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Pellet-fed gasifier stoves approach gas-stove like performance during in-home use in Rwanda

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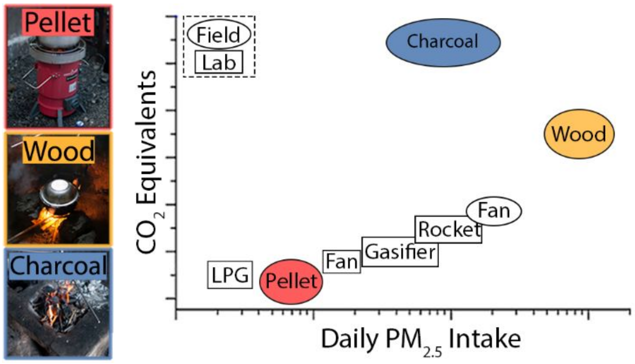

Abstract

Nearly all households in Rwanda burn solid fuels for cooking. A private firm in Rwanda is distributing forced-draft pellet-fed semi-gasifier cookstoves and fuel pellets. We measured in-use emissions of pollutants including fine particulate matter ($PM_{2.5}$), organic and elemental carbon (OC, EC), black carbon (BC) and carbon monoxide (CO) in 91 uncontrolled cooking tests (UCTs) of both pellet and baseline (wood; charcoal) stoves. We observed >90% reductions in most pollutant emission factors/rates from pellet stoves compared to baseline stoves. Pellet stoves performed far better than gasifier stoves burning unprocessed wood, and consistent with ISO tiers 4 and 5 for $PM_{2.5}$ and CO, respectively. Pellet stoves were generally clean, but performance varied; emissions from the dirtiest pellet tests matched those from the cleanest traditional stove tests. Our real-time data suggest that events occurring during ignition and the end of testing (e.g., refueling, char burnout) drive high emissions during pellet tests. We use our data to estimate potential health and climate cobenefits from stove adoption. This analysis suggests that pellet stoves have the potential to provide health benefits far above previously tested biomass stoves and approaching

modern fuel stoves (e.g., LPG). Net climate impacts of pellet stoves range from similar to LPG to negligible, depending on biomass source and upstream emissions.

Introduction

Nearly three billion people rely on solid fuel burning stoves that emit particulate matter and gaseous pollutants contributing to adverse health and climate impacts.[1] Household cooking alone contributes 12% of global ambient fine particulate matter ($PM_{2.5}$),[2] a major risk factor for disease.[3] Exposure to air pollution as a whole results in an estimated 8.9 million deaths annually,[4] with at least one-third directly attributable to household air pollution (HAP) from residential solid fuel combustion.[5] Residential solid fuel use contributes ~25% of global black carbon (BC)[6], an important climate forcer and the component of these emissions contributing most to increased surface temperature.[7]

Technologies and distribution programs to address impacts of residential solid fuel combustion have frequently not met their goals or the potential suggested during lab-based cookstove development and testing. Improved cookstove (ICS) interventions have shown mixed results in attaining significant reductions of indoor $PM_{2.5}$ concentrations[8] or measurable health benefits.[9,10] Emissions from field measurements of in-use ICS are typically ~3 to 5 fold higher than those from controlled laboratory-based results,[11–13] due likely to variation in stove operation and fuel characteristics. One response to these issues has been a shift towards the promotion of modern fuels such as liquid petroleum gas (LPG), [14,15] a paradigm summarized as "making the clean available instead of trying to make the available clean".[16] However, such interventions may be hindered by access to the technology (e.g., affordability). The initial cost for LPG is a widely reported barrier for low-income homes, and exclusive use of the fuel is likely limited to higher-income, and often urban, users.[17] Even if adopted, continued use of a traditional solid-fuel stove ("stacking") for just minutes a day may negate much of the potential health benefits afforded by the modern stove.[18]

Therefore, a robust clean-burning solid fuel cookstove (e.g., pellet-fed gasifier) may provide a viable step in household transitions towards cleaner energy by providing consistent and significant emissions reductions using a potentially affordable and available cookstove/fuel combination. Pellets are a homogenous fuel supply that reduces inherent variability in biomass size, shape, and moisture content. Wathore et al.[12] found that heterogeneity in fuel and loading was key to observed reduced performance of a forced-draft ICS in Malawi, and likely a driver of highly variable observed emissions; the use of a homogenous fuel source (e.g., pellets) was recommended. Johnson and Chiang[18] highlighted the opportunity for fuel-processing enterprises to provide affordable alternative fuels that simultaneously reduce emissions and shift user behavior. This approach does however require redirecting focus from the stove itself to the broader system including upstream feedstock sourcing, fuel processing, and marketing/distribution.

One such initiative is by Inyenyeri, a social enterprise currently active in Rwanda (www.inyenyeri.com). Based in Gisenyi, Rwanda, Inyenyeri currently distributes the Mimi Moto forced-draft, pellet-fed semi-gasifier cookstove through a business model that claims to emphasize customer service and affordability.[19] The Mimi Moto is currently the best-performing wood fuel cookstove in the Clean Cookstove Catalog of lab-based measurements.[20] Therefore, it offers the potential to drastically reduce indoor emissions (and exposure) compared to traditional solid fuel stoves. Inyenyeri customers sign a monthly contract to purchase pellets (at a rate currently cost-competitive with charcoal) and are provided the stove, fuel delivery, training, and repair at no additional cost. Jagger and Das[21] detail Inyenyeri's pilot phase, business model development, and company/pellet production scale-up, and summarize their customer service efforts as "major innovations".

With high reliance on solid fuels, a substantial disease burden associated with HAP, and rapidly depleting forests, Rwanda is a highly appropriate location for a cooking intervention. Nearly all Rwandan homes (>99%) use solid fuels (wood and charcoal) for cooking, with wood the primary fuel in 96% of rural homes.[22] HAP from solid fuel use is the fourth leading risk factor for morbidity and mortality in Rwanda, and respiratory infection the leading cause of life lost.[23] ICS programs have been implemented there for decades, though stove quality and uptake has varied greatly, and residential solid fuel use continues to drive unsustainable fuelwood harvesting and public health burdens.[24] Though the gross domestic product of Rwanda has recently grown rapidly, it still ranks 163 of 193 globally in per-capita gross domestic product.[25] Therefore, access to technologies such as ICS is cost-limited in Rwanda.

This study assesses in-use emissions of the Mimi Moto cookstove and traditional counterparts in urban and rural homes in and around Gisenyi, Rwanda. Specific objectives are to: 1) measure emission factors and rates from in-home use of three stove types, 2) explore seasonality in emissions, 3) characterize optical properties of the emitted aerosols, 4) analyze real-time emissions behavior of each stove type, and 5) estimate potential health and climate cobenefits associated with the use of the Mimi Moto stove.

Materials and Methods

Study Location and Stoves

The study was conducted in Gisenyi, Rwanda (pop. 54,000), a city located on Lake Kivu and the border of the Democratic Republic of Congo,[26] and the location of the Inyenyeri headquarters and fuel pellet manufacturing facility. The fuel pellets are made by compressing sawdust sourced from local lumber mills, primarily from eucalyptus wood. Pellets retail for 200 RWF kg^{-1} (~\$0.23 kg^{-1}) (at the time of this study, and specific to this location) compared to wood which is typically free (harvested), or charcoal for around 360 RWF kg^{-1} (~\$0.42 kg^{-1}).[21] This translates into an approximate 20% savings compared to charcoal on per-fuel-energy basis (see

Supplemental Information (SI) Table S1 for energy contents); even greater savings are expected considering improved stove efficiency (Table S2).

Distinct homes were studied for emission tests using pellets, unprocessed biomass (wood), and locally-manufactured charcoal. 'Pellet' homes utilized either one or two Mimi Moto stoves and burned only pellets during study visits. 'Wood' homes utilized the three stone fire (TSF) burning either elephant grass (*Pennisetum purpureum*), eucalyptus wood (*Eucalyptus saligna*), or a mixture of the two. Charcoal stoves were either free-standing metal coalpots[27] or Jiko-style charcoal stoves[28] built into the kitchen. Photos of representative stoves are shown in SI Figure S1. Households were randomly selected from a subset of current Inyenyeri customers for the pellet homes, and through local contacts for the wood and charcoal homes. We tested in a total of 14 pellet, 4 wood, and 4 charcoal homes in each of two measurement 'seasons' (November/December 2017 and May/June 2018). Uncontrolled cooking tests (UCTs) were conducted at each household for lunch and supper on the same day, beginning around 10:00 AM and 4:00 PM, respectively, for a total study sample size of 91 UCTs. UCTs are intended to capture inherent variability due to real-world differences in user behavior, fuel and ingredient preparation, and other variables.[11,12,29]

Sampling

Emissions testing was conducted with the STove Emissions Measurement System (STEMS), described in detail elsewhere.[12] The STEMS runs on a 12V battery, logs data to an SD card and laptop, and measures real-time (2 s) carbon dioxide (CO_2), carbon monoxide (CO), temperature, relatively humidity, and particle light scattering (B_{sp}) using a laser photometer (optical wavelength, $\lambda = 635$ nm) calibrated against a photoacoustic extinctiometer at $\lambda = 870$ nm (PAX, Droplet Measurement Technologies). A 2.5 µm cut-point cyclone (BGI Inc.) is used at the inlet of the STEMS, and integrated 47 mm filter samples are collected with two filter trains, each at 3.0 l min^{-1}. One train contains only a bare quartz fiber filter (QFF) (Tissuquartz, Pall Corporation), and the other contains a Teflon membrane filter (Zefluor 2.0 µm pore size, Zefon) followed by a "backup" QFF for quantification of gas-phase adsorption artifacts [30]. A portable aethalometer (microAeth AE51, AethLabs) integrated into the STEMS measures real-time PM light absorption (B_{ap}) at $\lambda = 880$ nm. To avoid filter overloading, an external flow meter (Honeywell AWM3150V) and vacuum source were used in place of the microAeth's internal pump, with flow rate set between 15-40 cm^3 min^{-1}; microAeth filter loading artifacts were corrected following Park et al.[31]. Additional details on STEMS sensors, filter analysis and uncertainties, and data quality assurance are provided in SI Section S1, while details concerning aethalometer loading correction are provided in Section S2.

A six-armed stainless steel sampling probe captured naturally-diluted emissions from 41 ± 12 cm above the stove; emissions flow then through conductive silicone tubing to the STEMS. Background air was sampled for 5-10 min before and after each test. For a subset of tests (n=9), the CO data displayed cross-sensitivity with solvent (denatured alcohol) used in pre-test cleaning. Background readings for these tests were corrected as discussed in SI Section S1. A set-aside quantity of fuel was weighed before and after each test to determine mass of fuel consumed during the test. Fuel samples (~15 g) were stored in sealed plastic bags for moisture content analysis with a thermogravimetric moisture analyzer (VPB-10, Henk Maas, Netherlands) and elemental analysis (C, H, N, S, K, Na, Fe, Ca, and Ash) with a model 2400 CHN Elemental Analyzer and model 8000 Ion Coupled Plasma-Optical Emission Spectrometer (Perkin Elmer Corp.).

Configuration of the cookstove and cooking area varied by home/test (as listed in the Summary Spreadsheet in the SI), and included detached kitchen (42% of tests), outdoor covered area (24%), outdoor open area (14%), indoor kitchen (11%), indoor living area (4%), and indoor hallway (4%). Upon arrival to the household, a brief introduction to the study was provided in Kinyarwanda (the national language), and the study participants surveyed to assess their preferences and experiences relative to their stove. During testing, meal preparation steps and events such as fuel addition/reloading were recorded by the field assistant. Ingredients typically used in cooking were potatoes, beans, rice, vegetables, and small amounts of meat and fish. Pellets were ignited with kerosene or twigs and matches, while wood and charcoal stoves were ignited with twigs or tire pieces and matches. Char remaining at the end of test was weighed, when possible.

Emission Factor and Rate Calculations

Fuel-based emission factors (EFs) were calculated using the carbon balance method [32,33], which allows for EF estimation without a full-capture sampling approach. We assume that all fuel carbon was emitted as CO and CO_2. Other carbonaceous emissions (e.g., methane) contribute a relatively small fraction (<5%) and were ignored.[32] Mean dry fuel carbon contents from the elemental analysis were used and were 47.5%, 45.4%, and 81.9% for pellet, wood, and charcoal fuels, respectively. Fuel based EFs and per-test fuel consumption were used to calculate test-average emission rates (ERs). Additional details on EF and ER calculations and uncertainties are included in Section S3 and Tables S3 and S4 of the SI.

Time-Resolved Emissions Analyses

To analyze real-time instantaneous emission factors (IEFs) across tests, IEF values were normalized with respect to both test duration and mass of pollutant emitted for CO, B_{sp}, and B_{ap} using an approach similar to Preble et al.[34] In brief, fuel-consumption-weighted minute-average IEFs were normalized to total pollutant emitted $[IEF_{norm,i,t} = IEF_{i,t} * d_{Cnet,t} / \sum_{t_0}^{t_f}(IEF_{i,t} * d_{Cnet,t})]$, where i = CO, B_{sp}, or B_{ap}, d_{Cnet} is instantaneous fuel consumption as defined by background-corrected CO and CO_2 concentrations, t is a specific point during the test duration, t_0 is test start/ignition, and t_f is test end) and then integrated to develop cumulative distributions. This approach assumes a constant dilution rate, which is likely not completely accurate given the sampling approach, but should yield a useful indication of the distribution of emissions across test duration.

To allow further investigation of real-time combustion and aerosol properties, Patterns of Real Time Emissions Distribution (PaRTED) plots were developed using the procedure by Chen et al.[35] and previously employed by our group on data from Malawi[12] and India[13]. Minute-average particle single scattering albedo (SSA) and stove modified combustion efficiency [MCE = $\Delta CO_2/(\Delta CO+\Delta CO_2)$, where Δ indicates background-corrected mixing ratios in ppm] are displayed in a bivariate histogram, weighted by instantaneous PM scattering emission factor (IEF_{scat}; SI Section S4) and normalized by total scattering emissions to represent the distribution of total particle emissions. Scattering shows strong correlation ($R^2 = 0.84$) with gravimetric $PM_{2.5}$ results (SI Figure S2) and is used to represent $PM_{2.5}$ mass emissions.

Cobenefits Analysis

To evaluate potential health and climate cobenefits associated with the hypothetical full adoption of the pellet stove, we apply a framework previously developed[36] using emissions and fuel use data published in the literature (for LPG and four wood stove types: forced draft, gasifier, rocket, and TSF) and collected in the current study (for pellet, wood, and charcoal stoves). We estimate 100-year global warming commitments (GWC, tonnes of CO_2-equivalent per year of cookstove use) and daily $PM_{2.5}$ intake using field-measured EFs. For wood stove types, we consider only emissions during fuel combustion, as upstream processes (e.g., fuel harvesting and transport) are assumed negligible compared to combustion emissions. Pellet, charcoal, and LPG GWC calculations include estimated emissions from fuel processing and production, as described in Section S4 of the SI. Combustion phase emissions of methane (CH_4) was not measured but makes a substantial contribution to the GWCs, and was approximated using CH_4:CO ratios from the literature.[28,36] GWCs from other hydrocarbons and N_2O are small for biomass emissions[29,37,38] and are neglected here.

The IPCC value of 0.98 was used for the fraction of nonrenewable biomass (f_{NRB}) in Rwanda.[39] A fixed household cooking energy demand was assumed based on country-level household population[40] and fuel use[41] data. Annual fuel use for each cookstove was estimated using fuel energy contents and thermal efficiencies defined in SI Tables S1 and S2. Fuel use rate reductions relative to the baseline observed for field measurements were then used in the cobenefit modeling. GWC calculations used global warming potential (GWP) values recommended by the Gold Standard Foundation and IPCC, summarized in SI Table S5. Estimates of human exposure to $PM_{2.5}$ apply an individual intake fraction of 1300 ppm (1 ppm = 1 mg inhaled per kg emitted) to link emissions to human exposure. The exposure-response relationship for all-age mortality risk from ischemic heart disease (IHD) from Burnett et al.[42] is used to estimate adjusted relative risk of mortality due to IHD (dose-response for chronic obstructive pulmonary disease mortality is similar). Additional assumptions of the model employed here are described in SI Section S5 and Table S6.

Results and Discussion

Emission Factors and Rates

Emission factors and rates for $PM_{2.5}$ and CO are plotted in Figures 1a-d for the three stove/fuel combinations (pellet, wood, and charcoal). Pellet stoves had substantially (e.g., means reduced by 84-97% relative to wood) and significantly lower (Wilcoxon rank-sum test, $p<0.05$) EFs and ERs for both $PM_{2.5}$ and CO compared to the traditional stoves. Compared to previous field investigations of the Philips HD4012-LS forced-draft gasifier stove burning unprocessed wood, the Mimi Moto (pellet) $PM_{2.5}$ and CO EFs are much lower. For example, median pellet $PM_{2.5}$ EF (0.4 g kg^{-1}) is nearly 10× lower than the Philips in Malawi and Ghana (ranging between 2.5-4.7 g kg^{-1}).[12,27] CO EF differences are less dramatic, but the Mimi Moto pellet stove was still 3× lower than the Philips (14 vs. 45-49 g kg^{-1}, respectively). This difference in emissions performance could be due to many factors including wood fuel size, shape,[43] loading,[12] and moisture content. The Philips stove can accommodate a variety of woody biomass fuels,[44] but is often used with inconsistently cut and loaded wood. This suggests that the homogenization of a solid fuel (e.g., wood pelletizing) greatly improves the emissions performance of an already advanced cookstove design.

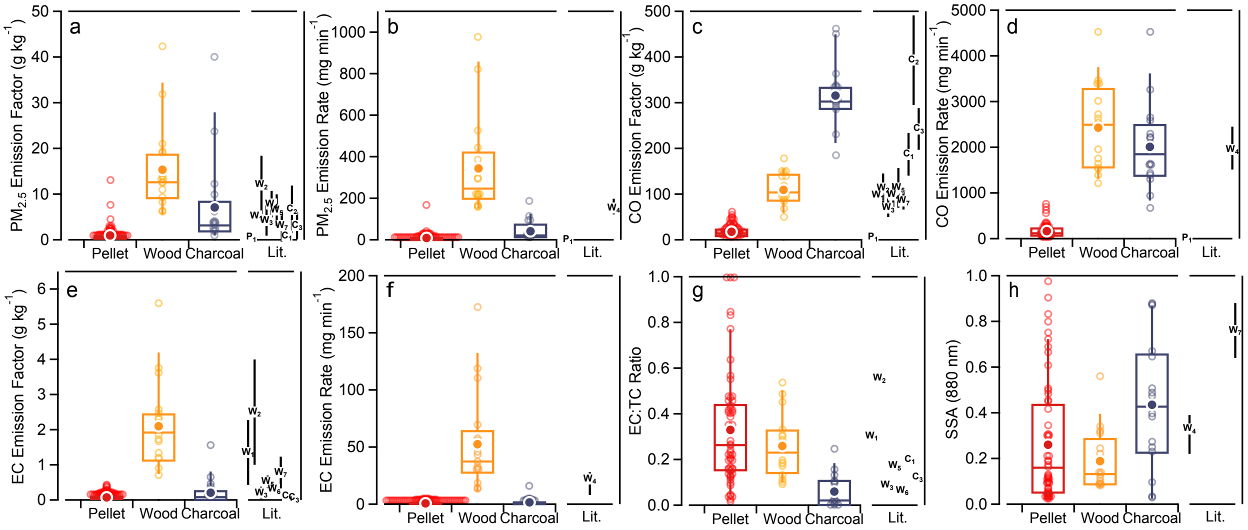

Figure 1. Box and whisker plots for $PM_{2.5}$ EF (a) and ER (b), CO EF (c) and ER (d), EC EF (e) and ER (f), EC:TC ratio (g), and SSA (h). Boxes and whiskers indicate 25th to 75th and 10th and 90th percentiles, respectively; central lines indicate median and dark circles indicate group mean; hollow circles are individual test data. Also shown with letters as markers are mean and standard deviations for controlled lab emissions test data reported for P_1: Mimi Moto pellet-fed forced-draft semi-gasifier stove [20], and field emissions test data for W_1-W_7: TSF/mud stove burning wood[11–13,27,29,45,46], C_1: Coalpot charcoal stove[27], and C_2-C_3: Jiko-style charcoal stoves[46,47].

Median $PM_{2.5}$ and CO EFs for pellet stoves observed in this study are similar to lab results reported in the Clean Cooking Catalog (0.37 vs 0.54 g kg^{-1} for $PM_{2.5}$; 14 vs 5.9 g kg^{-1} for CO), suggesting pellet stove field performance, at least for PM emissions, is on-par with controlled laboratory test results. This is likely due in large part to the homogeneous fuel supply. Figure S3 shows pellet PM and CO EFs grouped by the year in which they were acquired by the household, and shows generally that stoves more than one year old had significantly higher EFs. Similar to $PM_{2.5}$ EFs, pellet stoves have significantly lower $PM_{2.5}$ ERs compared to both traditional stove types. Differences between pellet and wood $PM_{2.5}$ ERs are greater than for the respective EFs due to the lower fuel consumption of pellet stoves compared to wood (median fuel consumption of 0.5 vs 1.2 kg hr^{-1}; SI Figures S4 and S5).

EFs in terms of useful energy delivered (MJ-del) were calculated, assuming fuel energy contents (Table S1) and stove thermal efficiencies (Table S2). Median $PM_{2.5}$ and CO EFs for the pellet tests were consistent with ISO Tier-4 for $PM_{2.5}$ and Tier-5 ("best") for CO (see SI Figure S6 for detail). The median $PM_{2.5}$ EFs for pellet tests which included a reload (i.e., refuel) event were significantly higher and met Tier-3 for $PM_{2.5}$, while those with no reload met Tier-4 for $PM_{2.5}$ (Figure S7). Note that this tier system is intended for use with laboratory data, and is employed here for comparison purposes only. In comparison to World Health Organization (WHO) indoor air quality guidelines, the median pellet $PM_{2.5}$ ER exceeded WHO emission rate targets for unvented stoves (3.3 vs. 0.23 mg min^{-1}), while the median CO ER met the guideline (125 vs. 160 mg min^{-1}).[48] Although controlled laboratory testing has identified the potential of gasifier stoves to meet the top emissions tiers,[49] to our knowledge no published studies have observed a solid-fuel cookstove meeting or approaching the highest tier designations for emissions performance during uncontrolled in-use (i.e., field) testing.

As expected, both traditional stoves were classified as Tier-0 ("no improvement over baseline"; Figure S8). Our field-based $PM_{2.5}$ and CO EFs for traditional wood and charcoal stoves were generally similar to previous field studies of wood-burning TSFs, as plotted in Figures 1a and 1c and cited in the figure caption. The wood PM EF 90% confidence interval about the mean (CI_{90}: [11.3, 22.5] g kg^{-1}) overlapped with specified ranges about the mean from W_2, but was higher than those from the other studies[11–13,27,46] as listed in Table S7 of the SI; wood CO EF CI_{90} overlapped with ranges from all other studies except for W_3. Therefore compared to previous field investigations, the traditional wood stoves studied here emitted more PM, but operated at similar combustion efficiencies (arithmetically inversely related to CO EF when using carbon balance approach). This may be due to the distinct type of fuel burned in this study (predominately elephant grass), as opposed to fuel wood. $PM_{2.5}$ and CO EFs and ERs for wood homes burning different types of wood (elephant grass vs. eucalyptus vs. mix) are reported in SI Figure S9; $PM_{2.5}$ and CO ERs are significant greater ($p < 0.05$) for elephant grass versus mixed-wood homes; no significant differences were observed between homes burning only elephant grass and only eucalyptus. For charcoal homes, the $PM_{2.5}$ EF CI_{90} overlapped with both C_2 and C_3, but not C_1. The CO EF CI_{90} from our work overlapped only with C_2, and was higher than C_1 and C_3. Therefore, emissions from both traditional wood and charcoal in this study were generally slightly higher compared to previous literature field data.

EC EFs and ERs are plotted in Figures 1e and 1f. Pellet EC EFs and ERs were significantly lower than for wood, but not for charcoal. Given the nature of charcoal combustion (surface oxidation of a pyrolyzed fuel vs. flaming combustion of devolatilized organics), low EC emissions are expected. Wood and charcoal EC EFs observed in this study are similar to previous field test results for these traditional stove types. Ratios of elemental carbon to total carbon (EC:TC) are plotted in Figure 1g. Pellet stoves had the highest EC:TC ratio, consistent with what has been observed in stoves operating at higher efficiency (and presumably combustion temperature).[12,45] Pellet EC:TC ratios were more variable than, and not significantly different from, those for wood stoves. Literature EC:TC ratios for traditional wood stoves are highly variable and span an order of magnitude (0.06-0.6), whereas the (more limited) literature data for charcoal stoves range between 0.1 and 0.2, indicating that charcoal PM emissions are dominated by OC vs EC.

SSA (λ = 880 nm) follows a similar trend as EC:TC ratio (SI Figure S10), with lower SSA (i.e., more light absorbing particles) generally corresponding to the higher EC:TC ratios for pellet and wood stoves, as observed previously for biomass burning aerosol.[50] SSA is not significantly different between pellet and wood stove types. EC:TC ratio (SSA) for charcoal are significantly lower (higher) compared to wood and pellet. The implied climate benefits from mitigating cookstove emissions are influenced by the aerosol EC:TC ratio assumed for the baseline technology.[36,51] Here, pellet stoves emit less particles that are relatively more light absorbing compared to wood and charcoal stoves. Both quantity and optical properties of emissions must be considered, as net radiative impacts are a function of both.

Examining distributions of the integrated emissions quantities, cumulative distribution functions (CDFs) of EFs (SI Figure S11) show that the majority of pellet tests have low EFs for $PM_{2.5}$ and CO, but that $PM_{2.5}$ EFs (and ERs) from high-emitting pellet tests overlap with low-emitting wood and charcoal tests. The distribution of pellet $PM_{2.5}$ EFs are strongly positively skewed (skewness, γ=4.5), with a mean EF (0.95 g kg^{-1}) nearly three times the median; wood and charcoal stoves had lower $PM_{2.5}$ EF skewness (γ = 1.4 and 2.1, respectively). This emphasizes that: a) ICS performance can be highly variable in the field, and b) pellet stoves offer tremendous potential to reduce emissions, but only when operated properly. High-emitting pellet tests are discussed in more detail in Section 3.2.

Differences in $PM_{2.5}$ and CO EFs in the same home across seasons are plotted in SI Figure S12. We observed no significant differences for $PM_{2.5}$, OC, or EC EFs for all fuels. For charcoal homes only, a significant difference (p=0.04) in CO EF was observed, with an increase in CO EF during the second deployment. Intraclass correlation coefficients calculated for $PM_{2.5}$ and CO EFs for each fuel type also indicated no significant differences between seasons. Within fuel types, no significant difference in fuel moisture content was observed between deployments, a likely driving factor of seasonality in previous field studies.[13]

Time-Resolved Emissions

Time-resolved instantaneous EFs (IEFs) can give insight into how stove operation affects net emissions performance. Figure 2 plots normalized CO, PM_{scat}, and BC IEFs against normalized time for pellet, wood, and charcoal stoves as well as for high emitting pellet stoves (designated “pellet-high”). The time-resolved emissions plots illustrate when, on average, each stove type emitted each pollutant during field testing. We define pellet-high stove tests as those with $PM_{2.5}$ EFs $\geq 90^{th}$ percentile (6 tests). Condensed testing notes are summarized in the SI spreadsheet for pellet-high tests; of these 6 tests, 1 had a dead stove battery (i.e., no forced-draft mode), 3 included refueling during testing, and 3 utilized kindling for ignition (as opposed to kerosene). Therefore, stove operation plays a key role in the emissions performance of these advanced ICS.

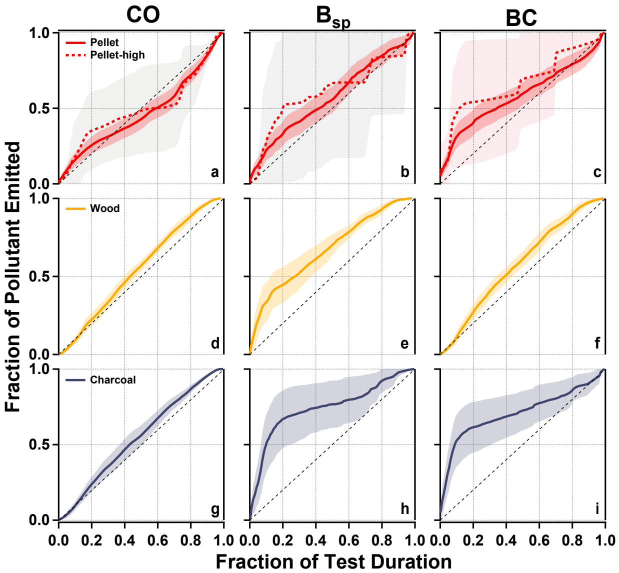

Figure 2. Normalized average cumulative emissions of CO, PM scattering (B_{sp}), and BC (PM absorption, B_{ap}) with 95% confidence intervals about the mean indicated by shading for pellet (a-c), wood (d-f), and charcoal (g-i) stove types. Test duration (x-axis) is normalized to the portion of testing wherein stove emissions are occurring (i.e., excluding pre- and post-background periods). Pollutant mass emissions (y-axis) are normalized to the total mass of pollutant emitted during the test duration, where 0 and 1 represent zero and total emissions from each test, respectively. Theoretical constant emission rate lines (1:1) are plotted for comparison purposes. Note that BC panel for ‘pellet-high’ only contains data for 4 of 6 high-emission pellet tests due to data quality issues in two tests.

Pellet stoves emitted slightly more CO during the beginning of testing (26% of CO emitted during first quintile as shown in Figure 2a). This trend was amplified for pellet-high stoves, which emitted on average 35% of total CO during the first quintile. Both wood and charcoal stoves tended to emit CO steadily throughout testing (Figures 2d and g). More distinctive time-resolved patterns are observed for PM_{scat}. For example, pellet stoves emitted PM (assuming PM_{scat} represents PM mass) at a higher rate towards the beginning of testing (i.e., following ignition), then emitted steadily until testing was completed. Pellet-high stoves emitted PM the most rapidly near the beginning of testing, and then near the end of testing, as represented by two distinct "bumps" in Figure 2b (likely during pellet refueling and burnout). Pellet-high and wood stoves emitted roughly half of total PM within the first quintile of testing (50 and 45%, respectively). Charcoal emitted 67% of PM scattering emissions during the first quintile (Figure 2e), emphasizing the outsized contribution of PM ignition emissions for the charcoal stoves. Ignition practices (especially starting material) have significant impact on overall emissions,[52] and charcoal tests relied on diverse materials (e.g, pieces of tire, leaves) for ignition. BC (B_{ap}, a proxy for EC mass as shown in SI Figure S1b) shows trends similar to PM scattering. For example, for pellet and pellet-high stoves, 40% and 54% of total BC emissions occur within the first quintile of testing (compared to 33% and 50% for B_{sp}). For pellet-high stoves, BC emissions remain steady after ignition, and then occur in two distinct bumps near the end of testing (Figure 2c), similar to PM scattering. BC emissions for wood stoves are steady near the beginning of testing, and then increase as the test continues (i.e., during steady flaming conditions) (Figure 2f). Charcoal BC emissions occur predominantly during and following ignition (Figure 2i), similar to PM, with 62% of BC emitted within the first quintile of test duration.

These time-resolved emissions plots are consistent with first-hand observations during testing. For example, pellet stove operation during the beginning and end of cooking phases was critical in affecting visible emissions. During ignition, use of too much kerosene would result in small plumes of black smoke, whereas too little kerosene would mean a longer ignition time. Especially important was the period towards the end of cooking where refueling or burnout and disposal of the pellets could result in high visible emissions, reflected in the pellet PM scattering and BC trends ("bumps") seen in Figure 2 (and indicated in Figure S13 for the Pellet-high tests). If the pellets were nearly all consumed, and the fan left to run, this would often result in high visible emissions until the combustion chamber (with remaining pellets and char) was removed and the pellets transported outside. These findings reinforce the importance of proper pellet stove operation.

Real-time Optical Properties

Figure 3 shows PaRTED plots[12,35] for the three stove types tested. Lower SSA (left on the horizontal axis) indicates more contribution from absorption to total aerosol light extinction. Higher MCE (up on the vertical axis) represents more efficient combustion. Pellet stoves operated at high MCE (median MCE ± IQR: 0.98 ± 0.02) and emitted PM of highly variable SSA. A cluster in the top-right portion of Figure 3 for pellet stoves shows highly scattering PM emitted at high MCE: 41% of PM emissions occurred at high MCE (>0.90) and between SSA of 0.7 and 1.0. When stratified into Pellet-high and Pellet-low (i.e., non high-emitting) tests, as plotted in SI Figure S14, it is evident that Pellet-high tests emitted highly scattering PM (69% of pellet-high PM had SSA>0.5), and contribute substantially to the high MCE/SSA cluster in Figure 3.

Wood stoves operated at a lower MCE (0.92 ± 0.02) and also emitted PM with widely variable SSA, with a tendency for lower SSA with increasing MCE (as observed by a negative slope in the PaRTED plot distribution for wood). Wood stoves emitted 83% of PM at MCE < 0.90, suggesting that these low efficiency combustion events (occurring in the nominal "smoldering" mode) had outsized contributions to aerosol emissions. Charcoal stoves operated at the lowest MCE (0.85 ± 0.03) and emitted primarily scattering particles, as observed in the clusters between SSA of 0.8 and 1.0, accounting for 71% of PM emitted. The trend observed for the wood tests are similar to those from a previous study of wood burning TSF.[12]

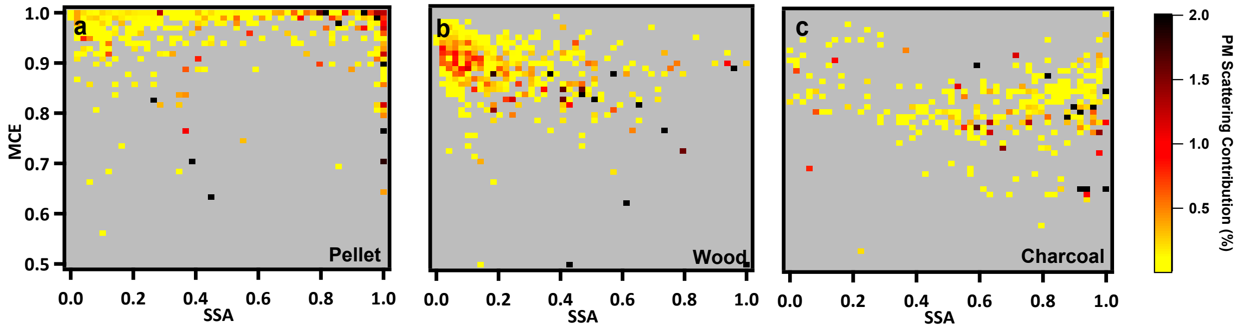

Figure 3. Bivariate histogram (PaRTED) plots showing distribution of PM (fraction of total aerosol scattering) as a function of MCE and SSA at the time of emission for pellet (a), wood (b), and charcoal (c) stoves.

PaRTED plots weighted by estimated fuel consumption (represented by the sum of net CO and CO_2 IEFs) as opposed to PM scattering are shown in SI Figure S15. These plots show different clustering compared to that of Figure 3. Pellet stove PM are not clustered in the high SSA region of the plot, but are rather relatively uniformly spread across SSA space. For wood stoves, there exists a distinct cluster around MCE of 0.9 and SSA of 0.15. Therefore, the vast majority of wood fuel consumption resulted in a highly absorbing aerosol emitted at the nominal transition between flaming and smoldering combustion (where MCE ≈ 0.9). For charcoal, fuel use was uniformly dispersed across SSA, similar to pellet stoves, but at substantially lower MCE.

Health and Climate Cobenefits of Cookstove Options

Figure 4 plots estimated daily PM intake (primary horizontal axis) and GWC (vertical axis) associated with the cookstove types tested in this study (using field emissions data). For comparison, we also include estimates for other representative stove/fuel combinations (wood forced-draft, gasifier, rocket, and TSF, charcoal, and LPG) based on laboratory test data and for unprocessed biomass used in a forced draft stove from field emission measurements.[12] Three scenarios were modeled for pellet stoves assuming: 1) default nonrenewable biomass fraction for Rwanda (f_{NRB}=98%) and pellet manufacturing facility electricity demand provided by hydropower (i.e., no upstream emissions), 2) f_{NRB}=98% and facility electricity demand provided by diesel generators (upstream emissions estimated using literature emissions data for diesel generator set), and 3) f_{NRB}=0% (i.e., treating sawdust feedstock as a ‘fully renewable’ waste product as opposed to biomass consumed) and facility electricity demand provided by hydropower. Scenarios 1 and 2 are plotted as solid red circles, while scenario 3 is plotted as a red square. Scenario 3 (i.e., 100% renewable fuel) is also plotted for wood and charcoal stoves with square markers.

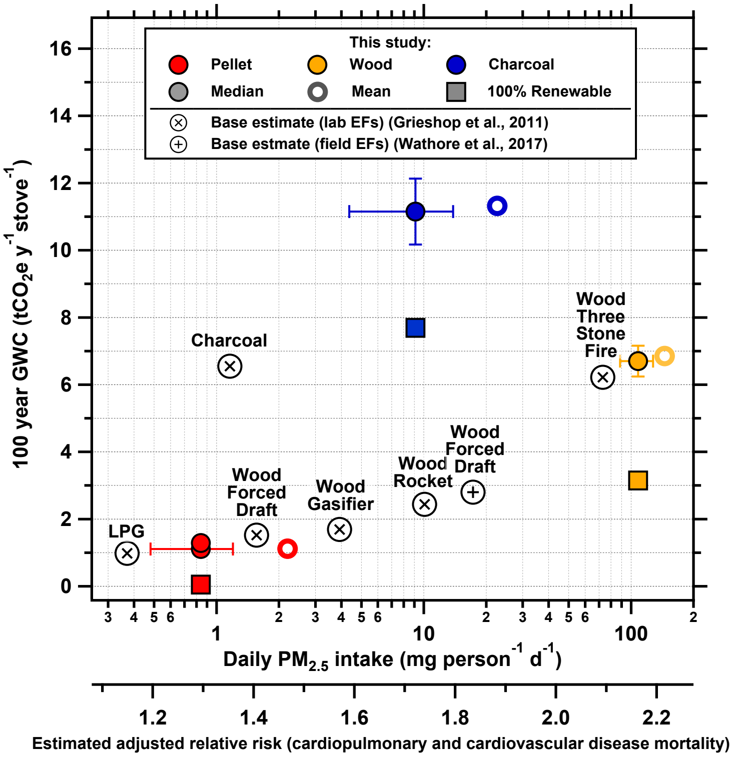

Figure 4. Estimated health and climate impacts of fuel/cookstove combinations measured in this study (colored points) and based on laboratory-based emission measurements (markers with ‘X’) of Wood, Charcoal, and LPG Stoves and field-based measurements of a gasifier stove burning unprocessed biomass (marker with ‘+’). Errors bars represent the 90% confidence interval for estimated impacts, due to the range of emission factors measured (for study stove types). Colored circles for ‘Pellet’ and ‘Charcoal’ include estimated upstream emissions from fuel production (also included for LPG; assumed negligible for wood); the upper circle for the ‘Pellet’ case represents ‘Scenario 2’ in which pellet production is assumed to be powered by electricity from a diesel generator.

Pellet stoves are associated with substantially lower estimated health impacts than the wood and charcoal stoves tested, as well as all estimated wood ICS types. Our field emissions results suggest that pellet stoves have the potential to provide health cobenefits approaching LPG, the current “gold standard” in terms of reducing cookstove pollutant exposures. Estimated daily $PM_{2.5}$ intake using median EFs is approximately a factor of two higher than for LPG, corresponding to an estimated adjusted relative risk (RR) for cardiopulmonary and cardiovascular disease mortality of 1.3 vs. 1.2 for pellet vs. LPG, respectively. Compared to previous field observations of a similar advanced ICS using unprocessed biomass ('Wood Forced Draft'; Philips), pellet stoves provide a reduction in estimated RR from 1.8 to 1.3. Estimated health impacts for unimproved wood EFs from this study were similar to wood TSF values from lab results, with the greater impacts reflecting the poorer emissions performance in field versus lab testing. Charcoal health impacts were significantly greater than those estimated based on laboratory charcoal EFs, largely driven by the high start-up emissions observed for these stoves during our tests (Figure 2h) that are likely not present during lab testing. However, even these high-emitting charcoal stoves reduce estimated daily $PM_{2.5}$ intake by an order of magnitude relative to wood stoves, with a corresponding RR reduction of 0.5.

In terms of estimated climate impacts, pellet stoves are similar to LPG in scenario 1 (median GWC of 1.2 vs. 0.98 $tCO_2e\ y^{-1}\ stove^{-1}$ for pellet vs. LPG), because of the high f_{NRB} assumed for Rwanda. A 'worst case' estimate of pellet climate impacts (scenario 2) increases the GWC by 15%. However, if the sawdust feedstock is considered as renewable (as in scenario 3), climate impacts are negligible due to the low emissions of the pellet stove and the consumption of a "waste" feedstock. Bailis et al.[53] reports a range of f_{NRB} for Rwanda from 52-65%, suggesting greater biomass renewability and subsequently lower climate impacts from all stove options; for pellet stoves this would result in GWC values roughly in the middle of scenarios 1 and 3. Estimated climate impacts for wood stoves were similar to lab-based wood TSF values. Charcoal stoves have the highest GWC, largely due to the upstream impacts (i.e., inefficient kiln-based pyrolysis) from charcoal production.[36]

Figure 4 shows that moving from a traditional TSF to wood ICS (rocket type) has the potential to yield significant reductions in terms of estimated health risk, though in reality this potential is often not realized.[8,13] Progressing further towards advanced wood ICS (gasifier and forced draft), further reductions in $PM_{2.5}$ intake are realized, though again the field results indicate that this potential is often not reached. Finally, within forced-draft wood gasifier stoves, the use of a homogenous fuel supply (pellets) yields cobenefits significantly greater compared to a non-homogenous fuel, and approaching that of an LPG stove. Therefore, in-use emissions data from pellet stoves suggest: 1) fuel homogenization can reduce $PM_{2.5}$ exposures by more than an order of magnitude, 2) this stove type has the potential to offer health benefits approaching those from modern fueled stoves, and 3) given a sustainably harvested feedstock, these pellet-fed gasifiers are essentially carbon-neutral.

Implications

There has been a major push to promote modern appliances (e.g., electrical induction, LPG) as opposed to solid biomass ICS. This is due to the tendency of field ICS to not yield expected exposure reductions, for example because field performance does not reach that observed during laboratory testing.[16] However these modern technologies are, and will likely remain, unattainable for the world's poorest.[15] In Rwanda for example, it is estimated that rural residents are willing to spend on average \$2.50 for an ICS[24] compared to the typical upfront cost of ~\$30 (and the requirement to purchase fuel) for an LPG stove. With roughly 70% of rural Rwandan homes gathering firewood as their primary cooking fuel, little money is typically spent on cooking fuel (though charcoal production contributes substantially to the rural economy).[24] Therefore, advanced technologies such as LPG are likely out of reach for many Rwandans. A solid-fuel/cookstove combination capable of significant emissions reductions may serve as a "bridge" for resource-constrained communities to move towards clean and climate-neutral household energy. This is especially true in urban and peri-urban areas where households already expend substantial resources for charcoal purchase.

Our results show that the Mimi Moto pellet stove may provide enormous emissions reductions compared to traditional wood and charcoal stoves, and health and climate cobenefits far above other biomass stoves that have been deployed in the field, and approaching those offered by LPG. In a renewable fuel use scenario, we estimate this fuel/stove combination to have negligible climate impacts. In the current study, the Mimi Moto met revised ISO/IWA Tier 4 and 5 designations for indoor emissions during in-use testing of $PM_{2.5}$ and CO, respectively, a first for a solid biomass cookstove tested in the field. Homogeneity of the fuel supply (i.e., pelletizing) undoubtedly contributes to the low emissions observed here. Use of pellets, where available, in other forced-draft gasifier stoves (e.g., Philips HD4012-LS) may result in similar emissions performance. Forced draft stoves using raw biomass have not met the potential shown based on laboratory data (Figure 4). For example, field measurements by Coffey et al.[27] and Wathore et al.[12] yielded CO EFs 2-3 times greater, and $PM_{2.5}$ EFs ~5 times higher than those observed in lab testing. Therefore, fuel heterogeneity represents a major obstacle for performance of an advanced solid fuel cookstove such as the Philips forced-draft gasifier. Although the Philips and Mimi Moto stoves vary in design (e.g., the Mimi Moto features a removable combustion chamber to simplify refueling), our study suggests that the homogenization of fuel supply represents a critical step to reduce the "gap" between lab and field performance, and overall emissions.

If the use of biomass is the most viable option (as opposed to adoption of LPG or electricity) for a given community given socioeconomic constraints, there exists a need to focus on the stove/fuel system as opposed to the stove alone. This has implications for local scale industry, as there then exists the need to manufacture and distribute the fuel (e.g., pellets), offering possible economic opportunities via small- or medium-scale industry. Another advantage would be the decoupling of fuel supply from global markets and volatile fuel prices, though there are other issues such as the need for biomass supply, an industrial base, reliable power, and the infrastructure for fuel distribution. Our results focus on a relatively small-scale demonstration and show great potential. However, meeting this potential at a larger scale will require meeting key challenges including the complete adoption of the technology and scale up in Rwanda and beyond.[54] A recent set of studies in China has highlighted challenges related to fuel production,[55] adoption,[56] and net impacts on household air pollution[57] to show that even high-performing stoves in an industrialized nation face complex obstacles to reach their expected performance and level of use.

An additional caveat highlighted by our study is that when operated incorrectly, pellet-fed gasifier stoves may have emissions performance similar to traditional wood and charcoal stoves. Field observations highlighted the importance of the ignition, refueling, and burnout phases of operation, when the stove is most likely to perform poorly. Therefore, the educational program provided by Inyenyeri may be improved to highlight the importance of using kerosene as opposed to kindling, to urge customers to monitor their stoves during refueling and towards the end of cooking, and to properly dispose of pellet char as opposed to letting it smolder. With initial field observations of the Mimi Moto in Rwanda promising, and the business model of Inyenyeri continuing to be refined and documented,[21] the stove and enterprise may be able to provide customers with health and climate benefits that are cost competitive with other fuels in this nation, as well as others with similar socioeconomic constraints.

Supplemental Information

The Supplemental Information (SI) provides description of the filter analysis and data quality assurance protocols, black carbon loading correction, emission factor/rates calculations and associated uncertainties, PaRTED analysis methods, GWC and PM intake assumptions and calculations, as well as summarized and tabulated emission metrics from cited studies. Additionally, SI figures report study average PM optical properties, fuel consumption rates and test durations, PM and CO EFs and ERs plotted with IWA tiers, test-wide PM and CO EF CDFs, seasonality of emissions, PaRTED results for Pellet-low and Pellet-high tests and for all stoves weighted by fuel consumption, and photos of typical stoves tested in the study. A separate XLSX file includes information on all individual tests (e.g. test conditions, emission factors).

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References

(1) Bonjour, S.; Adair-rohani, H.; Wolf, J.; Bruce, N. G.; Mehta, S.; Prüss-ustün, A.; Lahiff,

M.; Rehfuess, E. A.; Mishra, V.; Smith, K. R. Solid Fuel Use for Household Cooking : Country and Regional Estimates for 1980 – 2010. *Environ. Health Perspect.* **2013**, *121* (7), 784–790. https://doi.org/10.1289/ehp.1205987.

(2) Chafe, Z. A.; Brauer School of Population and Public Health, U. of B. C. V. B. C. C. M.; Klimont, Z.; Van Dingenen, R.; Mehta, S.; Rao, S.; Riahi, K.; Dentener, F.; Smith, K. R. Household Cooking with Solid Fuels Contributes to Ambient PM2.5 Air Pollution and the Burden of Disease. *Environ. Health Perspect.* **2014**, *122* (12), 1314–1320. https://doi.org/10.1289/ehp.1206340.

(3) Apte, J. S.; Brauer, M.; Cohen, A. J.; Ezzati, M.; Pope, C. A. Ambient PM2.5 Reduces Global and Regional Life Expectancy. *Environ. Sci. Technol. Lett.* **2018**, *5* (9), 546–551. https://doi.org/10.1021/acs.estlett.8b00360.

(4) Burnett, R.; Chen, H.; Szyszkowicz, M.; Fann, N.; Hubbell, B.; Pope, C. A.; Apte, J. S.; Brauer, M.; Cohen, A.; Weichenthal, S.; Coggins, J.; Di, Q.; Brunekreef, B.; Frostad, J.; Lim, S. S.; Kan, H.; Walker, K. D.; Thurston, G. D.; Hayes, R. B.; Lim, C. C.; Turner, M. C.; Jerrett, M.; Krewski, D.; Gapstur, S. M.; Diver, W. R.; Ostro, B.; Goldberg, D.; Crouse, D. L.; Martin, R. V.; Peters, P.; Pinault, L.; Tjepkema, M.; van Donkelaar, A.; Villeneuve, P. J.; Miller, A. B.; Yin, P.; Zhou, M.; Wang, L.; Janssen, N. A. H.; Marra, M.; Atkinson, R. W.; Tsang, H.; Quoc Thach, T.; Cannon, J. B.; Allen, R. T.; Hart, J. E.; Laden, F.; Cesaroni, G.; Forastiere, F.; Weinmayr, G.; Jaensch, A.; Nagel, G.; Concin, H.; Spadaro, J. V. Global Estimates of Mortality Associated with Long-Term Exposure to Outdoor Fine Particulate Matter. *Proc. Natl. Acad. Sci.* **2018**, *115* (38), 9592–9597. https://doi.org/10.1073/pnas.1803222115.

(5) Forouzanfar, M. H.; Alexander, L.; Anderson, H. R.; Bachman, V. F.; Biryukov, S.; Brauer, M.; Burnett, R.; Casey, D.; Coates, M. M.; Cohen, A.; Delwiche, K.; Estep, K.; Frostad, J. J.; Astha, K. C.; Kyu, H. H.; Moradi-Lakeh, M.; Ng, M.; Slepak, E. L.; Thomas, B. A.; Wagner, J.; Aasvang, G. M.; Abbafati, C.; Abbasoglu Ozgoren, A.; Abd-Allah, F.; Abera, S. F.; Aboyans, V.; Abraham, B.; Puthenpurakal Abraham, J.; Abubakar, I.; Abu-Rmeileh, N. M. E.; Aburto, T. C.; Achoki, T.; Adelekan, A.; Adofo, K.; Adou, A. K.; Adsuar, J. C.; Afshin, A.; Agardh, E. E.; Al Khabouri, M. J.; Al Lami, F. H.; Alam, S. S.; Alasfoor, D.; Albittar, M. I.; Alegretti, M. A.; Aleman, A. V.; Alemu, Z. A.; Alfonso-Cristancho, R.; Alhabib, S.; Ali, R.; Ali, M. K.; Alla, F.; Allebeck, P.; Allen, P. J.; Alsharif, U.; Alvarez, E.; Alvis-Guzman, N.; Amankwaa, A. A.; Amare, A. T.; Ameh, E. A.; Ameli, O.; Amini, H.; Ammar, W.; Anderson, B. O.; Antonio, C. A. T.; Anwari, P.; Argeseanu Cunningham, S.; Arnlöv, J.; Arsic Arsenijevic, V. S.; Artaman, A.; Asghar, R. J.; Assadi, R.; Atkins, L. S.; Atkinson, C.; Avila, M. A.; Awuah, B.; Badawi, A.; Bahit, M. C.; Bakfalouni, T.; Balakrishnan, K.; Balalla, S.; Balu, R. K.; Banerjee, A.; Barber, R. M.; Barker-Collo, S. L.; Barquera, S.; Barregard, L.; Barrero, L. H.; Barrientos-Gutierrez, T.; Basto-Abreu, A. C.; Basu, A.; Basu, S.; Basulaiman, M. O.; Batis Ruvalcaba, C.; Beardsley, J.; Bedi, N.; Bekele, T.; Bell, M. L.; Benjet, C.; Bennett, D. A.; Benzian, H.; Bernabé, E.; Beyene, T. J.; Bhala, N.; Bhalla, A.; Bhutta, Z. A.; Bikbov, B.; Bin Abdulhak, A. A.; Blore, J. D.; Blyth, F. M.; Bohensky, M. A.; Bora Basara, B.; Borges, G.; Bornstein, N. M.; Bose, D.; Boufous, S.; Bourne, R. R.; Brainin, M.; Brazinova, A.; Breitborde, N. J.; Brenner, H.; Briggs, A. D. M.; Broday, D. M.; Brooks, P. M.; Bruce, N. G.; Brugha, T. S.; Brunekreef, B.; Buchbinder, R.; Bui, L. N.; Bukhman, G.; Bulloch, A. G.; Burch, M.; Burney, P. G. J.; Campos-Nonato, I. R.; Campuzano, J. C.; Cantoral, A. J.; Caravanos, J.; Cárdenas, R.; Cardis, E.; Carpenter, D. O.; Caso, V.; Castañeda-Orjuela, C. A.; Castro, R. E.; Catalá-López, F.; Cavalleri, F.;

Çavlin, A.; Chadha, V. K.; Chang, J. C.; Charlson, F. J.; Chen, H.; Chen, W.; Chen, Z.; Chiang, P. P.; Chimed-Ochir, O.; Chowdhury, R.; Christophi, C. A.; Chuang, T. W.; Chugh, S. S.; Cirillo, M.; Claßen, T. K. D.; Colistro, V.; Colomar, M.; Colquhoun, S. M.; Contreras, A. G.; Cooper, C.; Cooperrider, K.; Cooper, L. T.; Coresh, J.; Courville, K. J.; Criqui, M. H.; Cuevas-Nasu, L.; Damsere-Derry, J.; Danawi, H.; Dandona, L.; Dandona, R.; Dargan, P. I.; Davis, A.; Davitoiu, D. V.; Dayama, A.; De Castro, E. F.; De La Cruz-Góngora, V.; De Leo, D.; De Lima, G.; Degenhardt, L.; Del Pozo-Cruz, B.; Dellavalle, R. P.; Deribe, K.; Derrett, S.; Des Jarlais, D. C.; Dessalegn, M.; DeVeber, G. A.; Devries, K. M.; Dharmaratne, S. D.; Dherani, M. K.; Dicker, D.; Ding, E. L.; Dokova, K.; Dorsey, E. R.; Driscoll, T. R.; Duan, L.; Durrani, A. M.; Ebel, B. E.; Ellenbogen, R. G.; Elshrek, Y. M.; Endres, M.; Ermakov, S. P.; Erskine, H. E.; Eshrati, B.; Esteghamati, A.; Fahimi, S.; Faraon, E. J. A.; Farzadfar, F.; Fay, D. F. J.; Feigin, V. L.; Feigl, A. B.; Fereshtehnejad, S. M.; Ferrari, A. J.; Ferri, C. P.; Flaxman, A. D.; Fleming, T. D.; Foigt, N.; Foreman, K. J.; Fra Paleo, U.; Franklin, R. C.; Gabbe, B.; Gaffikin, L.; Gakidou, E.; Gamkrelidze, A.; Gankpé, F. G.; Gansevoort, R. T.; García-Guerra, F. A.; Gasana, E.; Geleijnse, J. M.; Gessner, B. D.; Gething, P.; Gibney, K. B.; Gillum, R. F.; Ginawi, I. A. M.; Giroud, M.; Giussani, G.; Goenka, S.; Goginashvili, K.; Gomez Dantes, H.; Gona, P.; Gonzalez De Cosio, T.; González-Castell, D.; Gotay, C. C.; Goto, A.; Gouda, H. N.; Guerrant, R. L.; Gugnani, H. C.; Guillemin, F.; Gunnell, D.; Gupta, R.; Gupta, R.; Gutiérrez, R. A.; Hafezi-Nejad, N.; Hagan, H.; Hagstromer, M.; Halasa, Y. A.; Hamadeh, R. R.; Hammami, M.; Hankey, G. J.; Hao, Y.; Harb, H. L.; Haregu, T. N.; Haro, J. M.; Havmoeller, R.; Hay, S. I.; Hedayati, M. T.; Heredia-Pi, I. B.; Hernandez, L.; Heuton, K. R.; Heydarpour, P.; Hijar, M.; Hoek, H. W.; Hoffman, H. J.; Hornberger, J. C.; Hosgood, H.; Hoy, D. G.; Hsairi, M.; Hu, G.; Hu, H.; Huang, C.; Huang, J. J.; Hubbell, B. J.; Huiart, L.; Husseini, A.; Iannarone, M. L.; Iburg, K. M.; Idrisov, B. T.; Ikeda, N.; Innos, K.; Inoue, M.; Islami, F.; Ismayilova, S.; Jacobsen, K. H.; Jansen, H. A.; Jarvis, D. L.; Jassal, S. K.; Jauregui, A.; Jayaraman, S.; Jeemon, P.; Jensen, P. N.; Jha, V.; Jiang, F.; Jiang, G.; Jiang, Y.; Jonas, J. B.; Juel, K.; Kan, H.; Kany Roseline, S. S.; Karam, N. E.; Karch, A.; Karema, C. K.; Karthikeyan, G.; Kaul, A.; Kawakami, N.; Kazi, D. S.; Kemp, A. H.; Kengne, A. P.; Keren, A.; Khader, Y. S.; Ali Hassan Khalifa, S. E.; Khan, E. A.; Khang, Y. H.; Khatibzadeh, S.; Khonelidze, I.; Kieling, C.; Kim, D.; Kim, S.; Kim, Y.; Kimokoti, R. W.; Kinfu, Y.; Kinge, J. M.; Kissela, B. M.; Kivipelto, M.; Knibbs, L. D.; Knudsen, A. K.; Kokubo, Y.; Kose, M. R.; Kosen, S.; Kraemer, A.; Kravchenko, M.; Krishnaswami, S.; Kromhout, H.; Ku, T.; Kuate Defo, B.; Kucuk Bicer, B.; Kuipers, E. J.; Kulkarni, C.; Kulkarni, V. S.; Kumar, G. A.; Kwan, G. F.; Lai, T.; Lakshmana Balaji, A.; Lalloo, R.; Lallukka, T.; Lam, H.; Lan, Q.; Lansingh, V. C.; Larson, H. J.; Larsson, A.; Laryea, D. O.; Lavados, P. M.; Lawrynowicz, A. E.; Leasher, J. L.; Lee, J. T.; Leigh, J.; Leung, R.; Levi, M.; Li, Y.; Li, Y.; Liang, J.; Liang, X.; Lim, S. S.; Lindsay, M. P.; Lipshultz, S. E.; Liu, S.; Liu, Y.; Lloyd, B. K.; Logroscino, G.; London, S. J.; Lopez, N.; Lortet-Tieulent, J.; Lotufo, P. A.; Lozano, R.; Lunevicius, R.; Ma, J.; Ma, S.; Machado, V. M. P.; MacIntyre, M. F.; Magis-Rodriguez, C.; Mahdi, A. A.; Majdan, M.; Malekzadeh, R.; Mangalam, S.; Mapoma, C. C.; Marape, M.; Marcenes, W.; Margolis, D. J.; Margono, C.; Marks, G. B.; Martin, R. V.; Marzan, M. B.; Mashal, M. T.; Masiye, F.; Mason-Jones, A. J.; Matsushita, K.; Matzopoulos, R.; Mayosi, B. M.; Mazorodze, T. T.; McKay, A. C.; McKee, M.; McLain, A.; Meaney, P. A.; Medina, C.; Mehndiratta, M. M.; Mejia-Rodriguez, F.; Mekonnen, W.; Melaku, Y. A.; Meltzer, M.; Memish, Z. A.; Mendoza, W.; Mensah, G. A.; Meretoja, A.; Apolinary Mhimbira, F.; Micha, R.; Miller, T. R.; Mills,

E. J.; Misganaw, A.; Mishra, S.; Mohamed Ibrahim, N.; Mohammad, K. A.; Mokdad, A. H.; Mola, G. L.; Monasta, L.; Montañez Hernandez, J. C.; Montico, M.; Moore, A. R.; Morawska, L.; Mori, R.; Moschandreas, J.; Moturi, W. N.; Mozaffarian, D.; Mueller, U. O.; Mukaigawara, M.; Mullany, E. C.; Murthy, K. S.; Naghavi, M.; Nahas, Z.; Naheed, A.; Naidoo, K. S.; Naldi, L.; Nand, D.; Nangia, V.; Narayan, K. M. V.; Nash, D.; Neal, B.; Nejjari, C.; Neupane, S. P.; Newton, C. R.; Ngalesoni, F. N.; Ngirabega, J. D. D.; Nguyen, G.; Nguyen, N. T.; Nieuwenhuijsen, M. J.; Nisar, M. I.; Nogueira, J. R.; Nolla, J. M.; Nolte, S.; Norheim, O. F.; Norman, R. E.; Norrving, B.; Nyakarahuka, L.; Oh, I. H.; Ohkubo, T.; Olusanya, B. O.; Omer, S. B.; Opio, J. N.; Orozco, R.; Pagcatipunan, R. S.; Pain, A. W.; Pandian, J. D.; Panelo, C. I. A.; Papachristou, C.; Park, E. K.; Parry, C. D.; Paternina Caicedo, A. J.; Patten, S. B.; Paul, V. K.; Pavlin, B. I.; Pearce, N.; Pedraza, L. S.; Pedroza, A.; Pejin Stokic, L.; Pekericli, A.; Pereira, D. M.; Perez-Padilla, R.; Perez-Ruiz, F.; Perico, N.; Perry, S. A. L.; Pervaiz, A.; Pesudovs, K.; Peterson, C. B.; Petzold, M.; Phillips, M. R.; Phua, H. P.; Plass, D.; Poenaru, D.; Polanczyk, G. V.; Polinder, S.; Pond, C. D.; Pope, C. A.; Pope, D.; Popova, S.; Pourmalek, F.; Powles, J.; Prabhakaran, D.; Prasad, N. M.; Qato, D. M.; Quezada, A. D.; Quistberg, D. A. A.; Racapé, L.; Rafay, A.; Rahimi, K.; Rahimi-Movaghar, V.; Ur Rahman, S.; Raju, M.; Rakovac, I.; Rana, S. M.; Rao, M.; Razavi, H.; Reddy, K. S.; Refaat, A. H.; Rehm, J.; Remuzzi, G.; Ribeiro, A. L.; Riccio, P. M.; Richardson, L.; Riederer, A.; Robinson, M.; Roca, A.; Rodriguez, A.; Rojas-Rueda, D.; Romieu, I.; Ronfani, L.; Room, R.; Roy, N.; Ruhago, G. M.; Rushton, L.; Sabin, N.; Sacco, R. L.; Saha, S.; Sahathevan, R.; Sahraian, M. A.; Salomon, J. A.; Salvo, D.; Sampson, U. K.; Sanabria, J. R.; Sanchez, L. M.; Sánchez-Pimienta, T. G.; Sanchez-Riera, L.; Sandar, L.; Santos, I. S.; Sapkota, A.; Satpathy, M.; Saunders, J. E.; Sawhney, M.; Saylan, M. I.; Scarborough, P.; Schmidt, J. C.; Schneider, I. J. C.; Schöttker, B.; Schwebel, D. C.; Scott, J. G.; Seedat, S.; Sepanlou, S. G.; Serdar, B.; Servan-Mori, E. E.; Shaddick, G.; Shahraz, S.; Shamah Levy, T.; Shangguan, S.; She, J.; Sheikhbahaei, S.; Shibuya, K.; Shin, H. H.; Shinohara, Y.; Shiri, R.; Shishani, K.; Shiue, I.; Sigfusdottir, I. D.; Silberberg, D. H.; Simard, E. P.; Sindi, S.; Singh, A.; Singh, G. M.; Singh, J. A.; Skirbekk, V.; Sliwa, K.; Soljak, M.; Soneji, S.; Søreide, K.; Soshnikov, S.; Sposato, L. A.; Sreeramareddy, C. T.; Stapelberg, N. J. C.; Stathopoulou, V.; Steckling, N.; Stein, D. J.; Stein, M. B.; Stephens, N.; Stöckl, H.; Straif, K.; Stroumpoulis, K.; Sturua, L.; Sunguya, B. F.; Swaminathan, S.; Swaroop, M.; Sykes, B. L.; Tabb, K. M.; Takahashi, K.; Talongwa, R. T.; Tandon, N.; Tanne, D.; Tanner, M.; Tavakkoli, M.; Te Ao, B. J.; Teixeira, C. M.; Téllez Rojo, M. M.; Terkawi, A. S.; Texcalac-Sangrador, J. L.; Thackway, S. V.; Thomson, B.; Thorne-Lyman, A. L.; Thrift, A. G.; Thurston, G. D.; Tillmann, T.; Tobollik, M.; Tonelli, M.; Topouzis, F.; Towbin, J. A.; Toyoshima, H.; Traebert, J.; Tran, B. X.; Trasande, L.; Trillini, M.; Trujillo, U.; Tsala Dimbuene, Z.; Tsilimbaris, M.; Tuzcu, E. M.; Uchendu, U. S.; Ukwaja, K. N.; Uzun, S. B.; Van De Vijver, S.; Van Dingenen, R.; Van Gool, C. H.; Van Os, J.; Varakin, Y. Y.; Vasankari, T. J.; Vasconcelos, A. M. N.; Vavilala, M. S.; Veerman, L. J.; Velasquez-Melendez, G.; Venketasubramanian, N.; Vijayakumar, L.; Villalpando, S.; Violante, F. S.; Victorovich Vlassov, V.; Vollset, S. E.; Wagner, G. R.; Waller, S. G.; Wallin, M. T.; Wan, X.; Wang, H.; Wang, J. L.; Wang, L.; Wang, W.; Wang, Y.; Warouw, T. S.; Watts, C. H.; Weichenthal, S.; Weiderpass, E.; Weintraub, R. G.; Werdecker, A.; Wessells, K. R.; Westerman, R.; Whiteford, H. A.; Wilkinson, J. D.; Williams, H. C.; Williams, T. N.; Woldeyohannes, S. M.; Wolfe, C. D. A.; Wong, J. Q.; Woolf, A. D.; Wright, J. L.; Wurtz, B.; Xu, G.; Yan, L. L.; Yang, G.; Yano, Y.; Ye, P.; Yenesew, M.; Yentür, G. K.; Yip, P.;

Yonemoto, N.; Yoon, S. J.; Younis, M. Z.; Younoussi, Z.; Yu, C.; Zaki, M. E.; Zhao, Y.; Zheng, Y.; Zhou, M.; Zhu, J.; Zhu, S.; Zou, X.; Zunt, J. R.; Lopez, A. D.; Vos, T.; Murray, C. J.; Temesgen, A. M. Global, Regional, and National Comparative Risk Assessment of 79 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks in 188 Countries, 1990-2013: A Systematic Analysis for the Global Burden of Disease Study 2013. *Lancet* **2015**, *386* (10010), 2287–2323. https://doi.org/10.1016/S0140-6736(15)00128-2.

(6) Bond, T. C.; Doherty, S. J.; Fahey, D. W.; Forster, P. M.; Berntsen, T.; DeAngelo, B. J.; Flanner, M. G.; Ghan, S.; Kärcher, B.; Koch, D.; Kinne, S.; Kondo, Y.; Quinn, P. K.; Sarofim, M. C.; Schultz, M. G.; Schulz, M.; Venkataraman, C.; Zhang, H.; Zhang, S.; Bellouin, N.; Guttikunda, S. K.; Hopke, P. K.; Jacobson, M. Z.; Kaiser, J. W.; Klimont, Z.; Lohmann, U.; Schwarz, J. P.; Shindell, D.; Storelvmo, T.; Warren, S. G.; Zender, C. S. Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment. *J. Geophys. Res. Atmos.* **2013**, *118* (11), 5380–5552. https://doi.org/10.1002/jgrd.50171.

(7) Lacey, F. G.; Henze, D. K.; Lee, C. J.; van Donkelaar, A.; Martin, R. V. Transient Climate and Ambient Health Impacts Due to National Solid Fuel Cookstove Emissions. *Proc. Natl. Acad. Sci.* **2017**, *114* (6), 1269–1274. https://doi.org/10.1073/pnas.1612430114.

(8) Aung, T. W.; Jain, G.; Sethuraman, K.; Baumgartner, J.; Reynolds, C.; Grieshop, A. P.; Marshall, J. D.; Brauer, M. Health and Climate-Relevant Pollutant Concentrations from a Carbon-Finance Approved Cookstove Intervention in Rural India. *Environ. Sci. Technol.* **2016**, *50* (13), 7228–7238. https://doi.org/10.1021/acs.est.5b06208.

(9) Mortimer, K.; Ndamala, C. B.; Naunje, A. W.; Malava, J.; Katundu, C.; Weston, W.; Havens, D.; Pope, D.; Bruce, N. G.; Nyirenda, M.; Wang, D.; Crampin, A.; Grigg, J.; Balmes, J.; Gordon, S. B. A Cleaner Burning Biomass-Fuelled Cookstove Intervention to Prevent Pneumonia in Children under 5 Years Old in Rural Malawi (the Cooking and Pneumonia Study): A Cluster Randomised Controlled Trial. *Lancet* **2017**, *389* (10065), 167–175. https://doi.org/10.1016/S0140-6736(16)32507-7.

(10) Smith, K. R.; McCracken, J. P.; Weber, M. W.; Hubbard, A.; Jenny, A.; Thompson, L. M.; Balmes, J.; Diaz, A.; Arana, B.; Bruce, N. Effect of Reduction in Household Air Pollution on Childhood Pneumonia in Guatemala (RESPIRE): A Randomised Controlled Trial. *Lancet* **2011**, *378* (9804), 1717–1726. https://doi.org/10.1016/S0140-6736(11)60921-5.

(11) Roden, C. A.; Bond, T. C.; Conway, S.; Osorto Pinel, A. B.; MacCarty, N.; Still, D. Laboratory and Field Investigations of Particulate and Carbon Monoxide Emissions from Traditional and Improved Cookstoves. *Atmos. Environ.* **2009**, *43* (6), 1170–1181. https://doi.org/10.1016/j.atmosenv.2008.05.041.

(12) Wathore, R.; Mortimer, K.; Grieshop, A. P. In-Use Emissions and Estimated Impacts of Traditional, Natural- and Forced-Draft Cookstoves in Rural Malawi. *Environ. Sci. Technol.* **2017**, *51* (3), 1929–1938. https://doi.org/10.1021/acs.est.6b05557.

(13) Grieshop, A. P.; Jain, G.; Sethuraman, K.; Marshall, J. D. Emission Factors of Health- and Climate-Relevant Pollutants Measured in Home during a Carbon-Finance-Approved Cookstove Intervention in Rural India. *GeoHealth* **2017**, *1* (5), 222–236. https://doi.org/10.1002/2017GH000066.

(14) Steenland, K.; Pillarisetti, A.; Kirby, M.; Peel, J.; Clark, M.; Checkley, W.; Chang, H. H.; Clasen, T. Modeling the Potential Health Benefits of Lower Household Air Pollution after a Hypothetical Liquified Petroleum Gas (LPG) Cookstove Intervention. *Environ. Int.* **2018**, *111* (June 2017), 71–79. https://doi.org/10.1016/j.envint.2017.11.018.

(15) Rosenthal, J.; Quinn, A.; Grieshop, A. P.; Pillarisetti, A.; Glass, R. I. Clean Cooking and the SDGs: Integrated Analytical Approaches to Guide Energy Interventions for Health and Environment Goals. *Energy Sustain. Dev.* **2018**, *42*, 152–159. https://doi.org/10.1016/j.esd.2017.11.003.

(16) Smith, K. R.; Sagar, A. Making the Clean Available: Escaping India's Chulha Trap. *Energy Policy* **2014**, *75*, 410–414. https://doi.org/10.1016/j.enpol.2014.09.024.

(17) Puzzolo, E.; Pope, D.; Stanistreet, D.; Rehfuess, E. A.; Bruce, N. G. Clean Fuels for Resource-Poor Settings: A Systematic Review of Barriers and Enablers to Adoption and Sustained Use. *Environ. Res.* **2016**, *146*, 218–234. https://doi.org/10.1016/j.envres.2016.01.002.

(18) Johnson, M.; Chiang, R. A. Quantitative Guidance for Stove Usage and Performance to Achieve Health and Environmental Targets. *Environ. Health Perspect.* **2015**, *123* (8), 820–826. https://doi.org/10.1289/ehp.1408681.

(19) Das, I.; Pedit, J.; Handa, S.; Jagger, P. Household Air Pollution, Microenvironment and Child Health: Strategies for Mitigating HAP Exposure in Urban Rwanda. *Environ. Res. Lett.* **2018**. https://doi.org/10.1088/1748-9326/aab047.

(20) Clean Cooking Alliance. Clean Cooking Catalog: Mimi Moto http://catalog.cleancookstoves.org/stoves/434 (accessed Feb 9, 2018).

(21) Jagger, P.; Das, I. Implementation and Scale-up of a Biomass Pellet and Improved Cookstove Enterprise in Rwanda. *Energy Sustain. Dev.* **2018**, *46*, 32–41. https://doi.org/10.1016/j.esd.2018.06.005.

(22) The World Bank. *Clean and Improved Cooking in Sub-Saharan Africa*; Washington, D.C., 2014.

(23) Institute for Health Metrics and Evaluation. Country Profile: Rwanda http://www.healthdata.org/rwanda (accessed Jan 26, 2018).

(24) Clean Cooking Alliance. *Global Alliance for Clean Cookstoves: Rwanda Market Assessment*; 2012.

(25) The World Bank. International Comparison Program: GDP Per Capita https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD?view=chart&year_high_desc=true (accessed Feb 9, 2018).

(26) National Institute of Statistics of Rwanda. *District Profile*; 2015.

(27) Coffey, E. R.; Muvandimwe, D.; Hagar, Y.; Wiedinmyer, C.; Kanyomse, E.; Piedrahita, R.; Dickinson, K. L.; Oduro, A.; Hannigan, M. P. Implications of New Emission Factors and Efficiencies from In-Field Measurements of Traditional and Improved Cookstoves. *Environ. Sci. Technol.* **2017**, *51* (21), 12508–12517. https://doi.org/10.1021/acs.est.7b02436.

(28) Jetter, J.; Zhao, Y.; Smith, K. R.; Khan, B.; Yelverton, T.; Decarlo, P.; Hays, M. D. Pollutant Emissions and Energy Efficiency under Controlled Conditions for Household Biomass Cookstoves and Implications for Metrics Useful in Setting International Test Standards. *Environ. Sci. Technol.* **2012**, *46* (19), 10827–10834. https://doi.org/10.1021/es301693f.

(29) Johnson, M.; Edwards, R.; Alatorre Frenk, C.; Masera, O. In-Field Greenhouse Gas Emissions from Cookstoves in Rural Mexican Households. *Atmos. Environ.* **2008**, *42* (6), 1206–1222. https://doi.org/10.1016/j.atmosenv.2007.10.034.

(30) Subramanian, R.; Khlystov, A. Y.; Cabada, J. C.; Robinson, A. L. Positive and Negative Artifacts in Particulate Organic Carbon Measurements with Denuded and Undenuded Sampler Configurations Special Issue of Aerosol Science and Technology on Findings from

the Fine Particulate Matter Supersites Program. *Aerosol Sci. Technol.* **2004**, *38*, 27–48. https://doi.org/10.1080/02786820390229354.

(31) Park, S. S.; Hansen, A. D. A.; Cho, S. Y. Measurement of Real Time Black Carbon for Investigating Spot Loading Effects of Aethalometer Data. *Atmos. Environ.* **2010**, *44* (11), 1449–1455. https://doi.org/10.1016/j.atmosenv.2010.01.025.

(32) Smith, K. R.; Khalil, M. A. K.; Rasmussen, R. A.; Thorneloe, S. A.; Manegdeg, F.; Apte, M. Greenhouse Gases from Biomass and Fossil-Fuel Stoves in Developing Countries: A Manila Pilot Study. *Chemosphere* **1993**, *26*, 479–505. https://doi.org/10.1016/0045-6535(93)90440-G.

(33) Roden, C. A.; Bond, T. C.; Conway, S.; Osorto Pinel, A. B. Emission Factors and Real-Time Optical Properties of Particles Emitted from Traditional Wood Burning Cookstoves. *Environ. Sci. Technol.* **2006**, *40* (21), 6750–6757. https://doi.org/10.1021/es052080i.

(34) Preble, C. V.; Hadley, O. L.; Gadgil, A. J.; Kirchstetter, T. W. Emissions and Climate-Relevant Optical Properties of Pollutants Emitted from a Three-Stone Fire and the Berkeley-Darfur Stove Tested under Laboratory Conditions. *Environ. Sci. Technol.* **2014**, *48* (11), 6484–6491. https://doi.org/10.1021/es5002715.

(35) Chen, Y.; Roden, C. A.; Bond, T. C. Characterizing Biofuel Combustion with Patterns of Real-Time Emission Data (PaRTED). *Environ. Sci. Technol.* **2012**, *46* (11), 6110–6117. https://doi.org/10.1021/es3003348.

(36) Grieshop, A. P.; Marshall, J. D.; Kandlikar, M. Health and Climate Benefits of Cookstove Replacement Options. *Energy Policy* **2011**, *39* (12), 7530–7542. https://doi.org/10.1016/j.enpol.2011.03.024.

(37) Zhang, J.; Smith, K. .; Ma, Y.; Ye, S.; Jiang, F.; Qi, W.; Liu, P.; Khalil, M. A. .; Rasmussen, R. .; Thorneloe, S. . Greenhouse Gases and Other Airborne Pollutants from Household Stoves in China: A Database for Emission Factors. *Atmos. Environ.* **2000**, *34* (26), 4537–4549. https://doi.org/10.1016/S1352-2310(99)00450-1.

(38) Smith, K. R.; Uma, R.; Kishore, V. V. N.; Zhang, J.; Joshi, V.; Khalil, M. A. K. Greenhouse Implications of Household Stoves: An Analysis for India. *Annu. Rev. Energy Environ.* **2000**, *25* (1), 741–763. https://doi.org/10.1146/annurev.energy.25.1.741.

(39) Intergovernmental Panel on Climate Change. Default values of fraction of non-renewable biomass https://cdm.unfccc.int/DNA/fNRB/index.html.

(40) United Nations. Household Size and Composition Around the World. **2017**, 1. https://doi.org/10.1007/JHEP05(2012)157.

(41) Ndayambaje, J. D.; Mohren, G. M. J. Fuelwood Demand and Supply in Rwanda and the Role of Agroforestry. *Agrofor. Syst.* **2011**, *83* (3), 303–320. https://doi.org/10.1007/s10457-011-9391-6.

(42) Burnett, R. T.; Pope, C. A.; Ezzati, M.; Olives, C.; Lim, S. S.; Mehta, S.; Shin, H. H.; Singh, G.; Hubbell, B.; Brauer, M.; Anderson, H. R.; Smith, K. R.; Balmes, J. R.; Bruce, N. G.; Kan, H.; Laden, F.; Prüss-Ustün, A.; Turner, M. C.; Gapstur, S. M.; Diver, W. R.; Cohen, A. An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. *Environ. Health Perspect.* **2014**, *122* (4), 397–403. https://doi.org/10.1289/ehp.1307049.

(43) Haslett, S. L.; Thomas, J. C.; Morgan, W. T.; Hadden, R.; Liu, D.; Allan, J. D.; Williams, P. I.; Keita, S.; Liousse, C.; Coe, H. Highly Controlled, Reproducible Measurements of Aerosol Emissions from Combustion of a Common African Biofuel Source. *Atmos. Chem. Phys.* **2018**, *18* (1), 385–403. https://doi.org/10.5194/acp-18-385-2018.

(44) Sustainable Green Fuel Enterprise. *Comparative Fuel Testing for the Philips Stove (Model HD4012) - Cambodia*; 2013.

(45) Garland, C.; Delapena, S.; Prasad, R.; L'Orange, C.; Alexander, D.; Johnson, M. Black Carbon Cookstove Emissions: A Field Assessment of 19 Stove/Fuel Combinations. *Atmos. Environ.* **2017**, *169*, 140–149. https://doi.org/10.1016/j.atmosenv.2017.08.040.

(46) Rose Eilenberg, S.; Bilsback, K. R.; Johnson, M.; Kodros, J. K.; Lipsky, E. M.; Naluwagga, A.; Fedak, K. M.; Benka-Coker, M.; Reynolds, B.; Peel, J.; Clark, M.; Shan, M.; Sambandam, S.; L'Orange, C.; Pierce, J. R.; Subramanian, R.; Volckens, J.; Robinson, A. L. Field Measurements of Solid-Fuel Cookstove Emissions from Uncontrolled Cooking in China, Honduras, Uganda, and India. *Atmos. Environ.* **2018**, *190* (March), 116–125. https://doi.org/10.1016/j.atmosenv.2018.06.041.

(47) Lefebvre, O. *Household Air Pollution Study Part 1 Black Carbon Emission Factor Measurement for Ethanol Charcoal and Kerosene Stoves in Kibera Kenya*; 2016.

(48) World Health Organization. WHO Guidelines for Indoor Air Quality: Household Fuel Combustion https://www.who.int/airpollution/guidelines/household-fuel-combustion/recommendation1/en/ (accessed Apr 22, 2019).

(49) Carter, E. M.; Shan, M.; Yang, X.; Li, J.; Baumgartner, J. Pollutant Emissions and Energy Efficiency of Chinese Gasifier Cooking Stoves and Implications for Future Intervention Studies. *Environ. Sci. Technol.* **2014**, *48* (11), 6461–6467. https://doi.org/10.1021/es405723w.

(50) Pokhrel, R. P.; Wagner, N. L.; Langridge, J. M.; Lack, D. A.; Jayarathne, T.; Stone, E. A.; Stockwell, C. E.; Yokelson, R. J.; Murphy, S. M. Parameterization of Single-Scattering Albedo (SSA) and Absorption Ångström Exponent (AAE) with EC/OC for Aerosol Emissions from Biomass Burning. *Atmos. Chem. Phys.* **2016**, *16* (15), 9549–9561. https://doi.org/10.5194/acp-16-9549-2016.

(51) Lacey, F.; Henze, D. Global Climate Impacts of Country-Level Primary Carbonaceous Aerosol from Solid-Fuel Cookstove Emissions. *Environ. Res. Lett.* **2015**, *10* (11), 114003. https://doi.org/10.1088/1748-9326/10/11/114003.

(52) Fedak, K.; Good, N.; Dahlke, J.; Hecobian, A.; Sullivan, A.; Zhou, Y.; Peel, J.; Volckens, J. Chemical Composition and Emissions Factors for Cookstove Startup (Ignition) Materials. *Environ. Sci. Technol.* **2018**, *52*, 9505–9513. https://doi.org/10.1021/acs.est.8b02218.

(53) Bailis, R.; Drigo, R.; Ghilardi, A.; Masera, O. The Carbon Footprint of Traditional Woodfuels. *Nat. Clim. Chang.* **2015**, *5* (3), 266–272. https://doi.org/10.1038/nclimate2491.

(54) Seguin, R.; Flax, V. L.; Jagger, P. Barriers and Facilitators to Adoption and Use of Fuel Pellets and Improved Cookstoves in Urban Rwanda. *PLoS One* **2018**, *13* (10), 1–16. https://doi.org/10.1371/journal.pone.0203775.

(55) Carter, E.; Shan, M.; Zhong, Y.; Ding, W.; Zhang, Y.; Baumgartner, J.; Yang, X. Development of Renewable, Densified Biomass for Household Energy in China. *Energy Sustain. Dev.* **2018**, *46*, 42–52. https://doi.org/https://doi.org/10.1016/j.esd.2018.06.004.

(56) Snider, G.; Carter, E.; Clark, S.; Yang, X.; Ezzati, M.; Schauer, J. J.; Wiedinmyer, C.; Baumgartner, J. Impacts of Stove Use Patterns and Outdoor Air Quality on Household Air Pollution and Cardiovascular Mortality in Southwestern China. *Environ. Int.* **2018**, *117*, 116–124.

(57) Clark, S.; Carter, E.; Shan, M.; Ni, K.; Niu, H.; Tseng, J. T. W.; Pattanayak, S. K.; Jeuland, M.; Schauer, J. J.; Ezzati, M.; Wiedinmyer, C.; Yang, X.; Baumgartner, J. Adoption and Use of a Semi-Gasifier Cooking and Water Heating Stove and Fuel Intervention in the

Tibetan Plateau, China. *Environ. Res. Lett.* **2017**, *12* (7), 075004. https://doi.org/10.1088/1748-9326/aa751e.