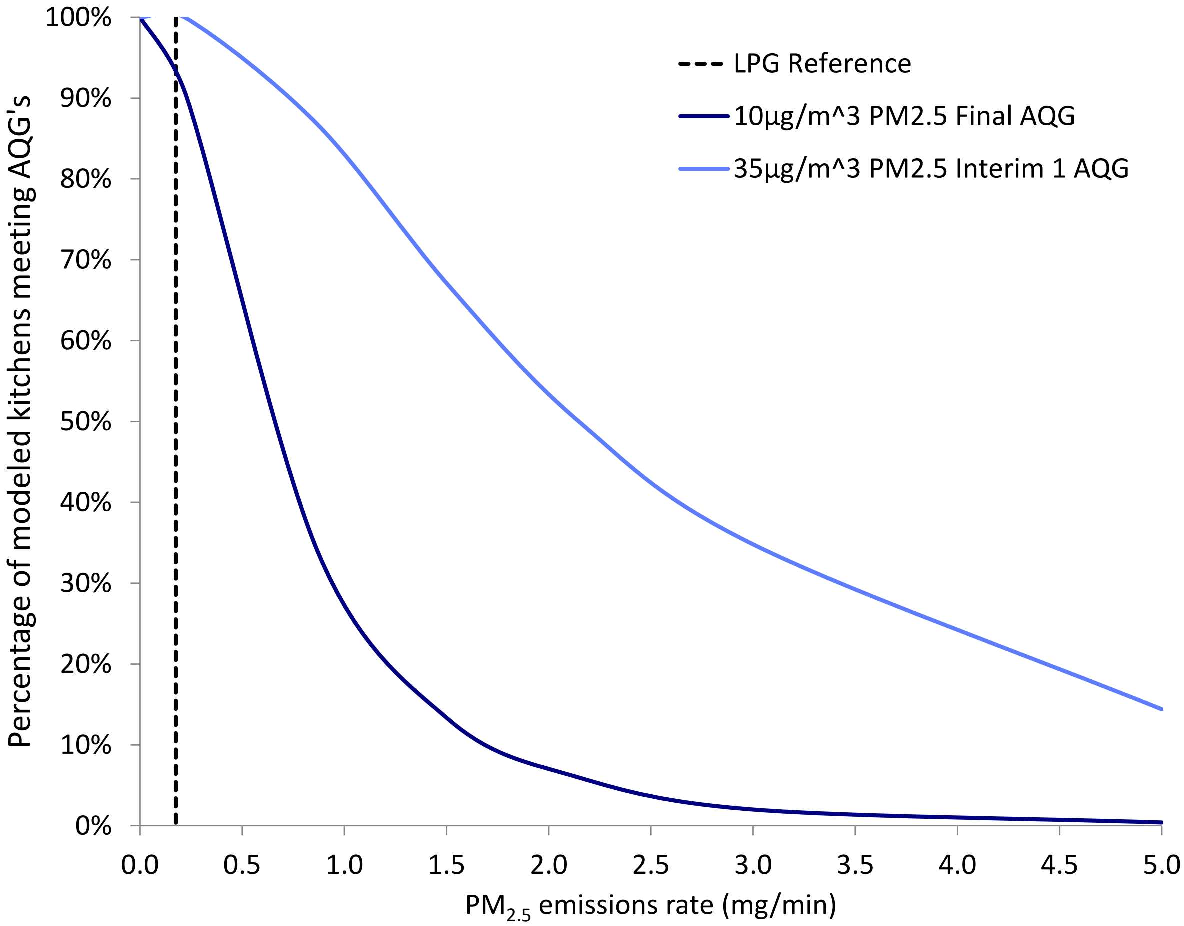
Table 4. Basis for input distributions for air exchange rates, kitchen volumes and stove burn times.

Study and metric	N	Mean	SD	Min	Max	Location	Method
Air exchange rate							
(26)	19	16	5	7	27	Maharashtra	CO decay
(8)	15	34	13	17	65	Tamil Nadu	CO decay
(34)	37	19	7	-	-	Tamil Nadu	CO decay
(25)	1	61	-	-	-	India	CO decay
Kitchen volume							
(26)	22	49	20	24	97	Maharashtra	Direct volumetric measurement
(8)	5	19	13	9	41	Tamil Nadu	Direct volumetric measurement
(9)	36	40	18	8	100	Gujarat	Direct volumetric measurement
(34)	60	20	12	5	70	Tamil Nadu	Direct volumetric measurement
(35)	80	36	7	-	-	Gujarat	Direct volumetric measurement
Stove burn time							
(9)	36	4.6	1.5	2.75	8	Gujarat	Questionnaire/recall
(26)	21	3.9	0.5	-	-	Maharashtra	Questionnaire/recall
(35)	80	3.1	0.7	-	-	Gujarat	Questionnaire/recall
(34)	49	4.3	2.2	-	-	Tamil Nadu	Stove temperature

7.6 Emission guidelines for meeting AQGs

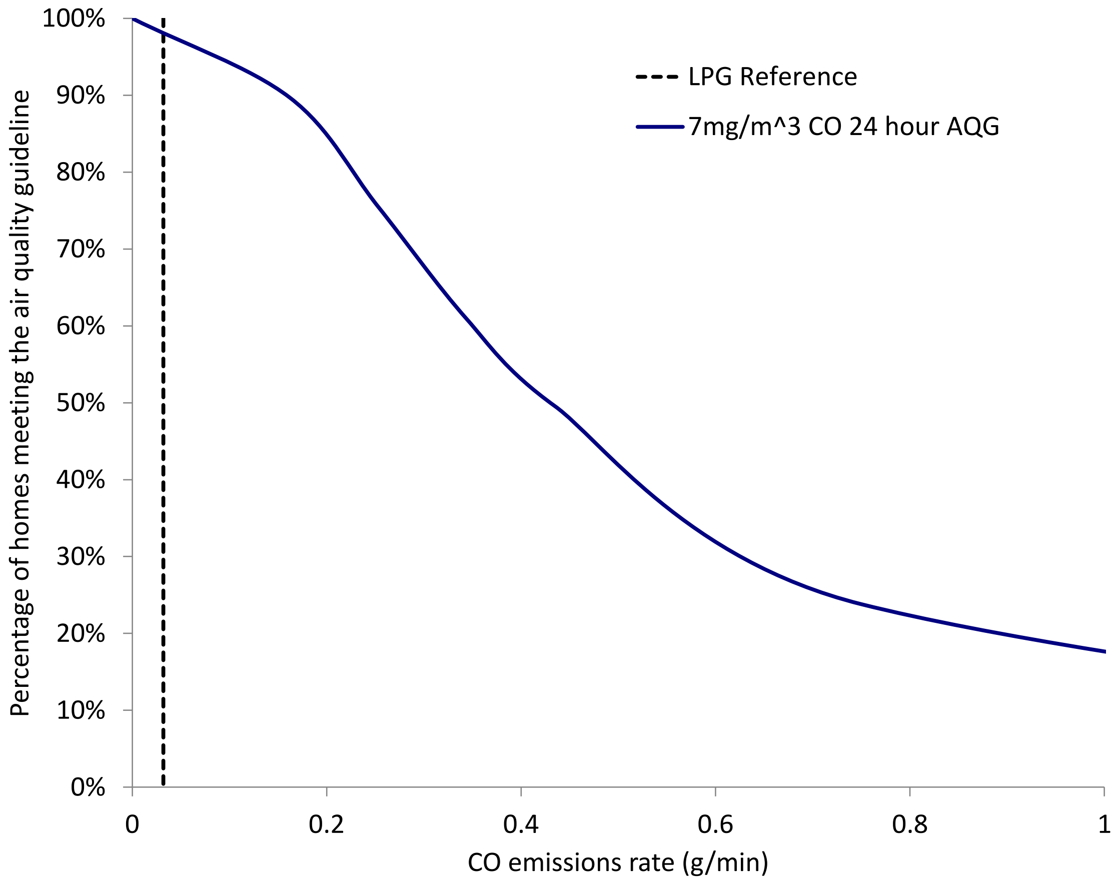
Comparison of the resulting distributions with WHO AQGs is shown in Figures 5 and 6, for which the percentage of homes predicted to meet $PM_{2.5}$ and CO AQGs is shown as a function of emission rate. The figures include a reference line for LPG emissions *(33)*, which show that almost 100% of homes with LPG level $PM_{2.5}$ emissions are predicted to meet the interim-1 $PM_{2.5}$ AGQ, and approximately 95% of those homes are predicted to meet the final AGQ. In current literature, the best performing solid-fuel biomass stoves, which make use of fans and/or gasify the solid fuel before combusting the resulting gases have emissions rates of ~3-5 mg min^{-1} *(36, 37)*. These emission rates indicate there is potential for current solid biomass fueled stoves to result in substantial fractions of homes meeting the interim-1 air quality target (~35% of modeled kitchens), but substantial improvement in $PM_{2.5}$ emissions from biomass stoves would be needed for similar percentages of homes to meet the final WHO AQG. It is also important to consider these emissions rates are derived from controlled laboratory conditions, and as detailed in section 3 of Review 2 (Emissions of Health-Damaging Pollutants from Household stoves), emissions performance during uncontrolled conditions differs and is often worse compared to during normal daily use.

Figure 5. Percentage of modeled kitchens predicted to meet $PM_{2.5}$ AQGs as a function of emissions rate.



*LPG $PM_{2.5}$ emissions reference is from USEPA (2013): 0.175g min^{-1}.

Figure 6. Percentage of modeled kitchens predicted to meet CO AQGs as a function of emissions rate.



*LPG CO emissions reference is from Smith et al. (2000).

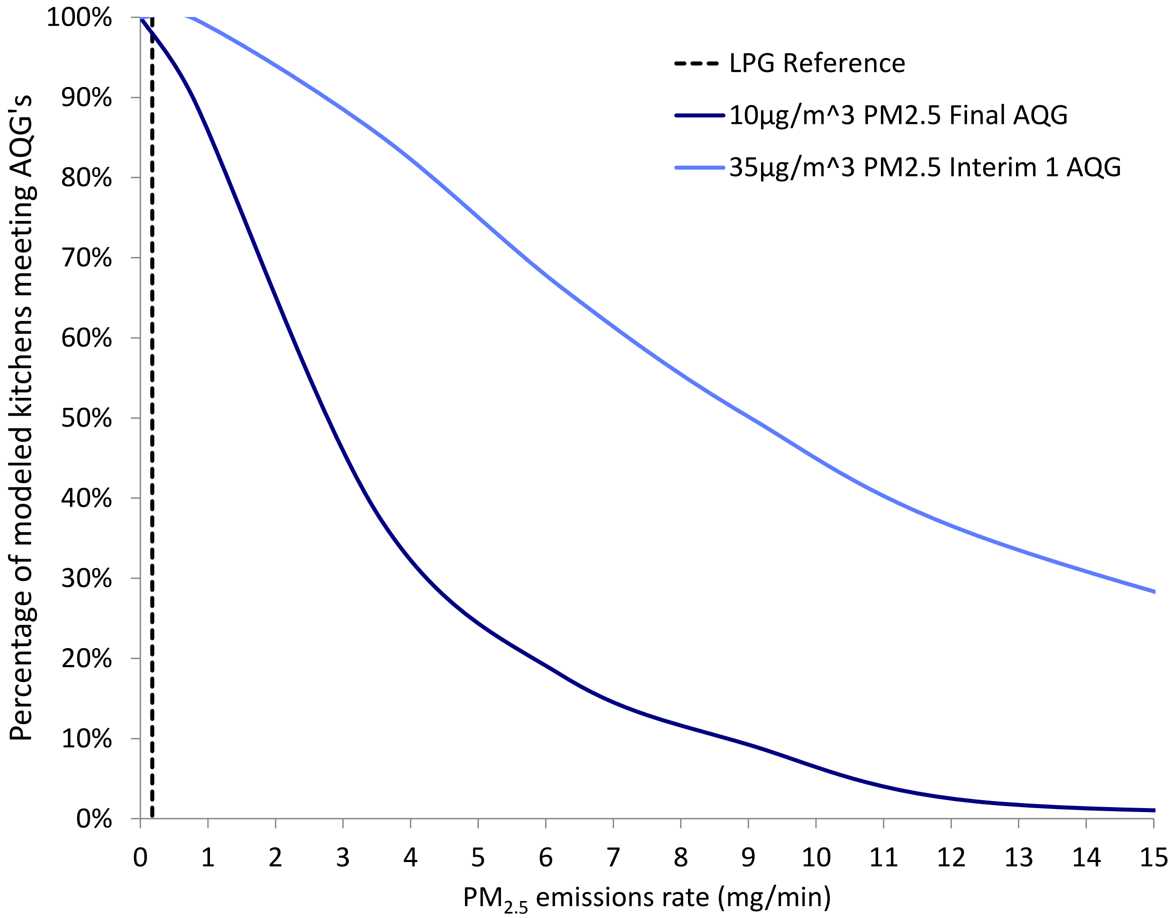
Over 95% of homes with LPG level CO emissions are predicted to meet the WHO 24-hr CO AQG. For most biomass cookstoves, meeting the CO emissions guidelines will likely be easier as the emissions performance of stoves is generally better relative to the WHO AGQs compared to that for $PM_{2.5}$. Advanced fan/gasifiers, for example, have demonstrated CO emissions rates of ~0.03-0.2 g min^{-1}, and rocket style stove are at ~0.1-0.5 g min^{-1} *(36, 37)*. However, charcoal stoves generally produce high CO emissions with rates ranging from 0.8-2 g min^{-1} *(36)*, suggesting that substantial progress with charcoal combustion technology and/or a shift in fuel sources will be required to reduce indoor charcoal users CO concentrations to levels below the WHO AQG of 7mg m^{-3}.

7.7 Considerations for chimney stoves

An important consideration for emissions rates from household energy devices is the use of chimney stoves as venting emissions outdoors reduces indoor concentrations and the resulting user's exposures to smoke. For example the RESPIRE study, which showed the effect of reduced biomass smoke exposures on childhood pneumonia rates *(38)*, demonstrated that a well-functioning chimney stove[3] reduced indoor concentrations of CO by 90% *(39)*. While fugitive emissions and re-infiltration of the vented emissions into the kitchen still contribute to the indoor concentrations of $PM_{2.5}$ and CO, there is a clear exposure benefit that well-functioning chimney stoves provide. Therefore, additional emissions guidance is provided for chimney stoves, which assume that only a fraction of the emissions enter the kitchen. As an input parameter for the model, we assumed a normal distribution for the fraction of emissions entering the kitchen ("f" in Equation 1), ranging from 1-50% with a mean of 25% and standard deviation of 10%. This distribution was conservatively based on reductions in indoor air pollution concentrations from the chimney stoves in the RESPIRE study (~90%) *(39)* and the Patsari Project in Mexico (~75%) *(40)*. The predicted distribution of $PM_{2.5}$ and CO concentrations rates indicate that chimney stoves could result in a large percentage of homes meeting AQGs with $PM_{2.5}$ and CO emissions substantially higher than those for stoves which vent directly into the kitchen. The limited published data on emission rates from chimney stoves indicate $PM_{2.5}$ emission rates of ~16-160 mg min^{-1} and CO emission rates of ~0.3-4 g min^{-1} *(36, 37)*. Although the chimney stoves with the lowest $PM_{2.5}$ and CO emissions appear to have the potential to help substantial percentages of homes meet the AGQs, the vented emissions would still contribute substantially to outdoor air pollution. Ideally, combustion in chimney stoves would also be improved to performance levels similar to advanced biomass or LPG stoves, thereby improving both indoor and outdoor air quality (see Figures 7-8).

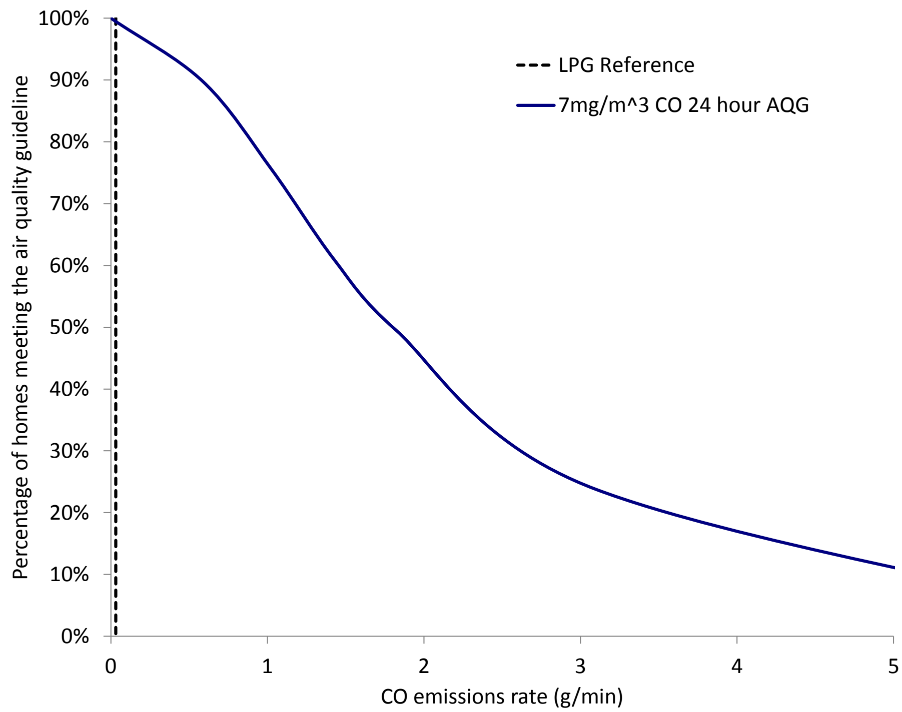
[3] The Lorena stoves used in the RESPIRE project were checked weekly by the field team and referred for repair and maintenance when required.

Figure 7. Percentage of modeled kitchens with chimney stoves predicted to meet $PM_{2.5}$ AQGs as a function of emissions rate.



*LPG $PM_{2.5}$ emissions reference is from Habib et al. (2008): 0.33g min^{-1}

Figure 8. Percentage of modeled kitchens with chimney stoves predicted to meet CO AQGs as a function of emissions rate.



*LPG CO emissions reference is from Smith et al. (2000)

7.8 Emission Rates Guidelines

To determine emissions guidelines for meeting WHO AQGs, the relationships shown in Figures 4-8 were applied to determine emission rates at increasing levels of protection (percentage of homes predicted to meet the given AQGs). This stepped framework of stricter emissions performance and increasing levels of protection reflects the needed progression towards cleaner technologies and fuels. The initial emission guidelines aim for 60% of homes to meet the interim-1 annual AQG for $PM_{2.5}$ and the 24-hr AQG for CO, and the final target aims for 90% homes to meet the final annual AQG for $PM_{2.5}$ and the 24-hr AGQ for CO.

Tables 5 and 6 below present the targets for $PM_{2.5}$ and CO emission rate guidelines for unvented and vented technologies and corresponding predicted levels of protection. Although the highest levels of protection would be achieved by technologies reaching the final emissions target, widespread use of technologies meeting the first target would represent a major improvement compared to most currently-employed household cooking, heating, and lighting technologies in developing countries. Emissions performance from the best currently available solid biomass technologies suggest that improvements in $PM_{2.5}$ emission rates are needed for both unvented and vented stoves to meet the initial target (unvented 1.75 mg min^{-1}; vented 7.15 mg min^{-1}), although meeting the initial CO targets (unvented 0.35 g min^{-1}; vented 1.45 g min^{-1}) could be achieved by these stoves today. Furthermore, the use of clean-burning gas and liquid fuels such as LPG, natural gas, biogas, and ethanol, as well as solar or electricity represent technologies which can provide high levels of protection immediately, although for these fuels and energy sources, there are additional factors that will impact adoption and consistent usage such as resource availability, distribution, affordability, and user acceptability.

Table 5. $PM_{2.5}$ emission rate targets for meeting WHO AQGs.

Particulate Matter 2.5					
Emissions Target	Emission Rate (mg/min)	Percentage of modeled kitchens meeting AQG IT-1	Percentage of modeled kitchens meeting Final AQG	Mean 24 Hour Concentration (μg/m^3)	Median 24 Hour Concentration (μg/m^3)
Unvented					
Initial	1.75	60%	9%	39	28
Final	0.23	100%	90%	5	4
Vented					
Initial	7.15	60%	4%	43	33
Final	0.80	100%	90%	4	3

Table 6. CO emission rate targets for meeting WHO AQGs.

Carbon Monoxide				
Emissions target	Emission Rate (g/min)	Percentage of modeled kitchens meeting 24 hr AQG	Mean 24 Hour Concentration (mg/m^3)	Median 24 Hour Concentration (mg/m^3)
Unvented				
Initial	0.35	60%	8	6
Final	0.16	90%	4	3
Vented				
Initial	1.45	60%	8	6
Final	0.59	90%	3	2

7.9 Considerations for the application of emissions performance guidance

The guidance provided here is directed at the performance of household energy devices, most critically cookstoves. This guidance is intended as a practical measuring stick for technology development and program implementation in relation to the WHO AQGs. Given this context, the guidance should be applied to technologies that are being used in accordance with the manufacture's recommended instructions and fuels, and are in good working condition. While deviations from intended use, degradation of performance over time, and use of multiple fuels and devices are certainly important factors impacting emissions and indoor air quality, these factors should be considered as part of programmatic monitoring, impact evaluations, or other field studies. Measurement of a technology's performance against these guidelines is not intended to replace those assessments, which are critical for understanding the broad range of real-world impacts associated with household energy interventions.

This indoor air quality guidance protects people when the stove is used indoors. Cooking outdoors, however, is prevalent in many locations, and often varies according to weather conditions. Although reducing emissions regardless of location is critical for improving outdoor air quality, these guidelines should be considered specifically for the indoor environment.

Finally, these emissions rates are linked directly to indoor air quality, but not to personal exposure. Personal exposure depends on many additional behavioural factors and potential contributions of other pollution sources, which are beyond the purview of these emissions guidelines.

8. Recommendations for future research

8.1 Improvements in stove performance testing

As discussed in Review 2 (Emissions pollutants), stove emissions have been measured in highly controlled simulated cooking conditions in near laboratory settings as well as in largely uncontrolled conditions in homes. Although measurement of a stove's emissions during normal use clearly provides the most realistic estimate of performance, testing of devices in homes is generally not as suitable for benchmarking against a performance standard due to the inherent variability and lack of replicability of uncontrolled test conditions. Current laboratory testing protocols, however, which are better suited for benchmarking stoves, do not generally produce emissions performance estimates that are representative or predictive of normal use in homes. Efforts are needed, therefore, to develop standardized test protocols and other analytical approaches which are more predictive of field performance, and can be readily and fairly conducted for benchmarking stove performance metrics. Better linking of laboratory and real world performance through new protocols has also been recommended in the International Workshop Agreement: Guidelines for evaluating cookstove performance *(41)*.

8.2 Improvements for future modelling efforts

Future improvements in model inputs and approaches would assist in providing a more robust means for linking household energy use with indoor air quality and exposure. Recommended steps are outlined below:

- Models could be improved with more comprehensive and region-specific input data. Published data on kitchen volumes, stove burn times, and ventilation rates are relatively scarce. To facilitate development of a systematic and comparable database, a set of standardized protocols for collecting these data could also be provided.
- Modelling IAQ from multiple emission sources would aid in understanding the relative contributions from lighting, heating, and multiple cookstoves.
- Modelling of ventilation improvements of various kinds would also be valuable.
- User-friendly software platforms for predicting indoor air quality based on location-specific input data would aid in providing guidance more appropriate for specific locations. Relatively simple web-based tools or software could be developed such that users can produce distributions of predicted $PM_{2.5}$ and CO concentrations for the fraction of homes with specific characteristics which would meet the WHO AQGs.
- More studies reporting emissions performance during normal daily stove use from various stove/fuel combinations being used around the world would provide a baseline and valuable context for model results and for comparing laboratory and field results.

Ideally these studies could be combined with real-world kitchen concentration data to inform on emissions-IAP concentration relationships and help validate future model development. Extending these efforts to include exposure estimates would also provide a valuable step for understanding links with health impacts.

- Better accounting of pollutant mixing would help address the stratification of IAP concentrations in kitchens. Multi-zone modelling or incorporation of mixing factors into the modelling approaches could be an important refinement to increase model accuracy. In addition, to our knowledge, there are no published studies which have sought to explicitly characterize the fraction of emissions that vent outdoors before being mixed throughout the kitchen.

9. Appendix 1: Initial application of the box model to HAP

A single-zone model was applied to indoor air pollution from cooking with biomass in developing countries early in the early 1980s by Smith et al., in the article, *Air pollution and rural biomass fuels in developing countries: A pilot village study in India and implications for research and policy (9)*. The authors used a single zone model to estimate indoor concentrations of benzo(a)pyrene and particulate matter[4] as part of the rationale for carrying out a field study Gujarat, India , as there were few physical measurements of IAP associated with biomass cookstoves reported in the literature at the time. The single zone model predicted that particulate matter could reach concentrations at tens of mg m^{-3} during cooking, which was verified by their findings and the many studies which have been conducted on IAP and solid fuel use since. Given the high concentrations of pollutants measured during the study, one of the authors' main conclusions related directly to the development of air quality standards for the household energy sector:

> "..cooks receive a larger total dose than residents of the dirtiest urban environments, and receive a much higher dose than is implied by the World Health Organization's recommended level or any national public standards…. It might be argued that the appropriate standards against which to compare cooking exposures are occupational and not public exposure standards. Cooking, after all, is an occupation in a sense... we believe, the proper comparison should be public standards or, perhaps, some new class of indoor or domestic standards yet to be developed and probably intermediate between occupational and public standards." (p. 2360)

In this first study, although no ventilation measurements were conducted, they could be imputed from the results. Later, in the same villages in Western India, Smith and colleagues conducted the first measurements of air exchange rates in biomass-using rural houses using the decay of indoor pollutant concentrations, which verified the imputed levels *(42)*.

10. Appendix 2: Quantitative illustrations of modelling approaches

10.1 Single zone model

The single zone model is the simplest of the modelling approaches presented here, and thus requires the fewest inputs and assumptions. The input parameters as described in the text include volume (V [m^3]), fresh air rate (Q [m^3 min^{-1}]), emission rate (G [μg min^{-1}]), loss parameter (α [min^{-1}]), and fraction of emissions directly vented, or capture efficiency (α), which can be used to predict the steady state concentration (Css [μg m^{-3}]) with the following equation:

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[4] The box model presented in the Smith et al. 1983 paper was based on a working paper, Smith K. R., Ramakrishna J. and Menon P. (1981) Air Pollution from the combustion of traditional fuels: A brief survey. East-West Resource Systems Institute, Honolulu, Hawai, Working Paper WP-81-5.

Equation 2 $$C_{SS} = \frac{(1-\varepsilon)\times G}{Q + \alpha\times V}$$

To illustrate, consider that fine particles from cooking are emitted at G = 5,000 μg min^{-1}. Consider that V = 30 m^3 and Q = 12.5 m^3 min^{-1} for the room, that α = 0.05 min^{-1} for particle deposition onto upper room surfaces, and that ε = 0 (no stove chimney/hood). By Equation (1), C_{SS} = 357 μg m^{-3}. To account for pollutant removal at the source, the emission rate G is multiplied by the complement of a given chimney's capture efficiency (ε), which if we assume to be 0.9, would result in a steady state concentration of 35.7 μg m^{-3}.

10.2 Three zone model

The three-zone model, which is summarized in the main text of the review (section 4.2), provides a step towards partially accounting for the spatial differences in air pollutant concentrations within a room. The input parameters for the model are the rate circulating airflow in the zones (Q_x [m^3 min^{-1}]), zone volumes of V_1, V_2 and V_3 (m^3) which sum to the room volume V, deposition loss rate to the ceiling zone (α [min^{-1}]), fraction of emissions escaping from eves or venting holes before mixing (f), and the capture efficiency of the hood or chimney (ε). Zones 2 and 3 have balanced air exchanges with the exterior of the home at volumetric rates, respectively, Q_2 and Q_3 (m^3 min^{-1}), which sum to the overall rate Q. For fine particles, the deposition loss parameter is assumed to apply in ceiling zone 2. In addition, if there is a room opening at ceiling level above the stove, a fraction (f) of the Q_{stove} airflow could directly leave the kitchen without mixing into the air of ceiling zone 2.

If the constant emission persists for sufficient time, the pollutant concentration in the zone of occupancy (zone 3) is predicted to reach a steady-state level $C_{3,SS}$ (mg m^{-3}) specified by the following equation:

Equation 3 $$C_{3,SS} = \frac{(1-f)^2\times(1-\varepsilon)\times Q_{stove}\times G}{[Q_3+(1-f)\times Q_{stove}]\times[Q_2+(\alpha\times V_2)+(1-f)\times Q_{stove}] - [1-f]^3\times Q_{stove}^2}$$

To illustrate, consider the previous scenario in which fine particles from cooking are emitted at G = 5,000 μg min^{-1}. Again consider that the kitchen volume is 30 m^3, but let V_1 = 0.79 m^3, V_2 = 3.75 m^3, and V_3 = 25.46 m^3. Again consider that the total fresh air flow into the kitchen is 12.5 m^3 min^{-1}, but let Q_2 = 1.25 m^3 min^{-1} and Q_3 = 11.25 m^3 min^{-1}. Again let α = .05 min^{-1} for particle deposition onto ceiling zone 2 surfaces, and let ε = 0. Finally, let Q_{stove} = 1 m^3 min^{-1}, and f = 0.1. By Equation (2), $C_{3,SS}$ = 146 μg m^{-3}. In contrast, $C_{1,SS}$ = 5,130 μg m^{-3} and $C_{3,SS}$ = 1,980 μg m^{-3}.

The predicted concentration of 146 μg m^{-3} in the zone of occupancy is lower than the 357 μg m^{-3} concentration predicted by the single zone model for the same parameters G, Q, V, and α. The main reason is that some pollutant loss occurs from the ceiling zone to outside the room before the pollutant can enter the zone of occupancy. If we were to set f = 0 and assume that all the fresh air entered and exited from the zone of occupancy, then $C_{3,SS}$ would equal 333 μg m^{-3}, which is similar to the value predicted by the single zone model.

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