Analyzing the costs and benefits of clean and improved cooking solutions

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EXECUTIVE SUMMARY

Approximately 40% of the global population relies on solid fuels such as coal, fuelwood, dung and charcoal and uses traditional stoves to meet household cooking and heating needs. Especially for the global rural poor, such traditional stoves offer key practical advantages; most notably, they can be constructed at home and the solid fuels they require can be collected from the neighboring environment. Unfortunately, it is increasingly apparent that these technologies and fuels have a range of negative effects on household well-being, on the local and regional environment, and on the global climate system.

In light of the negative effects of traditional stoves and solid fuels, increasing attention and resources are being directed into interventions that would aid a transition away from their use, and towards cleaner and improved cookstove (ICS) options. Yet important questions remain about the economics of such interventions and whether it makes sense for households to adopt potentially more expensive stoves and fuels in exchange for reductions in HAP and the drudgery of fuel collection.

This report aims to provide insights on some of the complications inherent in the household (and social) cost-benefit calculus of interventions to promote new cooking technologies and practices. The private household perspective is important because it indicates whether households are likely to adopt such technologies on their own, and which factors are most important in determining whether households will perceive ICS adoption to be beneficial to them. The social perspective, meanwhile, is important for highlighting the extent of the divergence between private and overall societal net benefits, due to the negative externalities generated by use of traditional options, and to make the case for additional policy intervention to correct for these externalities. The various costs and benefits included in each of these perspectives is summarized in Figure E1 (we model two social perspectives, the first of which neglects important climate-altering pollutants such as black carbon that are not currently included in carbon finance calculations). Our analysis relies on mathematical equations to represent these various costs and benefits as functions of a large number of parameters. Then, we implement a simulation-based approach that allows these parameters to vary according to what is documented in the peer-reviewed and, to a lesser extent, the practitioner literatures. This method accordingly produces a range and distribution of cost-benefit outcomes that would be plausible in the real world.

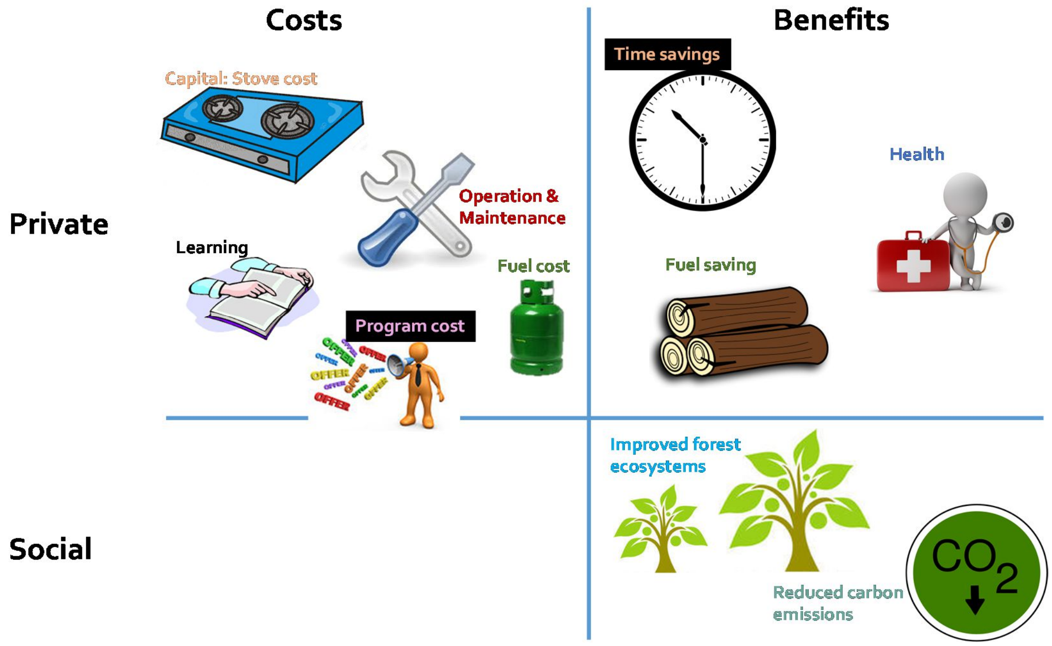

Figure E1. Private and social costs and benefits of improved cook stove interventions. Note: Intervention program cost may not always be privately-borne.

We find that the balance of costs and benefits of changes in cooking technologies is highly variable. From a private perspective, time and health contribute strongly to net benefits at mean parameter values (Figure E2). Meanwhile, the largest costs are the stove and promotion program costs, and, for those stoves requiring commercial fuels, fuel costs. In addition, all options look more attractive from a social perspective (Figure E3), especially if black carbon, organic carbon and carbon monoxide emissions of traditional stoves are included (electric stoves perform badly under a narrow emissions perspective).

These mean values mask considerable variation in outcomes across the Monte Carlo simulations, which show that at least half of all trials for the biomass, charcoal, and LPG ICS deliver negative net benefits from a household perspective, while electric stoves produce private net benefits in only 64% of trials. The range of outcomes between the 10^{th} and 90^{th} percentiles is large in all cases, spanning -\$6.9 to \$7.5/hh-month, depending on the technology (LPG has the widest range, and the biomass ICS is narrowest). Many of the parameters that contribute most heavily to this variation in private outcomes have to do with the extent of ICS use, time savings, fuel costs, and fuel efficiency, while parameters related to health gains play a somewhat lesser role. These results perhaps provide one explanation for why private adoption of ICS technologies remains low.

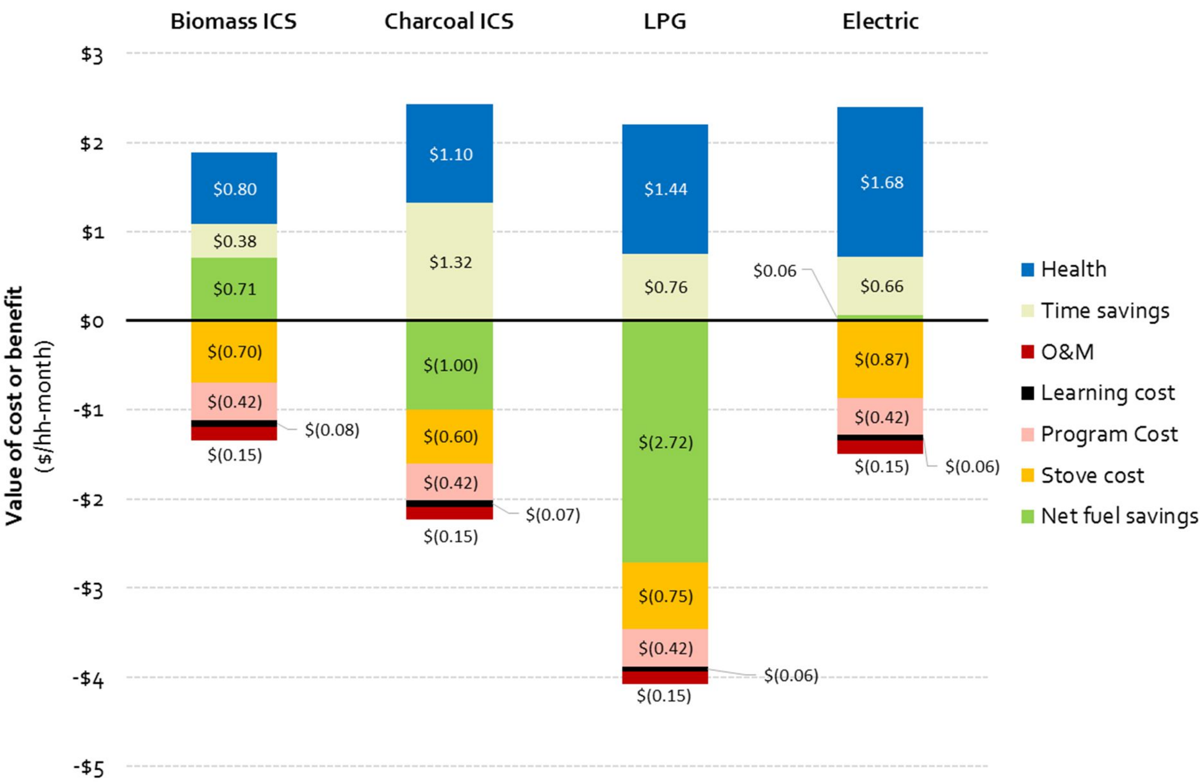

Figure E2. Composition of private costs and benefits for the five ICS options (<u>Note</u>: All parameters are set to mean simulation values)

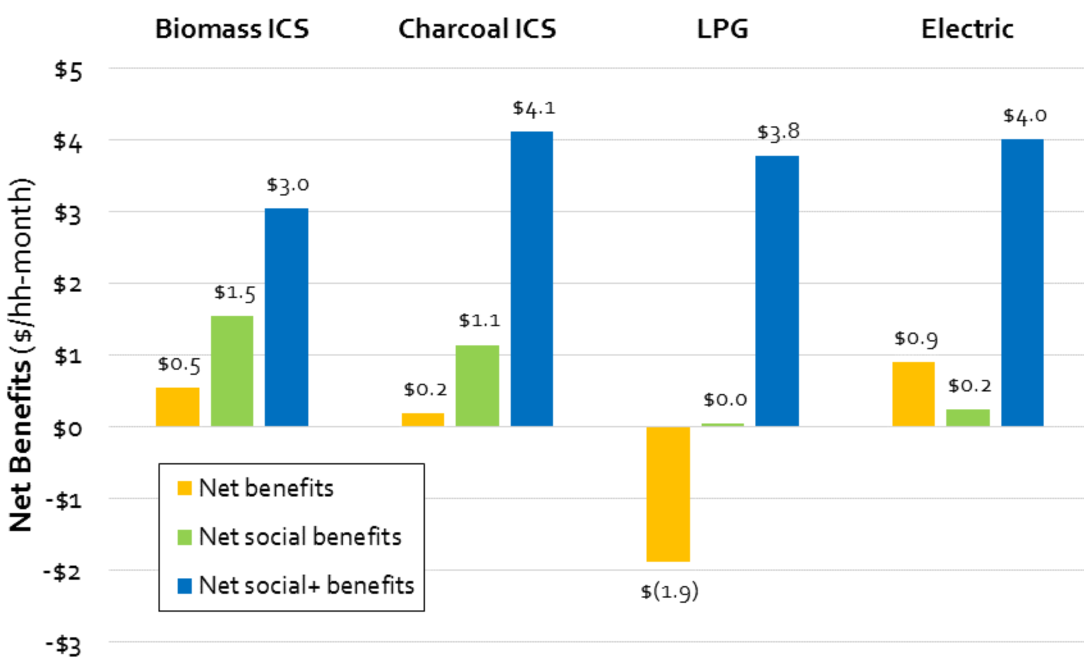

Figure E3. Change in net benefits for the five ICS options under private and social perspectives (<u>Note</u>: All parameters are set to mean trial values)

Finally, from a social perspective, we observe that the outcomes from the simulations mostly shift to the right, and that the range of outcomes increases considerably, largely driven by the relative changes in emissions when using cleaner stoves and fuels. Interestingly, the biomass ICS has the narrowest range of outcomes, and has a significant proportion (21%) of negative outcomes under the social+ perspective that incorporates black carbon. This is because emissions savings from such stoves are rather modest compared to options that use more efficient fuels, especially LPG. Electric stoves often generate social benefits except when the emissions from electricity generation are extremely high, or when black carbon emissions are ignored.

Table E1. Summary of key simulation results for South Asia, for each ICS considered in this report

Indicator	Biomass ICS	Charcoal ICS	LPG	Electric
Private net benefits				
% of trials with NPV > 0	45%	51%	38%	65%
10th percentile NPV	(3.2)	(4.3)	(6.9)	(2.5)
Median NPV	(0.2)	0.1	(1.0)	1.1
90th percentile NPV	3.8	5.9	4.4	7.4
Social net benefits				
% of trials with NPV > 0	68%	67%	71%	37%
10th percentile NPV	(2.2)	(3.0)	(3.0)	(19.4)
Median NPV	1.2	1.5	2.2	(1.7)
90th percentile NPV	7.7	8.7	12.0	5.1
Social + net benefits				
% of trials with NPV > 0	79%	91%	90%	80%
10th percentile NPV	(1.5)	0.2	(0.02)	(2.1)
Median NPV	3.1	6.9	8.8	4.3
90th percentile NPV	16.4	26.7	41.5	20.8

Notes: Social includes emissions calculations related to CO_2, CH_4, N_2O. Social + adds CO, BC, and OC. All NPV are in /hh-month.

In conclusion, our results support the idea that the global community working on clean cooking technologies should more seriously consider the benefits of a shift to cleaner fuels and more efficient technologies, rather than focusing so much on cheaper biomass-burning alternatives. There is evidence from around the world that some poor rural households like LPG, electric, and charcoal stoves due to their lower household emissions and their convenience and ability to produce significant time savings (van der Plas and Abdel-Hamid 2005, Brooks et al. 2014). Yet fuel costs, supply and infrastructure problems (especially for electricity and LPG), and institutional hurdles to greater diffusion of such technologies remain important, and the emissions reductions potential of fossil-fuel based cooking is generally misunderstood. To combat the serious ills arising from traditional cooking methods, the policy community must refocus its attention on such issues.

1. INTRODUCTION

Approximately 2.8 billion people worldwide, or 40% of the global population, rely on solid fuels such as coal, fuelwood, dung and charcoal to meet their household cooking and heating needs (Smith et al. 2013). The vast majority of these households use low-efficiency traditional stoves or heaters, which were developed specifically to handle solid fuels. Especially for the global rural poor, a key advantage of such traditional stoves is that they can be constructed at home, and that the solid fuels that are combusted in them can be collected from the neighboring environment, in contrast to cleaner-burning commercial fuels such as gas and electricity.

Unfortunately, it is increasingly apparent that these traditional cooking and heating technologies and fuels have a range of negative effects on household well-being, on the local and regional environment, and on the global climate system. At the household level, combustion of solid fuels produces household air pollution (HAP) that is damaging to health and now the largest environmental contributor to the global burden of disease (Lim et al. 2013). Moreover, the collection of biomass fuel from the environment takes significant time and impedes household members' productivity (Jeuland and Pattanayak 2012). HAP also spills out of housing and contributes to degradation of ambient and regional air quality, with a variety of negative consequences (Ramanathan and Carmichael 2008, Jeuland et al. 2014). The harvesting of biomass fuels in many locations also results in net loss of forested area or in degradation of forest ecosystems (Jagger and Shively 2014). Finally, the burning of solid fuels releases large amounts of black carbon and other carbon-based greenhouse gases (Bond et al. 2013, Bailis et al. 2015).

In light of these negative effects of traditional stoves and solid fuels, increasing attention and resources are being directed into interventions that would aid a transition away from these highly-polluting technologies, and towards cleaner and improved cookstove (ICS) options (see definition in Box 1).[1] Yet important questions remain about the economics of such interventions and whether it makes sense for households to adopt potentially more expensive stoves and fuels in exchange for reductions in HAP and the drudgery of fuel collection. From a household

[1] Hereafter, we refer to improved cookstoves (ICS) as any technologies that reduce HAP, regardless of the fuel that is used, and regardless of whether these actually produce measurable improvements in health. We reserve the term "clean cookstoves" for those which are clean from a household air pollution (HAP) perspective, such as LPG, electric, or very high efficiency biomass-burning stoves. Note that these definitions relate only to emissions, and not to efficiency and safety, which are two other attributes of cookstoves deemed important by the GACC.

Box 1. Definitions of improved & traditional cookstoves

In this study, we refer to a **traditional cookstove** as a cheaply-built stove with a rudimentary design such as minimal outlet for ventilation (see Figure 1 for a typical mudstove that is used in rural India).

An **improved cookstove (ICS)** (Figure 2) as any technology that reduces HAP, regardless of the fuel that is used, and regardless of whether these actually produce measurable improvements in health. We reserve the term **clean cookstove** for a technology that is clean from a household air pollution (HAP) perspective, e.g., LPG, electric, or very high efficiency biomass-burning stoves. **ICS** can be characterized by the type of fuel being used (biomass or non-biomass) as well as their emissions, efficiency, and safety level.

Figure 1. Typical traditional mud *chulha* used in rural northern India.

Figure 2. Two types of ICS: (Right) Forced-draft biomass ICS; (Left) Electric coil ICS.

perspective, this cost-benefit calculus is complicated by a variety of factors that relate to dietary tastes, risk and time preferences, the perceptions and reality of health impacts, and the ease of use or other aesthetic attributes of cooking options (Jeuland et al. 2014, Jeuland et al. 2014). Admittedly, many of these aspects are difficult to incorporate into a cost-benefit analysis because they are highly subjective and context-specific; as such, any cost-benefit calculations related to ICS adoption must be interpreted with some caution.[2]

Nonetheless, the literature on ICS often argues that the net benefits provided by such technologies are large, and that the economic case for scaled-up dissemination is clear, even without including social benefits. For example, Larson (2014) estimates that the global net benefits of switching from traditional to various improved cookstoves (ICS) lies between US18 to US54 billion per year. An earlier cost-benefit analysis by Hutton et al (2007) produced somewhat different (but also very positive)

[2] In theory, one could use the private demand for ICS to obtain total measures of net private benefits of ICS. There are at least two problems with such an approach, however. First, and perhaps most importantly, little is actually known about the demand for these technologies across diverse contexts, in part because many of the new technologies are not yet readily available in competitive markets. Second, there is often concern that households misperceive the private costs and benefits of these technologies, for various reasons including present bias, lack of understanding of the health and safety risks of traditional stoves, and lack of knowledge of or confidence in ICS performance.

benefit-cost ratios. In fact, the latter study argued that ICS interventions in many locations even have negative net costs, e.g., cost savings in terms of spending on fuel alone. These prior analyses suffer from two important shortcomings, though. First, neither relies on theoretically consistent (or complete) valuation measures. Second, both are simplified and largely deterministic, with limited sensitivity analyses. It is therefore difficult to derive insights from their results, and to understand the main contributors to net benefits, Table 1 compares the approaches in these two studies, with that in a comparison study conducted by Jeuland & Pattanayak (2012), which is also described further below. The present study most closely resembles that in J&P, but with some notable updates.

Importantly, the prior economic calculations that suggest high net benefits are hard to square with the reality of partial purchase and lack of long-term use of ICS technologies that results following even aggressive promotion attempts to lower the acquisition costs for ICS. There are now numerous examples of clean and improved stove dissemination programs that result in low adoption and a puzzling lack of long-term usage (Barnes et al. 1994, Ruiz-Mercado et al. 2011, Hanna et al. 2012, Gall et al. 2013), while a small number of studies observe high demand and subsequent impacts on livelihoods, e.g., improved health, and fuel and time savings (Bensch and Peters 2015). At first glance, the inconsistency across empirical studies of adoption, and their contradiction of the global cost-benefit results, is confusing. One explanation for the divergence, however, is that the simplified and deterministic representation of costs and benefits may ignore important dimensions of this complex decision problem (Jeuland et al. 2014).

Informed by insights that economic outcomes are likely highly context-specific, Jeuland and Pattanayak (2012) (JP) adopted a somewhat different approach to modeling the costs and benefits of ICS. Unlike the two studies discussed above, these authors developed a series of equations with more than thirty parameters that contribute to a large variety of costs and benefits of cooking alternatives. The authors then relied on findings in the literature to specify plausible variation in each of these parameters, and used Monte Carlo analysis to simulate a range and distribution of feasible outcomes. Importantly, their literature search showed that the ranges of variation of many of the model parameters were quite large. Additionally, their analyses were conducted at the household level and this allows for additional heterogeneity, which is otherwise masked by aggregation to the regional level. Correspondingly, JP found that about half of the simulation trials yielded negative net benefits when only private benefits were included. A majority of positive net benefit outcomes only emerged once the social benefits of reduced carbon emissions were added to private benefits. Their results thus suggest one plausible explanation for why the response to new stoves that is commonly observed in field interventions is often tepid.

A critical step in cost-benefit analyses of complex interventions such as this one is therefore to conduct an exhaustive search to collect data and amalgamate knowledge from a broad range of fields. In this regard, the purpose of this study is to update the relationships and parameters in the JP model, in order to provide revised estimates of the benefits and costs computed in JP. Such an analysis is warranted given the significant advances in understanding of the effects of ICS that have been achieved over the past few years. In particular, we improve on JP's accounting of health benefits, using new evidence on the HAP exposure-risk relationship, and on their calculation of the climate change mitigation benefits of cleaner cooking technologies. We also include new data that has emerged from the recent push for more field-based data collection on a variety of issues related to the use of different cookstove technologies. Following this re-analysis, we reflect on the lessons that emerge from these calculations and on some of the major information gaps that remain.

Table 1. Comparison of 4 major cost-benefit analyses of improved cooking technologies

Study	Hutton et al (2007)	Larsen (2014)	Jeuland & Pattanayak (2012)	This study
Outcome	Benefit-cost ratio	Benefit-cost ratio	Net benefits	Net benefits
Benefits considered	Health - Mortality and morbidity (ALRI, COPD, lung cancer); Fuel savings; Time (collection, cooking); Environment (tree loss; greenhouse gas)	Health - Mortality and morbidity (ALRI, COPD, lung cancer, IHD); Fuel savings; Time (cooking)	Health - Mortality and morbidity (ALRI, COPD); Fuel savings; Time (collection, cooking); Environment (tree loss; greenhouse gas)	Health - Mortality and morbidity (ALRI, COPD, lung cancer, IHD); Fuel savings; Time (collection, cooking); Environment (tree loss; greenhouse gas)
Costs considered	Price & installation; program; fuel	Price; fuel	Price; program; maintenance; fuel	Price; learning; program; maintenance; fuel
ICS considered	LPG; ethanol; Biomass ICS	Biomass and coal ICS; LPG	Biomass and charcoal ICS; LPG; Electric ICS	Biomass and charcoal ICS; LPG; Electric ICS
Level of analyses	WHO region	WHO region	Household	Household (in South Asia and ROW)[1]
Modeling/ valuation of health benefits	Valuation of ICS effectiveness at reducing illness & mortality using COI & productivity approach	Dose-response function for PM2.5 + valuation using /DALY avoided & VSL	Valuation of ICS effectiveness at reducing cases & deaths using COI & VSL	Dose-response function for PM2.5 + valuation of cases and deaths avoided using COI & VSL
Modeling/ valuation of climate benefits	Conversion of reduced emissions to carbon equivalents	Not included	Conversion of reduced emissions to carbon equivalents	Conversion of reduced emissions to discounted carbon equivalents
Sensitivity analysis	Three levels (low, medium, high) for each model parameter	None	Monte-Carlo simulation w/ uniform parameter distributions	Monte-Carlo simulation w/ various parameter distributions
Findings	BCR of biomass ICS adoption is generally ***negative***, implying negative costs; BCR of LPG adoption ranges 3.2-22.3	BCR of biomass ICS adoption ranges 6-16; BCR of LPG adoption ranges 1.3-2.9	Median net private benefits < 0 for charcoal, electric, and biomass ICS; Median net social benefits < 0 only for charcoal	See section 4
Data sources	Mostly region-level statistics from the UN, WHO, and a few peer-reviewed articles	Peer-reviewed articles and author's own correlational analyses	Peer-reviewed studies related to ICS	Peer-reviewed studies, and non-academic sources related to ICS

Notes:
[1] A region-level CBA requires data on the distribution of households' stove usage, which is largely missing. Although global databases track the percentage of solid fuel users, they do not generally indicate how many households own non-traditional alternatives, nor how much those households use such alternatives.

2. Literature & Summary of Model Updates

This section discusses the rationale for the principal improvements made to the JP (2012) model. These comprise:

a) Application of a more consistent and complete approach to valuation of health improvements from reduced household air pollution resulting from the use of ICS alternatives;
b) Construction of a more consistent and complete approach to valuation of the climate emissions benefits of improved cooking technologies;
c) Incorporation of new evidence from recent rigorous studies of cookstove adoption; and
d) A set of other minor improvements, mostly related to updating of data sources using the growing body of empirical evidence on the household cooking problem.

The first two improvements imply changes in the underlying functional relationships of the model, that leverage new research findings which have advanced understanding of the interrelationships between variables and our outcomes of interest (in particular, more complete exposure-response functions, and better understanding of the link between anthropogenic emissions of different types and global climate change). The third and fourth primarily stem from inclusion of additional and often better-quality data than was previously available, sourced from stove field experiments or trials as well as other types of research studies.

a. <u>More consistent consideration of health benefits</u>. One of the main purported benefits of switching to cleaner stoves is that it lowers household air pollution (HAP) which is a risk factor for many illnesses, and that this reduction consequently improves health. To estimate effects on health, JP (similarly to Hutton et al.) relied directly on the findings from trials or observational studies that aimed to establish a relationship between the use of cleaner stoves and health improvement. Unfortunately, the evidence base that was utilized was highly variable in quality, and the number of studies going from use to comprehensive measures of health impacts was very small. Compared to JP, we therefore endeavor to include a more complete and consistent set of epidemiological and risk assessment results to estimate these improvements.[3] The major changes arise from two important modifications. First, we estimate directly the reduction in emissions of $PM_{2.5}$ following a switch from traditional stove to cleaner options. This change

[3] Larson (2014) uses the same exposure-response approach to estimate impacts on health outcomes.

depends on both technology and on use rates of the new stoves; our approach thus computes reductions as a function of use. Then, we use the newly-developed integrated exposure-response function (Burnett et al. 2014) to estimate the change in relative risk of illness stemming from the reduction in emissions and exposure implied by particular technologies and stove use patterns, accounting for the lag in the onset of health effects (Robinson 2007).[4] An example dose-response curve for relative risk of ALRI as a function of PM2.5 concentrations is shown in Box 2.

Box 2. Dose-response function for exposure to $PM_{2.5}$

A **dose-response function** is a relationship between some exposure (the 'dose') and a health effect (the 'response'). In this study, the dose is an exposure to fine particulates, or $PM_{2.5}$ that are emitted at high levels by traditional or solid-fuel burning stoves. We model the reduction in this dose as implied by the level of use of cleaner-burning options and data on the PM2.5 emissions associated with those cleaner-burning options. Figure 3 provides an example of such a dose-response function.

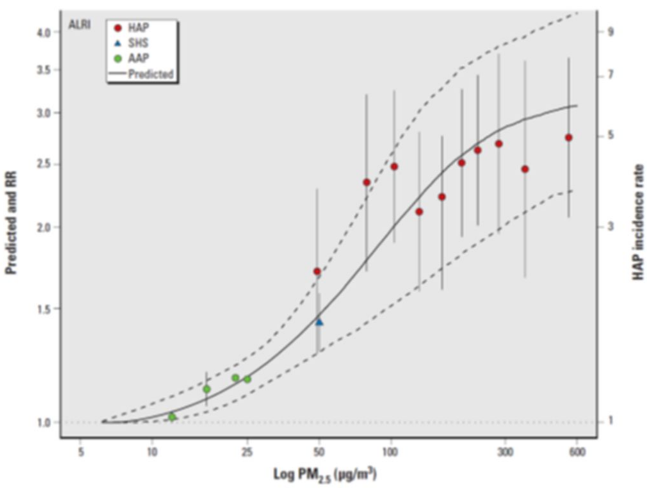

Figure 3. Dose-response function for ALRI in young children, and used in this study (from Burnett et al. 2014).

The Burnett integrated dose-response functions account for the following 'responses' to PM2.5: Chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), stroke, lung cancer, and, for infants, acute lower respiratory disease (ALRI). Note that our analysis omits stroke, due to lack of data on the prevalence and cost of illness of that condition.

Importantly, Burnett et al.'s integrated function includes ischemic heart disease (IHD) and lung cancer in addition to the two conditions previously included in JP, which were acute lower respiratory illness (ALRI) and chronic obstructive pulmonary disease (COPD). We thus include a larger range of health effects than JP, using the disease-specific parameters in the risk-exposure curve. This modification also requires a more thorough literature search in order to retrieve parameters for these various diseases' mortality rate, incidence or prevalence rates, and cost of illness (COI). For many of these parameters, we use data on mortality, incidence, and prevalence rates from databases provided by the United Nations and World Health Organization.

The main advantage of this approach –

[4] The dose-response function derived by Burnett et al (2014) is for mortality risk, but we assume that the same applies for morbidity as well.

described in more detail in Appendix A – is that there is a relatively rich body of evidence available on HAP emissions from different stove types, so we are able to calculate changes in exposure that result from more or less complete use of these various technologies.[5] This avoids two problems that otherwise plague any cost–benefit analysis of health improvements from clean stoves. First, for a variety of reasons, there are relatively few studies that have successfully documented health improvements resulting from a stove promotion intervention (Smith et al. 2011, Jeuland et al. 2014), such that linking particular technologies to specific changes in health relies on guesswork and extrapolation. Second, recent studies have pointed out that while emissions are lowered after switching from traditional stove to ICS, the magnitude of improvement may not be sufficient to see a meaningful impact in health (Ezzati and Kammen 2001, Burnett et al. 2014). As such, the indirect approach of calculating pollution reductions allows us to more precisely estimate the magnitude of health improvements based on plausible movements along the nonlinear dose-response function that follow adoption of cleaner technologies and cooking behaviors.

The approach also has some disadvantages, however. In line with current understanding on the health impacts of HAP, we focus on $PM_{2.5}$ levels, but other pollutants such as PAHs or carbon monoxide (CO) may also be of concern. In the case of kerosene in particular, there are also concerns that emissions of other harmful carcinogenic pollutants may increase, undermining health gains from reducing $PM_{2.5}$ (Lam et al. 2012). As such, we do not analyze kerosene ICS as a viable option in this study due to its potential hazards. In addition to this, actual exposure is difficult to measure as different household members are exposed to different levels of HAP depending on the amount of time they spend inside versus outside, or in the proximity of stoves and heaters that burn biomass. Most studies proxy for general exposure by placing a measurement device about 1.2 meters above the stove (Smith et al. 2007, Pennise et al. 2009, Chowdhury et al. 2013), and so do not indicate true exposure. And though there are a growing number of studies that measure actual exposure level by placing the measurement device directly on household members (Naeher et al. 2000, Bruce et al. 2004, Fitzgerald et al. 2012), individuals' behavior may also change when emissions decline. Third, perhaps reflecting implementation efforts, studies measuring exposure levels around wood ICS are very common whereas exposure level for other types of stoves (charcoal, LPG) remain scarce. In this regard, a laboratory study by MacCarty et al. (2010) that involved measuring the emissions levels for 50 stove-fuel combinations fills an important gap on the potential

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[5] We note, however, that this body of evidence is disorganized, and that systematic assessment of the PM reductions from different stove options is lacking.

reductions from less commonly-studied ICS, but without rigorous replication or field testing.

b. Global warming implications of cleaner cookstoves. The second improvement in the current model over that presented in JP is in the calculation of climate change-inducing emissions. To construct an approach that is based on a more complete accounting of emissions, we tap recent literature that links a wider range of emitted substances to climate change, and that calculates climate forcing from fundamentals. The first step of our revised approach is thus to directly estimate the time series of radiative forcing from a particular blend of emissions (associated with a particular type of stove) over a given time period (Shindell 2015). We then treat this time series of effects on the climate in an economically-consistent manner by discounting future radiative forcing relative to forcing in earlier years, using the social discount rate.[6] All emissions are normalized according to the time-discounted global warming potential of CO_2 (See Box 3).

Box 3. Global warming potential (GWP)

The **GWP** is a unit-less measurement of how much heat is trapped by the gas relative to carbon dioxide over a period of time that is usually measured in years. Hence, a gas with a 100 year GWP of 20 means this gas traps 20 times more heat than carbon dioxide over 100 years. However, the GWP treats the heat trapped in each year as equivalent. This results in a low relative GWP for gases other than carbon dioxide, which has a long lifespan.

In this study, we experiment with a new approach that uses discounting convert the standard GWP into a measure that accounts for discounting of the future GWP. This measure clearly depends heavily on the **social discount rate,** or the rate at which future benefits and costs are deemed less valuable to society compared to those in the present.

In addition, we rely on substantial new data and research on the climate forcing associated with black carbon. Bond et al. (2013) in particular have summarized current knowledge on the sources and greenhouse effects of black carbon (BC). Compared to Bond et al. (2004), this new synthesis updated the calculation of global warming potential (GWP) for BC and discussed the mechanisms through which BC emissions (and other concurrent emissions like organic carbon (OC) which has a net cooling effect) alter the climate system. Taking account of this new information theoretically allows for more nuanced calculations of the heterogeneity of carbon savings that emerges as a result of the location of biomass burning. For example, in South Asia, a large portion of the BC from residential fuel emissions settles on the Himalayas glaciers and contributes to warming (Bond et al. 2013), while in other places residential burning of biomass may have a net negative effect on warming due to atmospheric dynamics

[6] We include CO_2, CO, CH_4, N_2O, SO_2, BC and OC in this calculation. Professor Drew Shindell of the Nicholas School of the Environment at Duke University provided invaluable help in computing radiative forcing for these greenhouse gases.

and the relative effect of OC emissions. Here it is worth noting however that there remain large uncertainties about the specific forcing effects of many of the pollutants emitted during biomass burning (particularly those of black carbon and organic carbon). Obtaining realistic values for the climate-forcing contribution of various technologies in different locations therefore continues to be a major challenge.

Finally, the approach that we implement requires valuation of the damages from climate-modifying emissions. Here again we update the approach in JP, which specified the cost of carbon to be an uncertain, independent parameter in the calculation of climate benefits from ICS options. Our new methodology links the cost of carbon directly to the discount rate, as is done in all integrated assessment models on the economics of climate change. This approach improves the consistency of our valuation: Because the future damages will be more heavily weighted when the discount rate is lower, the cost of carbon should also be higher in such a case. A lower discount rate will also tend to put more weight on pollutants that have a long atmospheric residence time (e.g. CO_2, rather than BC). Meanwhile, our approach accommodates the fact that the social cost of carbon is lower today than in the future; thus our analyses are appropriate for understanding the benefits of changing cooking technology today.

c. Field evidence from recent stove trials and other studies. For the purpose of this study, cookstove-related parameters can generally be categorized into two groups: a) technical performance parameters related to specific stove/fuel combinations; and b) behavioral parameters that relate to households' usage of these technologies. Until recently, little was known about this second category of behavioral parameters, but recent social science evaluations of cookstove dissemination programs are quickly filling this gap (Fitzgerald et al. 2012, Hanna et al. 2012, Jeuland et al. 2014, Beltramo et al. 2015, Beltramo et al. 2015, Bensch and Peters 2015). Many of these recent studies utilize rigorous study designs (e.g., RCT or quasi-experimental designs). More importantly, these studies contain data and information on behaviors that affect the generation of benefits from environmental health technologies that was under-collected (and sometimes under-appreciated) in earlier work (see Whittington et al. (2012) for a relevant discussion of the importance of behavioral assumptions in similar environmental health interventions).

For our purposes, these new social science studies therefore contain a wealth of relevant and useful information. Several studies have collected information on monthly fuel usage and collection time (Hanna et al. 2012, Johnson et al. 2013, Brooks et al. 2014). Similarly, Jeuland et al (2014) weighed fuel stock prior to and after purchase of ICS. Such parameters (e.g., amount of fuel used per hour of cooking, amount of fuelwood collected per hour, amount of time spent cooking) are often seemingly peripheral to most research questions about ICS, but they serve an important function in helping us understand complex adoption patterns, and the extent to which behavioral responses to new technologies can undermine (or reinforce) some of the expected benefits, due to rebound effects, stove stacking, or complementarities with other behaviors. Nonetheless, a variety of parameters continue to be challenging to measure and obtain from the literature, including factors such as maintenance and learning cost. For these hard-to-find parameters, we continue to rely on a small literature or estimating their values from other proxy variables.

Finally, for technical stove and fuel parameters, such as price of the stove, we are now able to supplement the relatively thin evidence in JP with the much more substantial data provided in the Global Alliance on Clean Cookstoves (GACC) catalogue on cookstoves. The GACC maintains a user-input online catalogue of stoves of different types (http://catalog.cleancookstoves.org/) that provides price information as well as data on stove lifespan, and fuel requirements, for technologies available in different parts of the world.

Fuel prices can be difficult to obtain, especially for less commonly-studied fuel such as charcoal and LPG. Moreover, there can be large heterogeneity in prices even within a country, due to supply chain issues or other differences across regional markets. To supplement the existing data from the literature, we rely on large-scale community surveys such as the World Bank Living Standards Measurement Studies, as market prices of essential commodities such as fuels are recorded in these surveys (See http://go.worldbank.org/IPLXWMCNJo). The price of electricity (for electric stoves) is also easily obtained if we assume that electricity is generally provided by central power stations (as opposed to decentralized grids). Prices for energy obtained from the grid in different countries are fairly readily available.

d. Other important data-related updates (and limitations) of the model. We close this section by summarizing some of the other changes in the current model. As mentioned earlier, the GACC website now has a large and functional catalogue of cookstoves, which provides a wealth of information on these technologies. Research institutions such as the Aprovecho Research Center have also published reports on the field performances of various ICS, providing us with another source of information on stoves, which can be compared against laboratory specifications and other data that appear in the GACC catalogue. The U.S. Energy Information Administration maintains a useful catalogue of emissions from power stations around the world, although the emissions tracked are generally limited to the main pollutants from the Kyoto Protocol (CO_2, CH_4, and N_2O). Unlike JP, we also no longer assume that biomass is sustainably harvested in our model, but use new global data on the proportion of unsustainable harvesting in different locations (Bailis et al. 2015).

There continue to be important parameters for which data are scarce. One such parameter is the program cost associated with cookstove promotion efforts. Such costs are rarely recorded in peer-reviewed studies; we rely primarily on project documents, mostly from the World Bank, from cookstove intervention projects to obtain estimations of these costs. The estimates in these reports are somewhat higher than those derived by Mehta and Shahpar (2004). A second parameter that remains problematic and rarely measured concerns the maintenance cost for alternative stoves.

3. METHODOLOGY

We generally follow the methodology described in JP. As in that previous analysis, our model compares the costs and benefits of households' switching from traditional wood-burning stoves to a range of alternatives: a) improved wood-burning stoves, b) improved charcoal-burning stoves, c) liquefied petroleum gas (LPG) stoves, and d) electric stoves. The unit of analysis for the calculations is the individual household; the monthly costs of the switch in technologies for a household are compared with the monthly economic benefits that a household would receive. We compare the overall economic attractiveness of the different stove alternatives relative to the baseline of unimproved wood-burning stoves using a net benefits criterion, which is the standard economic criterion for project evaluation (Boardman et al. 2005).

We conduct our assessment from both a private and a social welfare perspective. For the private perspective, only the costs and benefits that accrue directly to households are included (Figure 4). The social perspective accounts for the full investment and use costs of the different stoves, as well as for changes in their effects on carbon emissions and forest loss due to unsustainable harvesting. In the private analysis, we apply a discount rate that is more consistent with market evidence on the private rate of time preference (5 to 15%), while the social analysis uses a real social discount rate that varies from 1 to 6%.

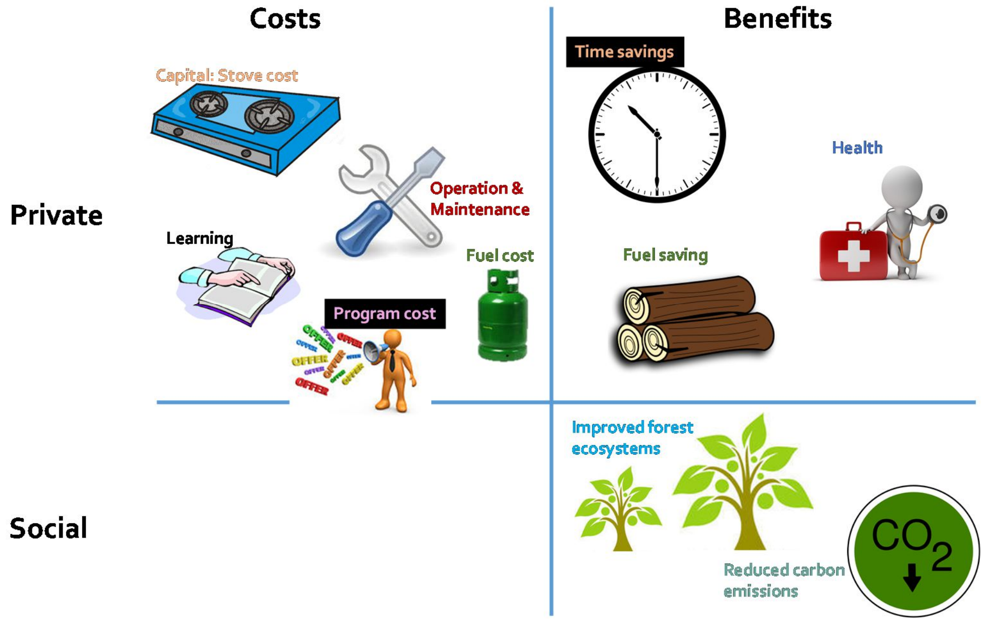

Figure 4. Private and social costs and benefits of improved cook stove interventions. Note: Intervention program cost may not always be privately-borne.

The costs and benefits of adoption of cleaner cookstoves.

Switching to a different cooking technology entails a variety of costs and benefits (Table 1). The costs include the capital investment in a new device and/or ventilation system, program expenses associated with distributing or marketing stoves, time and money spent for regular operation and maintenance (O&M), the net change in the cost of required fuels (which may also be a benefit depending on the relative time and money costs of acquiring fuel), and learning costs (in time and reduced quality of food preparation). The basic equations that underlie the calculations of these costs are summarized in Table 2, and described in additional detail in Appendix A (with parameters defined in Table 3).

We calculate total costs as the sum of the components described above. Time costs (and benefits) are valued at a fraction of the unskilled market wage, since the opportunity cost of non-work time that is allocated to cooking, fuel gathering, or other activities) is typically lower than the wage rate (Mackie et al. 2001, Jeuland et al. 2010). In the absence of subsidies to increase uptake of the new technologies, based on carbon-financing or other instruments, all of these costs will be privately borne and reflected in stove and fuel prices, or in time costs to the households that choose to adopt and use the new stoves. Our costs do not account for the inconvenience that may be associated with having to alter cooking practices to successfully use a new stove technology. We expect that such disamenities will sometimes be important to households, since improved stoves may be difficult to adapt to local cooking needs, may result in dissatisfaction with the preparation of food, may provide less effective indoor heating during cold weather and lower protection against mosquitoes and other insects, or may not conform to individuals' preferences for cooking technology for other reasons (Barnes et al. 1994, Smith 2000, Adler 2010).

Table 1. Typology of costs and benefits (from Jeuland & Pattanayak 2012)

Costs	Examples	Benefits	Examples
Capital ("hardware") [*Cap*]	Cost of new technologies: Improved cookstoves; ventilation / cooking space improvements; etc.	Morbidity & mortality reductions [*Morb*]; [*Mort*]	Benefits from reduced incidence of and mortality from disease (acute respiratory infections (esp. ALRI); COPD; etc.)
Program ("software") [*Prog*]	Cost of implementation/delivery: Marketing and promotion materials; NGO/government staff time; etc.	Time savings [*Timesav*]	Benefits of reduced cooking time (due to more efficient heating)
Operation and maintenance [*O&M*]	Cost of replacing / cleaning of equipment, including time	Aesthetic gains	Benefits from reduced in-house exposure to unpleasant soot and smoke; reduced indoor cleaning
Fuel [*Fuel*]	Cost of fuel, in collection and preparation time and/or money	Improved social standing	Benefits of improvements in household status from acquisition of improved stoves
Learning [*Learn*]	Costs of familiarization with the use of a new stove technology	Environmental [*Carb*]; [*Bio*]	Benefits from reduced emissions of black carbon and decreased tree cutting
Inconvenience	Costs related to any undesirable changes in cooking practices made necessary by the new stove		

Table 2. Equations governing costs and benefits included in this analysis

Equations		Appendix equation #
Costs		
Cap	$Cap = (cc_i \cdot crf)/12$	(A1)
Prog	$Prog = cp/12$	(A3)
O&M	$O\&M = \chi \cdot (Main_i)$	(A4)
Learn	$Learn = l \cdot v^t \cdot crf/12$	(A5)
Fuel	See Appendix for detailed derivation and discussion. For traditional: $Fuel = [Fuelu_0 \cdot f \cdot p_i + 30 \cdot Fuelu_0 \cdot (1-f) \cdot v^t]$ For biomass ICS: $Fuel = \chi * [Fuelu_i \cdot f \cdot p_i + 30 \cdot (Fuelu_i/Fuelu_0) \cdot (1-f) \cdot v^t + 30 \cdot prep \cdot v^t]$ For other stoves: $Fuel = \chi * Fuelu_i \cdot f \cdot p_i$	
Benefits		
Timesav	$Timesav = 30 \cdot time_0 \cdot \chi \cdot (1-te_i) \cdot v^t$	(A7)
Morb	$Morb = \sum_k (\sum_{t=1}^{5} CL_t \cdot COI_k \cdot (hhsize \cdot (PAF_0 - PAF_i) \cdot IR_k)/(1+\delta)^{t-1})/12$	(A18)
Mort	$Mort = \sum_k (\sum_{t=1}^{5} CL_t \cdot VSL \cdot (hhsize \cdot (PAF_0 - PAF_i) \cdot MR_k)/(1+\delta)^{t-1})/12$	(A19)
Carb	$Carb = c^{CO2} \cdot \chi \cdot (fuelu_0 \cdot GWP_{i,m} \cdot \mu_m \cdot \varepsilon f_0 - fuelu_i \cdot GWP_{i,m} \cdot \mu_{i,m} \cdot \varepsilon f_i)$	(A23)
Bio	$Bio = c^f \cdot \chi \cdot (1-\psi) \cdot (fuelu_0 - fuelu_i)$	(A24)
Total net benefits = Benefits – Costs = (*Morb + Mort + Timesav + Carb + Bio) – (Cap + Prog + O&M + Fuel + Learn)*		

Notes: Parameters are as defined in tables 2 and 3. All costs and benefits are expressed in per household per month. For detailed descriptions of the equations, please see Appendix A.

Table 3. Parameter definitions and units

Parameter	Description	Unit
c_i^c	Cost of stove type *i*	US/stove
c^p	Cost of promotion of new stoves, assumed to be the same for all types	US/hh
c_i^m	Cost of stove maintenance	US/hh-yr
T_i	Lifespan of stove *i*	yrs
χ	Rate of use of non-traditional stove	%
$cook_o$	Average daily cooking time with traditional stove	hrs/day
te_i	Time efficiency of stove *i* relative to traditional stove	Unitless ratio
ϵf_i	Fuel efficiency of stove *i*	MJ useful energy/MJ heat, or kW-hr/hr (electric)
μ_i	Energy conversion factor for stove *i*	MJ/kg fuel, or MJ/kW-hr (electric)
$fuelckg_0$	Amount of fuel used for cooking; traditional stove	kg/hr
f	Percentage of people buying wood	%
$collt_o$	Average daily wood fuel collection time	hrs/day
κ^t	Shadow value of time spent cooking (fraction of market wage)	Fraction
W	Unskilled market wage	US/hr
prep	Average daily fuel preparation time for ICS stove	hrs/day
p_i	Cost of fuel type *i*	/kg, or /kW-hr (electric)
l	Learning hours	hrs
IR_k	Incidence/prevalence of disease *k*	cases/100
MR_k	Mortality rate due to disease *d*	deaths/10000
COI_k	Cost-of-illness of disease *d*	US/case
c^{CO2}	Cost of carbon emissions	US/ton
ψ	% of biomass harvesting that is non-renewable	%
hhsize	Number of persons per household	persons/hh
sfu	% of households using solid fuels	%
δ_s	Discount rate (social)	None
δ_p	Discount rate (private)	
VSL	Value of a statistical life	US/life lost
c^f	Cost of tree replacement	US/kg

The benefits of switching to an ICS include health improvements from better indoor air quality, cooking time savings, aesthetic improvements and improved social standing from the use of cleaner stoves (all private), plus the environmental benefits to society, from reduced black carbon or greenhouse gas emissions and deforestation (Table 1). Total benefits are the sum of these components, and we assume that these accrue to households and society in direct proportion to the use rate for the clean technologies. This implies that positive externalities associated with high levels of use of improved stoves in a community and reduced ambient air pollution are not included, or alternatively that there are not diminishing returns from greater use of these technologies. To the extent possible, benefit valuation is done using welfare-based measures to take into account of broader social well-being (rather than income based measures focused on productivity). However, when such data are not readily available, income-based measurements are used instead. For example, we use cost-of-illness to value morbidity even though there is also psychological cost of suffering when one is ill. As described in Section 2, the model used in this analysis makes several improvements with respect to calculation of these benefits, particularly with respect to the valuation of health risk reductions and climate emissions benefits.

With regards to health benefits, it is important to note that our model still omits a variety of diseases that may be linked to HAP from cooking, such as asthma and visual impairment, for which the evidence is less compelling than for the four diseases we include, and for which the impacts are primarily related to morbidity rather than mortality. It also omits the effects of other pollutants from biomass-burning (Smith et al. 2013). We also assume that the relative risks of morbidity for those exposed are reduced similarly to those for mortality, since Burnett et al. (2014) only discuss additional mortality risk. The health valuation concepts (defined in Box 4) we use for valuing disease risk reductions are the avoided cost-of-illness (COI) per case (for acute illness) or per year (for chronic ones) for morbidity, and the value of a statistical life (VSL) for reduced mortality (Viscusi and Aldy 2003, Whittington et al. 2009).[7,8]

Box 4. Health benefits valuation

Health economists appeal to a range of valuation measures to estimate the benefits (or costs) of projects and policies that affect health. Our study uses the **cost-of illness (COI)** concept to value changes in morbidity, and the **value of a statistical life (VSL)** to value change in mortality, due to adoption of ICS.

The **COI** is the cost incurred in the treating and managing an illness. There are two components to COI – direct and indirect. Direct costs consist of medical costs of treatment (such as consultation, hospital, and drug) and nonmedical costs (such as transportation). Indirect costs are mostly productivity cost from being unable to work because of the illness. We note two important limitations of the COI measure: 1) We assume that all avoided morbidity cases result in savings of COI, which may overestimate benefits in settings where seeking of treatment is partial, and 2) COI does not include the demand for reduced pain and suffering due to illness, independent of the treatment costs incurred.

The **VSL** is a measure that is obtained by aggregating the benefits of small changes to mortality risk. For example, say that people in a group are willing to pay an average of $100 for a 0.001 reduction in mortality risk. The VSL for this group is then computed as $100/0.001 or $100,000, which is the willingness to pay for society to reduce the risk of a single death at the population level.

Another commonly used **productivity** measure of mortality benefits is based on the present value of lost future earnings due to premature deaths in a population. Such measures are typically thought to misrepresent the value of health improvements, because the benefits are based on a very narrow definition of individual well-being (based on earnings).

Our valuation of environmental benefits applies the social cost of carbon (Interagency Working Group on Social Cost of Carbon 2015) to climate emissions

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[7] Ideally, COI includes: a) private and public expenses for diagnosis, treatment and hospitalization (direct COI); b) other costs borne by patients, such as transport to hospitals or clinics (direct COI); and c) productivity losses for sick patients and caretakers during the period of illness and recovery (indirect COI). In practice, COI studies may not report all categories of such direct and indirect expenses.

[8] The VSL used in Larsen (2014) is larger than what we use here. To ensure that differences in results are not driven by this difference, we ran simulations with VSL figures comparable to Larsson's. The results remains similar.

that are converted to temporally-consistent (discounted) carbon dioxide equivalents, and uses the replacement cost for trees for deforestation and forest degradation. The latter approach ignores the cost of non-sustainable harvesting. We omit valuation of unsustainably harvested forest due to the lack of data on the ecosystem services lost from such harvesting across space (Ferraro et al. 2011), so the environmental benefits from reduced deforestation should be considered conservative.

Data and model parameterization

In order to estimate the costs and benefits of switching cookstoves, we supplemented JP's review of the literature in order to update assumptions about the range of possible values for the approximately thirty parameters that appear in the equations for costs and benefits (Table 4 and, for emissions, Table 5). For each model parameter, Tables 4 and 5 show the range of values obtained based on our reading of the literature for "typical" programs designed to promote different cookstove technologies, and provide details on the assumed distribution of these parameters, as informed by the literature. The complete set of studies providing these data are listed – by parameter – in Appendix B. For example, for parameters with a great deal of information, we generally chose lognormal distributions for the analysis (which ensure that a number of parameters do not take on infeasible negative values), while others with only a few data points required use of a uniform distribution.[9]

Following this model parameterization, we adapt the simulation approach applied in JP and first developed by Whittington et al. (2009) to determine the net benefits of households' switch from traditional stoves to the various alternative ICS. Specifically, we conduct two types of analyses: a) Monte Carlo simulations of the net benefits for the various stove options, allowing all uncertain parameters to vary simultaneously according to their assumed distributions; and b) one-way parameter sensitivity tests, presented as tornado diagrams, which generate insights concerning the factors most important in affecting economic outcomes (Vose 1996). Our analysis thus aims to uncover the extent of possible outcomes given reasonable parameter values drawn from the literature, and their sensitivity to particular parameters in the model. In addition, we specify likely correlations, also included in the Appendix, between parameters in the model in order to avoid putting undue emphasis on what we consider to be

[9] We use a lognormal distribution if we have more than 40 data points and a uniform distribution otherwise. For the social cost of carbon, we use a triangular distribution bounded by the average 5th, 50th, and 95th percentile estimates across IAM models used by the Interagency Working Group on the Social Cost of Carbon, each of which is an exponential function of the discount rate.

particularly unlikely combinations of model parameters (Table 4).

Table 4. Parameter ranges and distributional assumptions

				South Asia			Global		Correlations
Parameter	Description	Unit	Low	Mid	High	Low	Mid	High	
c_i^c	Cost of stove type *i*								
	Traditional stove	US		0			0		
	Wood-burning ICS			24.8 (13.6)‡			24.8 (13.6)‡		PM2.5 emissions (-0.5)
	Improved charcoal-burning			24.7 (17.4)‡			24.7 (17.4)‡		
	Liquid petroleum gas (LPG)		21	39	57	21	39	57	
	Electric		15	43	70	15	43	70	
c^p	Cost of promotion of new stoves	US/hh	1	5	9	1	5	9	
c_i^m	Cost of stove maintenance								
	Traditional wood-burning (*i* = 0)	US/hh-yr		0			0		
	All other stoves		0.4	3.7	7	0.4	3.7	7	
T_i	Lifespan of stove *i*								
	Wood-burning ICS	yrs		3.69 (2.05)‡			3.69 (2.05)‡		Cost of stoves (0.7)
	Improved charcoal-burning			4.40 (3.12)‡			4.40 (3.12)‡		
	LPG		4	6	8	4	6	8	
	Electric		3	5.5	8	3	5.5	8	
χ	Rate of use of non-traditional stove	%	0.16	0.48	0.8	0.16	0.48	0.8	
$cook_0$	Average daily cooking time with traditional stove	hrs/day	1.2	2.5	3.8	1.2	2.5	3.8	
te_i	Time efficiency of stove *i* relative to traditional								
	Wood-burning ICS	ratio	0.3	0.9	1.5	0.3	0.9	1.5	Cost of stoves (-0.5)
	Improved charcoal-burning		0.5	0.65	0.8	0.5	0.65	0.8	
	LPG		0.5	0.8	1.1	0.5	0.8	1.1	
	Electric		0.6	0.825	1.05	0.6	0.825	1.05	
ϵf_i	Fuel efficiency of stove *i*								
	Traditional stove	MJ useful energy/MJ produced heat (except electric)	7%	14%	21%	7%	14%	21%	
	Wood-burning ICS		7%	22%	37%	7%	22%	37%	Cost of stoves (**0.5**)
	Improved charcoal-burning		17%	32%	47%	17%	32%	47%	
	LPG		42%	53%	64%	42%	53%	64%	
	Electric	kW-hr/hr cooking	1.1	1.65	2.2	1.1	1.65	2.2	
μ_i	Energy conversion factor for stove *i*								
	Wood	MJ/kg fuel (except electric)		16			16		
	Charcoal			30			30		
	LPG			35			35		
	Electric	MJ/kW-hr		3.6			3.6		
$fuelckg_0$	Amount of fuel used for cooking; traditional stove	kg/hr	2	2.5	3	2	2.5	3	
f	Percentage of people buying wood	%	0	25	50	0	25	50	
$collt_0$	Average daily wood fuel collection time	hrs/day	0.4	2.2	4	0.4	2.2	4	
κ^t	Shadow value of time spent cooking (fraction of market wage)	Fraction	0.2	0.35	0.5	0.2	0.35	0.5	
W	Unskilled market wage	US/hr	0.08	0.3	0.62		0.53 (0.38)‡		
$prep$	Average daily fuel preparation time for ICS stove	hrs/day	0.1	0.4	0.7	0.1	0.4	0.7	
p_i	Cost of fuel type *i*								
	Wood	/kg (except electric)	0.01	0.05	0.09	0.01	0.05	0.09	
	Charcoal		0.13	0.22	0.31	0.13	0.22	0.31	
	LPG		0.3	0.75	1.2	0.3	0.75	1.2	
	Electric	/kW-hr	0.03	0.105	0.18	0.03	0.105	0.18	
l	Learning hours		15	27.5	40	15	27.5	40	
IR_k	Incidence/prevalence of disease *k*	cases/100 persons-yr							
	ALRI		5.8	33	60	8.0	15	30	
	COPD		3.4	4.3	4.9		4.0 (1.2)‡		
	Lung cancer		0.007	0.014	0.023		0.023 (0.030)‡		
	IHD		0.59	0.73	1.06		1.0 (0.62)‡		
MR_k	Mortality rate due to disease *d*								
	ALRI (children only)	deaths/10000	1.2	14.0	31.8		15.3 (16.1)‡		
	COPD	deaths/10000	1.9	4.6	8.6		1.62 (1.4)‡		
	Lung cancer	deaths/10000	0.33	0.67	1.25		1.29 (1.74)‡		
	IHD	deaths/10000	3.3	7.4	15.4		10.7 (12.3)‡		

COI_k	Cost-of-illness of disease *d*								
	ALRI	US/case	6	33	60	6	33	60	
	COPD	US/case	30	67.5	105	30	67.5	105	
	Lung cancer	US/case	110	1650	3200	110	1650	3200	
	IHD	US/case	30	45	60	30	45	60	
c^{CO2}	Cost of carbon emissions	US/ton	Function of discount rate			Function of discount rate			
ψ	% of biomass harvesting that is non-renewable	%	20	50	80		22.7 (19.5)ǂ		
$hhsize$	Number of persons per household	persons/hh	4	5.75	7.5		4.86 (1.22)ǂ		Time spent cooking (0.5)
$hh<5$	Number of children under 5 per household	children/hh	0.3	0.7	1.1		0.77 (0.34)ǂ		# of persons (0.7)
sfu	% of households using solid fuels	%	40	69.6	92		74 (24)ǂ		
δ_s	Discount rate (social)	None	1	3.5	6	1	3.5	6	
	Discount rate (private)		5	10	15	5	10	15	
VSL	Value of a statistical life	US/life lost	10000	45000	80000	10000	30000	50000	
c^f	Cost of tree replacement	US/kg	0.002	0.01	0.02	0.002	0.01	0.02	

Notes: All parameters with low-medium-high assumptions specified are assumed to vary over the range according to a uniform probability distribution; those with a mean and standard deviation are assumed to follow a normal or lognormal distribution, depending on the nature of the underlying data. ǂ Log-normal distribution

Table 5. Emissions parameter assumptions

Parameter	Description	Unit	Low	Medium	High
$\varepsilon_{PM,i}$	$PM_{2.5}$ (traditional wood-burning stove)	24-hr μg/m^3		695 (549)	
	$PM_{2.5}$ (wood-burning ICS)			303 (224)	
	$PM_{2.5}$ (improved charcoal stove)		50	185	320
	$PM_{2.5}$ (LPG)		20	70	120
	$PM_{2.5}$ (electric)			0	
$\varepsilon_{CO2,i}$	CO_2 (traditional wood-burning stove)	g CO_2/MJ	450	510	570
	CO_2 (wood-burning ICS)		300	345	390
	CO_2 (improved charcoal stove)		300	525	750
	CO_2 (LPG)		125	140	155
	CO_2 (electric)	g CO_2/kW-hr	10	650	1300
$\varepsilon_{CH4,i}$	CH_4 (traditional wood-burning stove)	g CH_4/MJ	0.6	2.05	3.5
	CH_4 (wood-burning ICS)		0.8	1.6	3
	CH_4 (improved charcoal stove)		0	1.325	2.65
	CH_4 (LPG)		0.002	0.049	0.1
	CH_4 (electric)	g CH_4/kW-hr	0.5	16	31.5
$\varepsilon_{N2O,i}$	N_2O (traditional wood-burning stove)	g N_2O/MJ	0.03	0.315	0.6
	N_2O (wood-burning ICS)		0.04	0.09	0.14
	N_2O (improved charcoal stove)		0.03	0.075	0.12
	N_2O (LPG)		0.044	0.277	0.45
	N_2O (electric)	g N_2O/kW-hr	0.1	6	21.5
$\varepsilon_{CO,i}$	CO (traditional wood-burning stove)	g CO/MJ	13	25	37
	CO (wood-burning ICS)		16	26	36
	CO (improved charcoal stove)		6	16	26
	CO (LPG)		0.1	0.6	1.1
	CO (electric)	g CO/kW-hr		NA	
$\varepsilon_{BC,i}$	BC (traditional wood-burning stove)	g BC/MJ	0.28	0.3	0.32
	BC (wood-burning ICS)		0.02	0.17	0.32
	BC (improved charcoal stove)		0.005	0.0135	0.022
	BC (LPG)		0.003	0.0035	0.004
	BC (electric)		0.003	0.02	0.037
$\varepsilon_{OC,i}$	OC (traditional wood-burning stove)	g OC/MJ	0.25	0.675	1.1
	OC (wood-burning ICS)		0.02	1.0	2.0
	OC (improved charcoal stove)		0.345	0.395	0.445
	OC (LPG)		0.001	0.002	0.003
	OC (electric)	g OC/kW-hr	0.005	0.036	0.067

Notes: All parameters are assumed to vary over a uniform range, except for $PM_{2.5}$ emissions from traditional and biomass ICS, which are assumed to be lognormally distributed according to mean (standard deviation).

The purpose of the Monte Carlo simulation procedure is to allow parameters to vary randomly such that each trial has a unique set of parameters. When running the model, we simulate the net benefits for the switch to each of the improved stove options over 10,000 realizations of values for these uncertain parameters. A useful way to summarize these results is to show a cumulative distribution function where the x-axis is the monthly net benefits in dollars per household per month and the y-axis is the proportion of results that fall below that dollar amount (see Box 5). Because the parameters have been sourced from the literature, we believe that the outcome distributions likely reflect those that are likely to exist in developing countries. Furthermore, we would expect to find site-specific circumstances in developing countries with a similar range of outcomes. Yet we emphasize that the frequency with which any specific combination of parameter values – or net benefit outcomes – would arise is unknown. As a result, these cumulative distributions should not be interpreted to represent the precise distribution of real-world outcomes.

Box 5. Cumulative distribution function

Individual results from the Monte-Carlo simulations are summarized in a cumulative distribution function (Figure 5). The X-axis shows the monthly net benefits per household and the Y-axis refers to the percentage of simulation trials that are less than or equal to that amount.

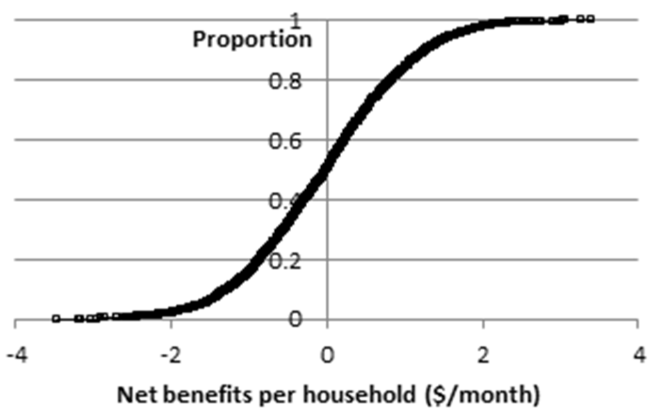


Figure 5. Example of a cumulative probability function for the net benefits per household per month.

4. RESULTS

We first provide some basic information about the composition of costs and benefits for different ICS options at the medium values of the model parameters, before turning to the more meaningful results from the simulation analysis. In what follows, we show three sets of results: 1) The private net benefits of ICS adoption (Private); 2) A narrow definition for social net benefits (Social), which consist of private benefits plus averted deforestation and a restricted set of climate benefits; and 3) A more complete definition for social net benefits (Social+), which consists of the former plus additional emissions reductions benefits. In the first definition of climate benefits, we include only changes in the relevant greenhouse gases considered under the Kyoto protocol (carbon dioxide, methane, and nitrous oxide), while the latter also includes black carbon, carbon monoxide, and non-methane hydrocarbons. These non-Kyoto protocol emissions, while not currently considered under international agreements, do have significant warming potential (IPCC 2013). This is especially true for black carbon which is produced in abundance by residential biomass fuel burning (Bond et al. 2013). In addition, we present sensitivity analyses for the private net benefit results. The purpose of these sensitivity analyses is to provide insights on which parameters have a large influence on the results.

<u>Composition of benefits and costs for mean parameter values</u>

Figure 6 shows the composition of private costs and benefits for the four ICS technologies considered here, using the mean values for all parameters used in the simulation trials. These mean values are included purely for illustrative purposes, since they do not pertain to any specific location and may not even be likely outcomes in the real world. Across all ICS types, the major costs are stove (capital) cost and program cost, while operation and maintenance and learning are relatively minor. Net fuel savings is positive and large for biomass ICS while negative and large for LPG and charcoal stoves. This is because unlike wood fuel, which can be collected, LPG and charcoal needs to be purchased from the market and the purchase cost outweighs the benefit of using less fuel. The exception to this is the electric stove where there is no net change in fuel cost. Other significant benefits include time savings and health, with the latter being larger for the cleaner-burning fuels (LPG and electricity). At the mean parameter values, all stoves deliver positive net benefits except for the LPG stove, due to the higher fuel cost for that option.

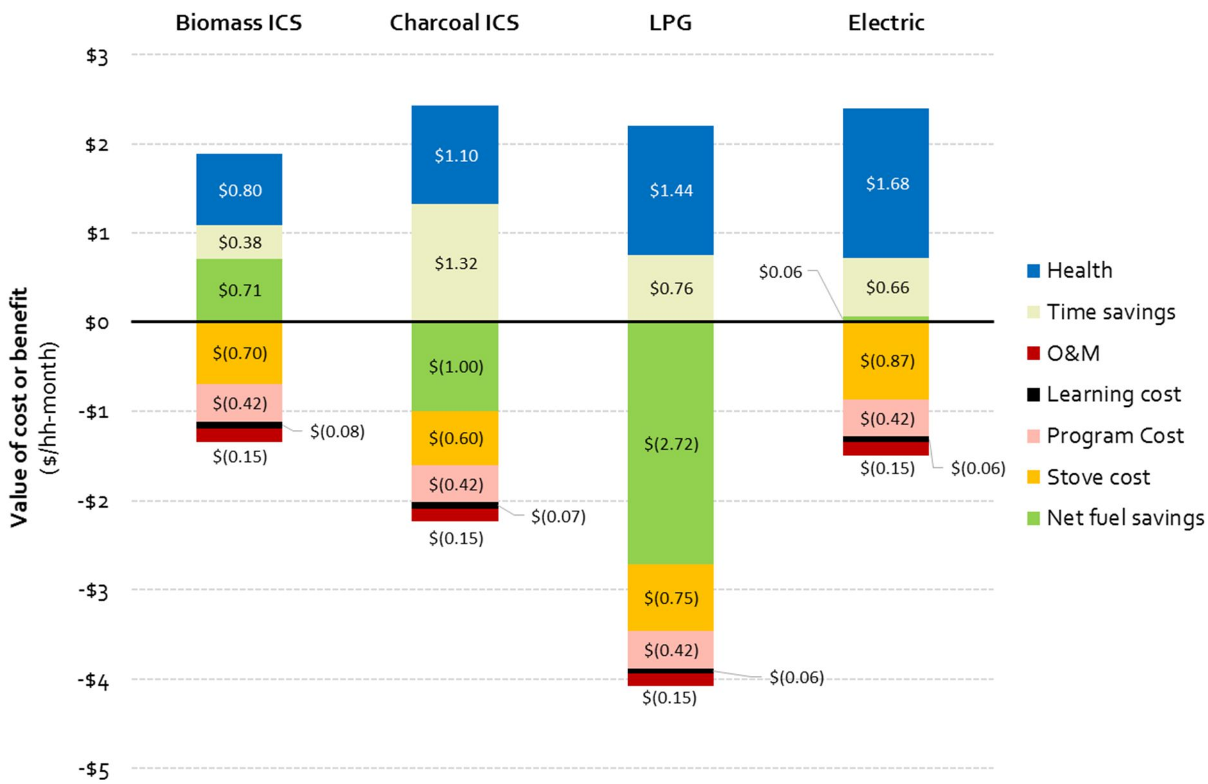


Figure 6. Composition of private costs and benefits for the five ICS options (Note: All parameters are set to mean simulation values)

Adding the social benefits to the overall net benefits at these medium parameter values yields the results shown in Figure 7. For all stoves except the electric ICS, adding the Kyoto pollutants to the calculation improves outcomes. The electric stove performs worse in this calculation because the resulting emissions mix is consistent with significant amounts of coal production, which generates large amounts of greenhouse gases. The charcoal and biomass ICS options only provide modest emissions reductions, whereas the LPG option provides the greatest reductions. Finally, in the social+ perspective, all stoves generate significant social benefits. This reflects the reductions in black carbon emissions, which are not offset by reduced production of OC, a net cooling agent. In this social+ perspective, electric stoves perform much better than in the social perspective, and are even favored over the biomass ICS.

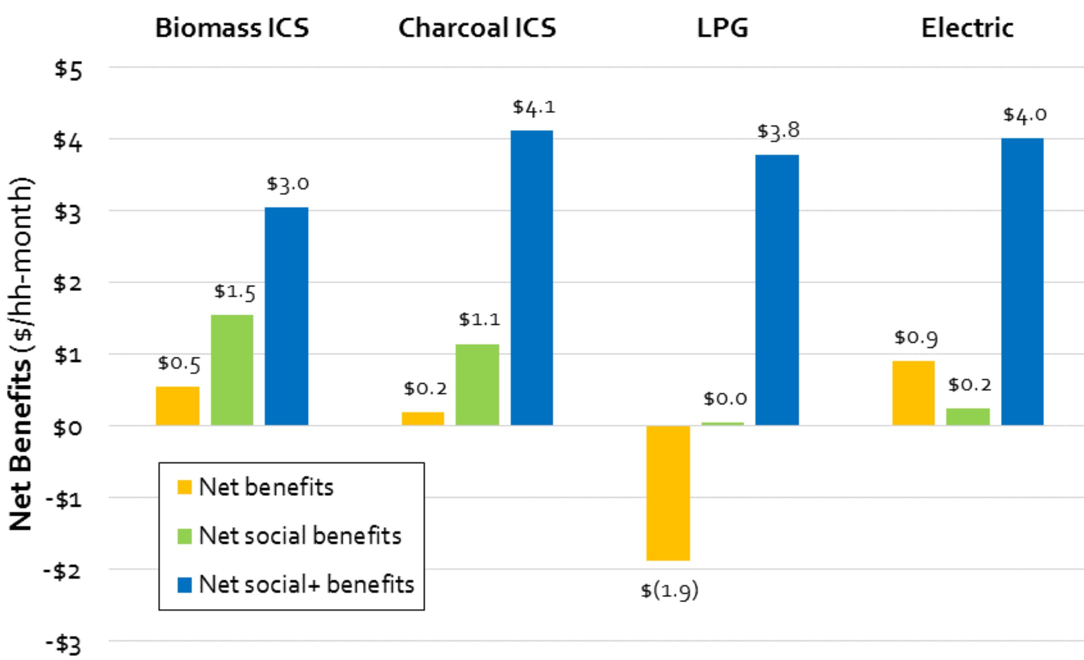


Figure 7. Change in net benefits for the five ICS options under private and social perspectives (Note: All parameters are set to mean simulation values)

Simulation results: Private net benefits

The previous results however ignore the variability in economic outcomes. We next turn to the results of the Monte Carlo simulation analysis of the four stove transitions to better understand this variability. Figure 8 shows the cumulative distribution functions for the four types of ICS included in this study. We observe that a LPG ICS stove delivers positive benefits in only about 37% of the trials; our prior decomposition suggests that this is due to the high relative cost of this fuel. Compared to the LPG option, biomass ICS only perform marginally better (with about 40% of trials yielding positive net benefits). The charcoal and electric options, meanwhile, produce positive private net benefits in about 50% and 64% all simulations, respectively. Compared to JP, our analysis is more positive on electric stoves; the main reason for this difference is the lower price of electric stove options considered in this study. The rapidly changing landscape of cookstoves interventions has introduced to the field ICS' that were not considered just a few years ago (e.g., Jeuland et al (2015) studies an intervention with a low-cost electric ICS in India). In turn, this allows us to gather more realistic parameters for use in the analyses. We also note that in practice, we may not expect households to be fully cognizant of all the benefits from ICS adoption. This is especially true for future benefits such as health improvements, or for non-market fuel collection benefits. As such, these simulations may help to explain why some ICS dissemination studies find relatively lower levels of adoption or sustained use of biomass ICS.[10]

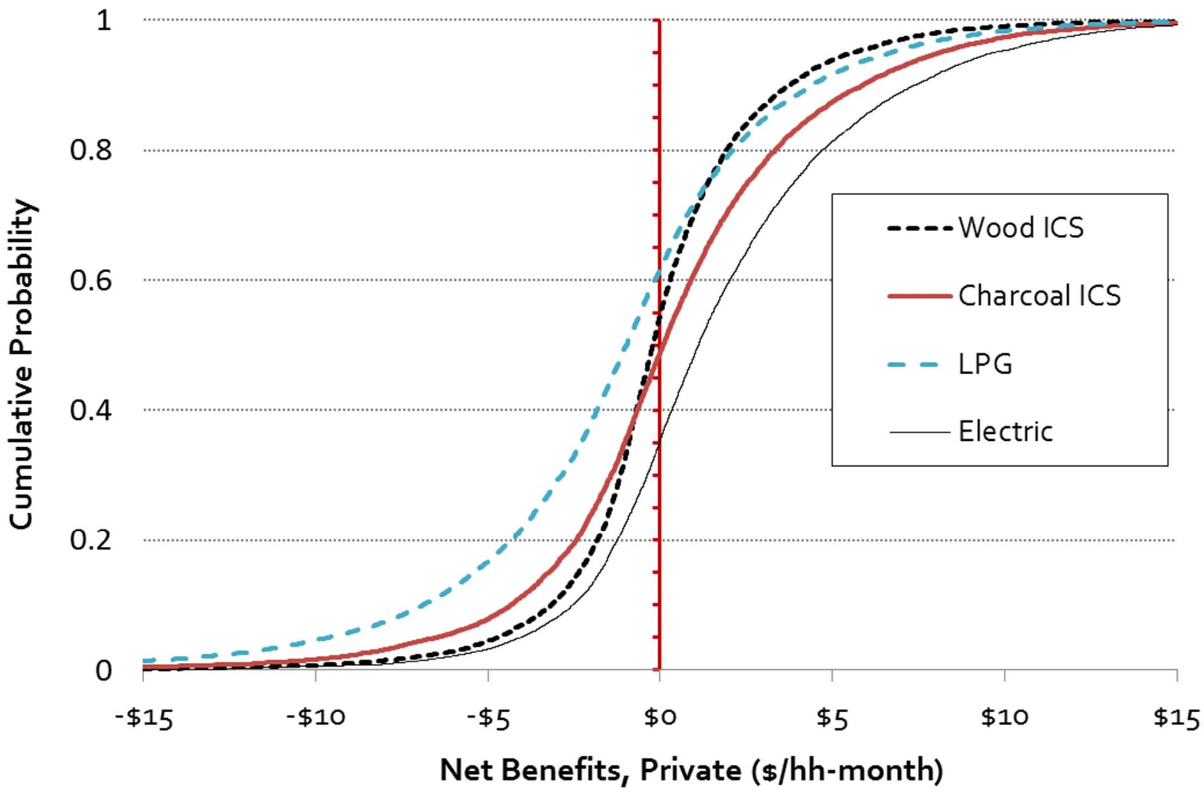


Figure 8. Cumulative distribution for net private benefits – South Asia

<u>Sensitivity analysis: Private net benefits</u>

To better understand the sources of variation in these private net benefit calculations, we conduct a one-way sensitivity analysis in which we hold all but one parameter constant. This allows us to better understand the drivers of the variation in results across the simulation trials as it tells us which parameters have the greatest influence on the net benefits (Figure 9).[11]

[10] For example, in Jeuland et al (2014), households were offered the opportunity to purchase biomass or electric ICS. At the lowest level of rebate (about 5% of ICS purchase price), only about 16% of households purchased a stove. The next highest level of rebate was at 20% of the ICS purchase price, and only 36% of households chose to buy. In terms of sustained use, Hanna et al. (2012) showed that a majority of households chose not to maintain use of their ICS even though it was given to them for free, suggesting that they may not have perceived them to deliver net benefits.

[11] Similar sensitivity analyses for social and social + net benefits are available upon request.

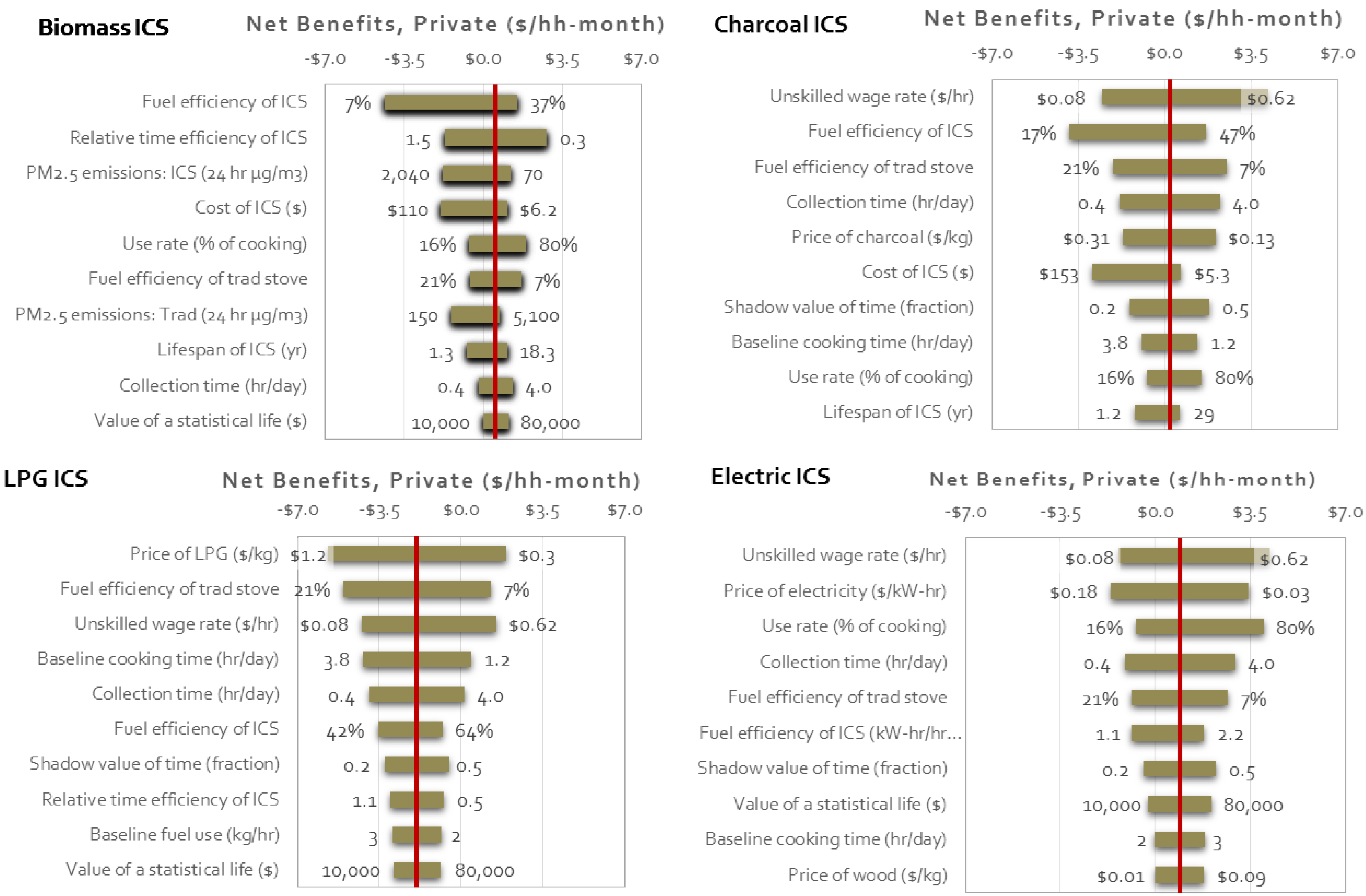


Figure 9. One-way sensitivity analyses for net private benefits – South Asia

The first and perhaps the most striking observation is that a large number of time-related parameters that include the wage rate and shadow value of time, the time spent cooking and collecting fuel, and the time efficiency of different stoves play significant roles in the determination of net benefits. For example, with all other parameters at their mean values, the net benefit for adoption of a biomass ICS becomes sharply negative when this stove requires more time for cooking than a traditional stove. Such a situation may seem unlikely to ICS proponents but it is possible when such stoves are hard to use effectively for some preparations or when multiple dishes must be prepared (MacCarty et al. 2010). Similarly, when biomass fuel is easy to collect (0.4 hours per day), the net benefits become negative (-$0.1/hh-month), as they do for LPG stoves (-$1/hh-month). For the commercial fuel stoves, when the value of time is low (reflected in the shadow value of time multiplied by the wage rate), the net benefits of adoption quickly turn negative. For these stoves, fuel costs are also very important in affecting net benefits.

Second, the ICS use rate shows up as an influential parameter for biomass, charcoal, and electric stoves. The importance of this parameter is to be expected as it enters into all of the equations that produce benefits. This provides motivation for better understanding how to move behavior in a way that increases households' stove usage (in addition to ownership), and for understanding how use is related to convenience factors such as time savings and fuel efficiency.

Third, compared to previous studies, health-related parameters appear to have a more limited role in changing overall net benefits. For the biomass ICS, the parameters for PM emissions levels from the ICS and from the traditional stove are important in determining net benefits. The other health-related parameter that shows up frequently is the value of a statistical life (for all but the charcoal ICS). Larson (2014) conducted a similar cost-benefit analysis of ICS adoption and found health improvements to be a major contributor to benefits. While different modeling assumptions and parameter assumptions are responsible for differences in our results (including our more sanguine treatment of partial stove use), our results should not be misinterpreted to argue that health benefits are inconsequential. For one, the electric and LPG stoves reduce PM emissions sharply, and the decomposition analysis from Figure 6 shows that health benefits are substantial. Figure 10 further shows the cumulative distributions with health benefits entirely removed. It is obvious that all cooking options become much less attractive when we ignore these benefits, with over 40% of simulations for all stoves, and 80% for LPG, yielding negative net benefits in this case. Thus, even though the health-production parameters do not play as prominent a role in the sensitivity analysis, this category of benefits still remains an important component of the overall benefits of ICS adoption. Finally, additional sensitivity analysis allowing for a larger VSL range (consistent with that in Larson's analysis) results in a slightly greater importance of this parameter in determining outcomes for all stoves, but it never rises higher than fourth (for the electric ICS) in the sensitivity charts for private benefits.

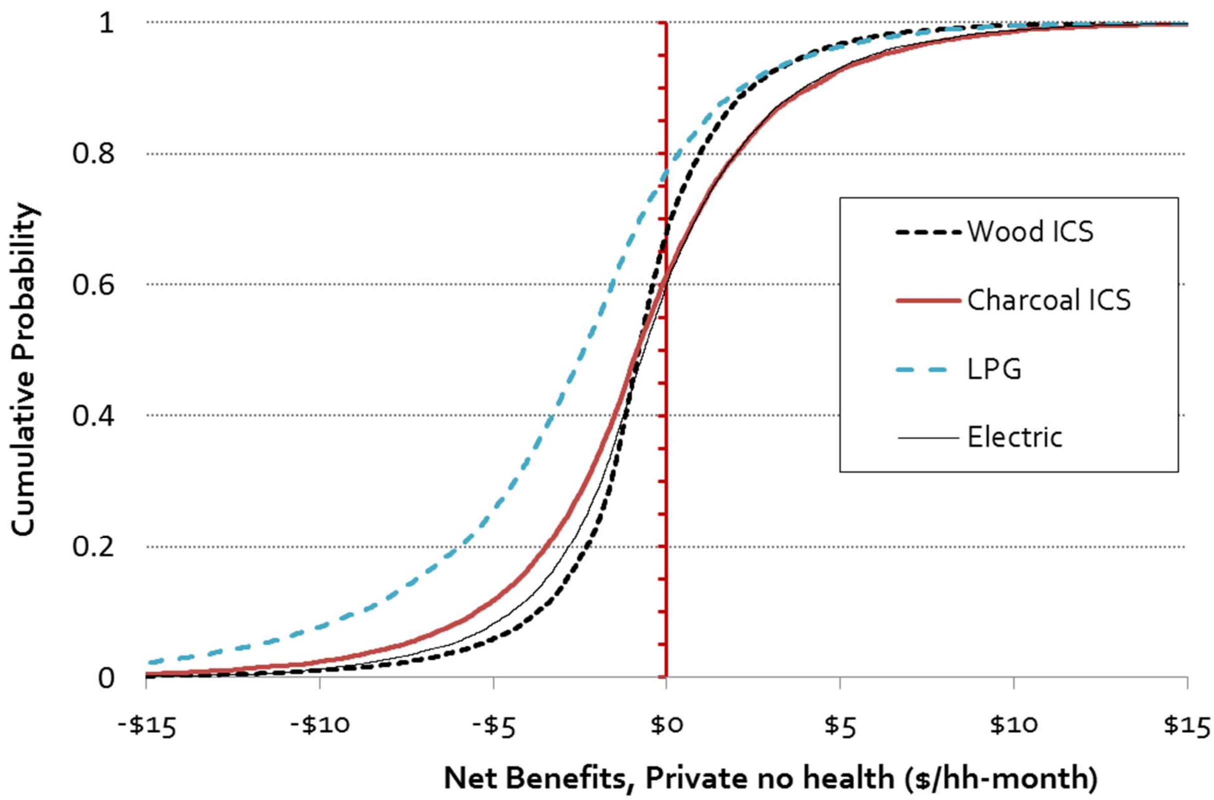


Figure 10. Cumulative distribution for net private benefits without health – South Asia

Simulation results: Social net benefits

Compared to Figure 8, and consistent with the basic results presented above that showed higher net social benefits for most ICS options, the curves for social benefits mostly shift to the right (Figure 11). This is unsurprising as the social impacts (in climate mitigation and reduced tree lost) tend to be positive, except for inefficient and electric ICS (in locations where electricity is largely generated from coal-fired power plants). Adoption of the biomass-burning ICS now delivers positive net benefits in about 70% of trials. The inclusion of social benefits thus increases the percentage of trials with positive outcomes by 30 percentage points. In contrast, the electric stove is now only beneficial in about 30% of the trials, and has the widest tail over the domain of negative net benefits. The percentages of trials with positive outcomes for the other 2 ICS all increase by a substantial amount, to about 70% for both charcoal and

LPG. Despite using present-value GWP for greenhouse gases, our results did not shift drastically to the right. Instead, compared to JP, our results for social net benefits show a fatter tail at the right side of the distribution, i.e. there are more trials with large positive results. This is because the magnitude by which present-value GWP for methane and nitrous oxide is larger than the conventional GWP is a function of the social discount rate. With the latter having a range of 1-6%, we see a more significant change between present-value and conventional GWP at larger discount rates. The implication is that the carbon benefits of ICS adoption considering these three pollutants alone are relatively modest.

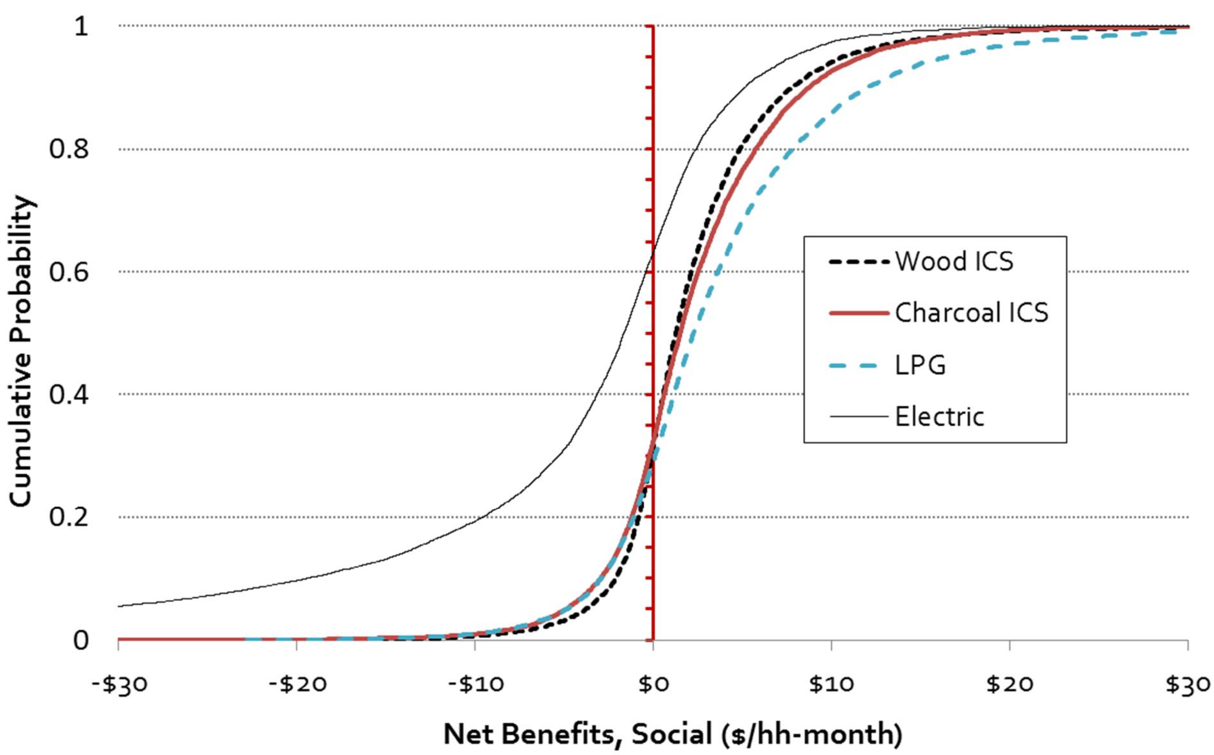


Figure 11. Cumulative distribution for net social benefits – South Asia (Social)

<u>Social net benefits+</u>

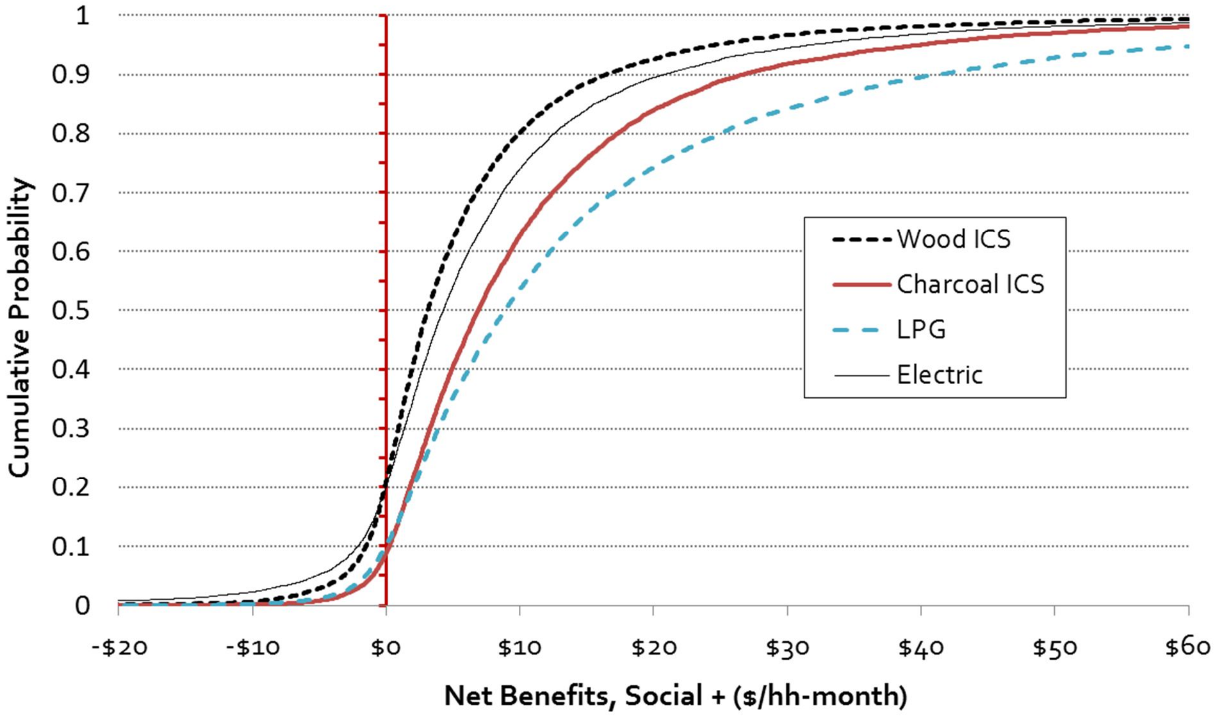
We next add additional combustion by-products that have potent cooling or warming effects and are emitted during residential biomass fuel combustion. These additional emissions comprise organic carbon (OC), black carbon (BC), and carbon monoxide (CO). Of these, BC has received a lot of attention from climate scientists due to its extremely high climate-forcing properties and the fact that it is emitted in large quantities by traditional cookstoves (Bond et al. 2004, Bond et al. 2013). Less commonly included however is OC, which has a net cooling effect and is also emitted in large quantity by traditional biomass stoves. Given these offsetting effects, it is unclear whether we should expect an increase in net benefits.

Two cumulative distributions are presented here – one for South Asia and another for rest of the world. The reason for this distinction is that BC has a non-trivial effect on global warming through decreasing the albedo effects of snow-caps and glaciers. According to Bond et al (2013), a significant portion of the BC found in the Himalayas is from residential biomass combustion. On the other hand, BC from the Arctic is mainly from vehicular and factory sources. Put together, this means that BC emitted from stoves in South Asia possibly have a larger warming impact than BC emitted elsewhere. This is reflected in the analysis by specifying a different greenhouse warming potential for BC (higher by 10%) in South Asia and in the rest of the world.[12] This is not the only source of heterogeneity in the cost and benefits of ICS adoption. However, it is a particular area we want to highlight given the growing attempts to include (and pay for) reductions in BC emissions as one of the important categories of positive benefits of ICS interventions (Bond and Sun 2005, Anenberg et al. 2013).

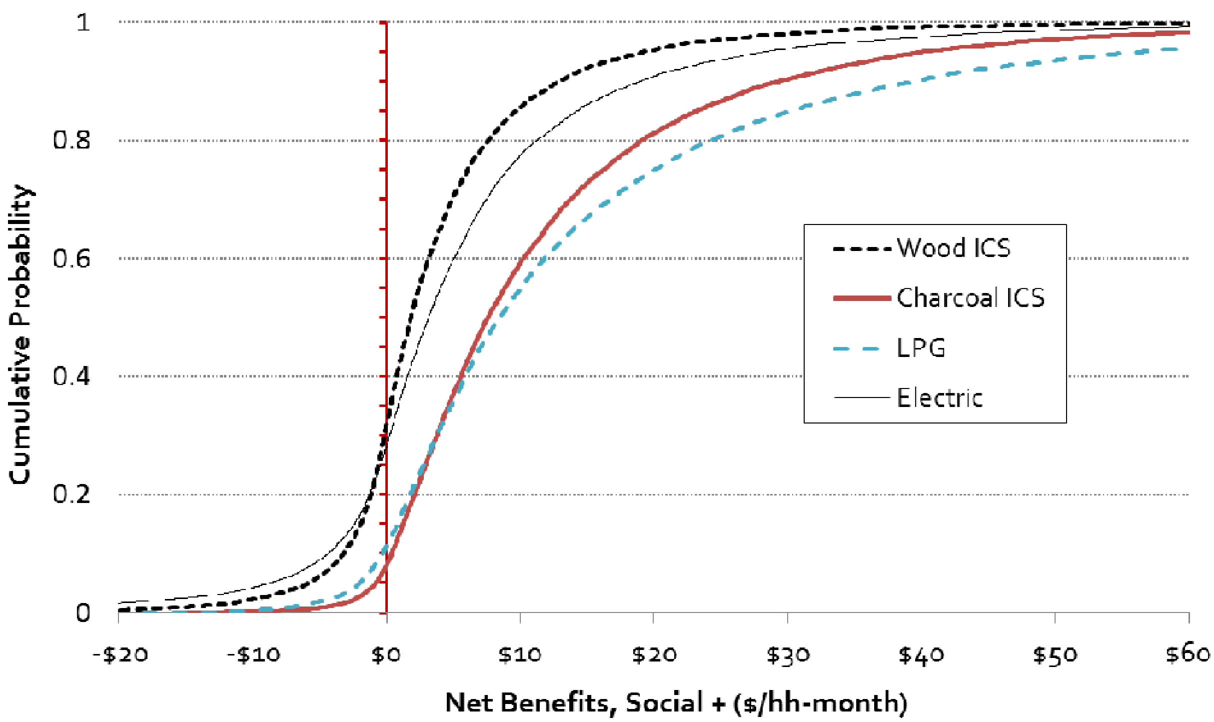
The cumulative distributions for this additional set of simulations are presented in Figure 12. For both South Asia and the rest of the world, about 90% of all trials for the charcoal ICS and LPG stoves are now positive. The main difference between the regions lies in the distributions for net benefits for the biomass and electric ICS.[13] For the latter, about 80% of the trials using South Asian parameters yield positive net benefits compared to 72% for the rest of the world. For the former, about 80% of trials yield positive net benefits in South Asia, compared with 68% in the rest of the world. From an economic standpoint, these result suggest that there should be a (carbon financing) premium for successful South Asian ICS intervention programs, even accounting for the differential variation in other parameters across the two regions. In addition, these results highlight the contradictions inherent in the current focus on biomass ICS options, since it appears that cleaner fuel options yield both larger private and social benefits, and a higher net value of emissions reductions.

[12] See Bond et al (2013), Figure 41.

[13] Here it is important to note that the electric ICS calculation does not include carbon monoxide, since we could not find extensive information on emissions of CO from power plants. Thus, the benefits may be somewhat overestimated for the electric ICS.



(Top) South Asia



(Bottom) Rest of the World

Figure 12. Cumulative distribution for net social benefits (including additional climate forcing agents)

5. Conclusion

To combat the multiple ill effects that stem from use of inefficient cooking technologies, the global community is increasingly engaged in efforts to promote cleaner-burning cookstoves. The benefits of adopting such technologies comprise private benefits in time and fuel savings as well as improved household health, and social benefits stemming from reduced climate-damaging emissions and unsustainable pressure on forest ecosystems.

Simplified and deterministic cost-benefit analyses appear to argue that households always benefit from such technologies (Hutton et al. 2007; Larsen 2014), but such predictions are difficult to square with the reality of low demand and adoption. Such analyses thus likely miss critical aspects of the household decision problem, perhaps due to miscalculation of costs and benefits, a lack of appreciation for the variability of private benefits across locations and households, and a misalignment of realized private benefits and those achieved under ideal (trial) conditions.

In this paper, we build on an approach previously applied by Jeuland & Pattanayak (2012) by incorporating a theoretically-consistent computation of greenhouse effects and health benefits, and increasing the database used to simulate a range of realistic distributions of net benefits. Similar to Jeuland & Pattanayak (2012), we also focused on the divide between social and private benefits. Our analyses show that biomass ICS, charcoal ICS, and LPG stove adoption is not consistently beneficial from a household perspective, with at least half of model simulations yielding negative net benefits for such stoves. Meanwhile, electric stoves more often deliver positive net benefits from a private perspective. These results may partly explain why adoption and usage of ICS is often low even when distributed freely (Hanna et al. 2012). At the same time, these results also emphasize that other types of challenges – for example related to a lack of reliable supply for alternative fuels, or taste preferences – may result in stacking of these alternatives alongside of more traditional options.

Using tornado charts, we also conducted sensitivity analyses to assess the contribution of model parameters to variation in net benefits. These analyses generate a number of policy-relevant insights. First, it is encouraging that the price of cookstoves' is not a major factor in determining net benefits, but empirical evidence also suggests that liquidity constraints play a role in suppressing adoption among the rural poor (Beltramo et al. 2015). Future interventions should continue to aim to reduce the upfront costs of stove adoption, perhaps building on recent progress in using local materials and craftsmen to design and manufacture stoves. Second, time savings and fuel costs play a very significant role in determining private benefits, and plausible variation in many of the time-related parameters explains a large amount of variation in our results. Thus, our results suggest that greater emphasis should perhaps be placed on improving the time-savings attributes of non-traditional stoves, and on better measuring the extent to which they provide these benefits. For example, the 'fuel efficiency' criterion under the IWA tiers of cookstoves performance focuses only on thermal efficiency whereas our literature search reveals that thermally efficient ICS are not necessarily time efficient, perhaps because they become more difficult to cook with (Table 4). Perhaps as importantly, commercial fuels are relatively expensive, so the challenge of sustained use of stoves seems at least as great as that of stove purchase, yet is ignored in most intervention strategies.

From a social perspective, the benefits of most stoves become larger due to avoided climate-damaging emissions, although biomass ICS still perform poorly in roughly one third of our global simulations. At first glance, this result may seem surprising, given that black carbon has a strong forcing effect on the climate. But black carbon is co-emitted with large amounts of organic carbon, which itself has a net negative forcing effect on climate that serves to counteract the effect of the former. The implication is that greater combustion and fuel efficiency produces far greater gains than stove type, at least from a climate perspective. Furthermore, despite the large and obvious benefits from more efficient fuels, at present, there are no mechanisms for awarding carbon credits for switching to LPG, electric cookstoves. As such, this is an area in immediate need of further work.

Of course, the problem of adoption of improved cooking technologies extends well beyond a simple balance of costs and benefits, and requires an integrated approach that appreciates cultural and aesthetic preferences for tradition as well as institutional and supply-side challenges (Ezzati and Kammen 2002, Jeuland et al. 2014). This study, like all cost-benefit analyses, therefore only paints a partial picture of the important issues. Nonetheless, our findings fail to provide strong support for the current push to promote higher efficiency biomass ICS in all locations where households rely on traditional stoves. Rather, they suggest that biomass stoves will produce economic gains for many households in some types of locations, while alternative fuels and choices with other households may be more appropriate. And due to the complex web of parameters that influence the production of net benefits, it will generally be difficult for planners to determine which options to pursue. Instead, more participatory and user-centered approaches, with the help of interventions that address other common barriers to technology adoption, will help to enhance the results of stove promotion efforts.

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Appendices

A. Detailed explanation of calculations

Costs

1. <u>Capital cost</u>

Capital cost (*Cap*) is calculated by amortizing the cost of the cookstove (c_i^m) over its lifetime in years (T_i) and the discount rate (δ), using the capital recovery factor (*crf*). A monthly cost is obtained by dividing this annualized cost by 12.

$$Cap = {c_i^m * crf}/{12}, \text{ where} \tag{A1}$$

$$crf = {\delta_p \cdot (1 + \delta_p)^T} \Big/ {(1 + \delta_p)^T - 1}. \tag{A2}$$

2. <u>Program cost</u>

The program cost (*Prog*) is the cost of implementing an ICS intervention program. While the cost of cookstove interventions may vary, there are insufficient data to distinguish program costs according to the type of intervention and ICS. Similarly, the annual program cost (c^p) is divided by 12 to obtain a monthly cost.

$$Prog = {c^p}/{12}. \tag{A3}$$

3. <u>Operation and maintenance cost</u>

Net operation and maintenance cost (*O&M)* is the difference between the maintenance cost of an ICS and that of a traditional stove. The cost of maintenance for a traditional stove ($Main_0$) is assumed to be zero as these stoves are easily replaced and typically much cheaper compared to their ICS counterparts. On the other hand, while it has been well-documented that regular maintenance is essential for continuing ICS usage, very few studies collected data on maintenance cost. To this end, we estimate the ICS' monthly maintenance cost ($Main_i$) by amortizing a *variable* fraction of the stove's cost by its lifetime.[14] Finally, we scale the difference in maintenance cost by the rate of usage (χ) of the ICS as a lower rate of usage would indicate a reduced need for regular upkeep.

$$O\&M = \chi * (Main_i - Main_0) = \chi * (Main_i). \tag{A4}$$

4. <u>Learning cost</u>

[14] In lieu of actual data on stoves' maintenance cost, we proxy by amortizing a fraction of stove's purchase cost where this fraction ranges from 50% to 100% of the stove's cost.

As with the stove purchase cost, we amortize the one-time learning cost (*l*, in hours) according to the lifetime (in years) of the cookstove and divide by 12 to get a monthly cost. Since *l* is measured in hours, we need a valuation relationship for this time. To approximate the opportunity cost of time, we assume that the shadow value of time is some proportion (κ^t) of the unskilled wage rate (*W*). As data on wage rates in developing countries is not readily available, especially for rural areas where most traditional stoves are used, we rely on the national minimum wage rate as a guide for this unskilled wage rate. However, because this minimum wage probably overstates the value of time in locations with low rates of formal labor market participation, we additionally scale this official minimum wage rate by a the shadow value of time parameter (κ^t) that represents the opportunity cost of time as a fraction of this minimum wage.

$$Learn = {}^{l \cdot v^t \cdot crf}/_{12}, \text{ where} \tag{A5}$$

$$v^t = \kappa^t \cdot W. \tag{A6}$$

5. <u>Fuel cost</u>

Calculation of net monthly fuel savings (*Fuel*) due to a switch from a traditional stove to a wood ICS requires several steps. The net value of fuel savings is calculated as the difference between the cost of fuel used in an ICS ($Fuelc_i$ in /month) and the cost of fuel used in a traditional stove ($Fuelc_o$). However, because most households do not use their ICS exclusively, we must weight these fuel savings by the ICS usage rate χ:

$$Fuelsav = \chi * (Fuelc_i - Fuelc_0) \tag{A7}$$

As fuel cost is not a commonly collected metric in surveys, we must find ways to approximate it using other data.

We first calculate $Fuelc_o$ (Equation A8):

$$Fuelc_0 = Fuelu_0 \cdot f \cdot p_{wood} + 30 \cdot collt_0 \cdot (1 - f) \cdot v^t. \tag{A8}$$

The first term on the RHS is the cost of purchasing fuelwood. This is derived by scaling fuel usage with the traditional stove ($Fuelu_o$ in kg/month) according to the proportion of wood purchased through the market place (*f*). We note that this traditional fuel use in weight is not always reported by cookstove studies because it may be hard to measure or estimate. We can therefore approximate $Fuelu_o$ using equation A9:

$$Fuelu_0 = 30 \cdot (cook_0 \cdot fuelckg_0). \tag{A9}$$

In this expression, $Fuelu_o$ is obtained by multiplying the time spent cooking on a traditional stove ($cook_o$, in hr/day) by the amount of fuel used per hour of cooking ($fuelckg_o$).

This wood is purchased and can thus be valued using the market price of wood (p_{wood} in /kg). The remainder of the fuelwood, which is self-collected, must then be valued based on the opportunity cost of collection time (the second term on the RHS of equation A8). We multiply baseline fuelwood collection time ($colt_o$ in hr/day) by the proportion of fuelwood that is collected and the opportunity cost of time v^t, defined previously. The use of v^t in equations A5, A8, and (later) A12 and A13 therefore assumes that the value of cooking time, fuel collection time, and time spent learning to use an ICS is equivalent.

Next, we calculate the fuel cost for an ICS (*Fuelc$_i$*).

6a. <u>Biomass ICS</u>: For a biomass-burning ICS, the calculation is similar, except that it includes an additional fuel preparation cost (*prep* in hr/day, again valued using v^t). This is because most biomass ICS' are designed to hold smaller pieces of fuel and thus may require additional fuel preparation.

$$Fuelc_i = Fuelu_i \cdot f \cdot p_{wood} + 30 \cdot (\frac{Fuelu_i}{Fuelu_0}) \cdot collt_0 \cdot (1 - f) \cdot v^t + 30 \cdot prep \cdot v^t \qquad \text{(A10)}$$

Finally, using information on the relative fuel efficiency of various cookstoves (εf_i) and energy content of different fuel types (μ_i, in MJ/kg), we can calculate the fuel use of the ICS (*Fuelu$_i$*) that is needed for the first term of equation A10:

$$Fuelu_i = Fuelu_0 \cdot {}^{\varepsilon f_0 \cdot \mu_0}/_{\varepsilon f_i \cdot \mu_i} . \qquad \text{(A11)}$$

6b. <u>ICS that use other fuels</u>. Fuel savings calculations for other ICS are similar except for two differences. First, there is no fuel collection or preparation cost as we assume that other fuels (i.e. charcoal and LPG) do not need these. Second, the unit used for calculating the fuel cost of an electric stove is slightly different since electricity usage is defined in kilowatt-hours rather than kilograms.

$$Fuelc_i = Fuelu_i \cdot f \cdot p_i \qquad \text{(A12)}$$

Benefits

6. <u>Time savings</u>

Equation (A5) values the time saved by cooking on the ICS relative to a traditional stove. Time saved is quantified by multiplying time spent cooking on a traditional stove (*time$_o$* in hr/day) by the time efficiency of ICS relative to a traditional stove (*te$_i$*). To arrive at a monthly figure that is indicative of usage (hr/month), we multiply the daily time savings by 30 (days) and by the rate of usage. Finally, we again value this time savings using the opportunity cost of time as defined above

$$Timesav = 30 \cdot cook_0 \cdot \chi \cdot (1 - te_i) \cdot v^t. \qquad \text{(A13)}$$

7. <u>Health benefits</u>

To value mortality and morbidity improvements from reduced exposure to household air pollution (HAP), we must first quantify health improvements. We use the exposure-response functions derived by Burnett et al (2014) for various respiratory-related diseases as they relate to concentrations of $PM_{2.5}$ (µg/m^3 in 24 hours). To calculate the level of $PM_{2.5}$ following the ICS intervention ($PM_{2.5}$), we use data on emissions from different ICS ($PM_{2.5,i}$) and scale the reductions from the traditional stove ($PM_{2.5,0}$) using the rate of ICS usage:

$$\mathrm{PM}_{2.5} = \chi \cdot \mathrm{PM}_{2.5,i} + (1 - \chi) \cdot \mathrm{PM}_{2.5,0} \qquad \text{(A14)}$$

Using this new concentration $\mathrm{PM}_{2.5}$, we use the Burnett relationship to calculate the relative risk (*RR*) of mortality (or morbidity) for specific diseases for each stove-fuel combination.[15] Because there are multiple causes for each disease, we must also assign the portion of risk attributable to stoves' emissions using the population attributable fraction (*PAF*). Calculation of the PAF for stove *i* (PAF_i) requires the fraction of population exposed to IAP and we use the proportion of solid fuel users (*sfu*) in the population as a proxy for this indicator (equation A15):

$$PAF_i = {sfu * (RR_k - 1)} \Big/ {sfu * (RR_k - 1) + 1} \tag{A15}$$

Next, to quantify the reduction in mortality from a specific disease *k* (in the above relationship the following diseases are included: acute lower respiratory illness, chronic obstructive pulmonary disease, ischemic heart disease, and lung cancer) given the use of stove *i*, the change in the PAF is multiplied by the mortality rate of the disease MR_k. For morbidity improvements, we multiply the change in the PAF by the incidence rate (for ALRI) or prevalence rate (for other diseases) (IR_k).

$$Morb_k = hhsize \cdot (PAF_0 - PAF_i) \cdot IR_k \text{ and} \qquad \text{(A16)[16]}$$

$$Mort_k = hhsize \cdot (PAF_0 - PAF_i) \cdot MR_k \tag{A17}$$

For valuing these benefits of reduced morbidity and mortality, we must account for the fact that the health improvements from HAP reductions are staggered in time by discounting those that occur in the future. To do this, we use the EPA's cessation lag concept, which assumes that 30% of the health benefits from IAP improvements are observed in the first year; 20% in the second year; and the remaining 50% are equally spread out over the next three years (Equations A18 and A19). We then sum the changes over all diseases and value mortality reductions using the value of a statistical life (*VSL* in /life). Morbidity improvements are valued using the cost-of-illness (*COI*$_k$ in /case), which is a conservative measure of the value of morbidity improvement:

$$Morb = \sum_k \left(\sum_{t=1}^{5} CL_{kt} \cdot COI_k \cdot (Morb_k)/(1+\delta)^{t-1} \right)/12, \tag{A18}$$

$$Mort = \sum_k \left(\sum_{t=1}^{5} CL_{kt} \cdot VSL \cdot (Mort_k)/(1+\delta)^{t-1} \right)/12, \tag{A19}$$

where CL_t=0.3 for t=1; 0.2 for t=2; and 0.5/3 for 3≤t≤5 for COPD; CL_t=0.7 for t=1; 0.1 for t=2; and 0.2/3 for 3≤t≤5 for ALRI; and CL_t=0.2 for t=1; 0.1 for t=2; and 0.7/3 for 3≤t≤5 for IHD and for LC.

8. Carbon emissions reductions

Carbon emissions reductions constitute an important potential social benefit of more efficient cookstoves. Cooking with biomass in inefficient stoves produces a range of climate-forcing pollutants. As in the calculation of the economic benefits of health improvements, there are two main components

[15] Parameters for the relative risk functions can be downloaded from here: http://ghdx.healthdata.org/sites/default/files/record-attached-files/IHME_CRCurve_parameters.csv

[16] For ALRI, we use the number of children under 5 (*hh<5*) instead of household size.

in valuing reductions in these emissions (*Carb*) – the value of the (marginal) changes and the total amount of the reduction.

Calculating the amount of emissions reduction is complicated by the fact that cookstoves emit a range of pollutants, some of which (e.g., black carbon, CO, and CO_2) increase warming, and others of which (namely organic carbon) reduce it. These various emissions must be normalized and expressed in commensurate terms, at least with respect to the time-varying aspects of their overall global warming potential (*GWP*). Our approach builds on Shindell et al. (2015) to calculate the *GWP* due to cookstoves using base parameters for the global warming for the main substances these emit, which relates to the energy content of fuels and efficiencies of stoves.

We start by multiplying emissions factors $\varepsilon_{j,i}$ of particular gases *j* for various stove-fuel combinations *i,m* (e.g., $\varepsilon_{CO2,i,m}$ in g CO2-eq/MJ), by the GWP_j for those particular gases (GWP_{CO2}). Equation A20 shows the GWP_j derivation for a stove-fuel combination *i* that includes only the three greenhouse gases – carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) – that were part of the Kyoto Protocol, and equation A21 is the one used in our analysis that generalizes this expression over additional pollutants (in our case this also includes black carbon (BC), organic carbon (OC), non-methane hydrocarbons (NMHC), carbon monoxide (CO), and sulfur dioxide (SO_2). An important detail of this calculation is that the carbon dioxide component of GWC is multiplied by the fraction of non-renewable biomass ψ, since renewable harvesting sequesters carbon at the same rate as it is consumed (it does not affect net emissions).

$$GWP_{i,m,Kyoto} = \varepsilon_{CO2,i,m} \cdot \psi + \varepsilon_{N2O,i,m} \cdot GWP_{N20} + \varepsilon_{CH4,i,m} \cdot GWP_{CH4} \quad \text{(A20)}$$

$$GWP_{i,m} = \varepsilon_{CO2,i,m} \cdot \psi + \textstyle\sum_{j\epsilon K} \varepsilon_{CO2,i,m} \cdot GWP_j, \text{ where } j = CO_2 \notin K \quad \text{(A21)}$$

For our purposes, the main challenge with the use of equation A21 is that the GWP of different pollutants changes over time in complex ways, since these substances have widely divergent lifetimes in the atmosphere. For example, CO_2 decays at a very slow rate and therefore exerts climate forcing over a long time horizon, while most of the climate forcing from BC is instantaneous. Climate scientists therefore typically compute an integral for GWP over some fixed time horizon *T* to express the forcing in commensurate terms. When used for valuation, this is equivalent to assuming that the discount rate δ over that fixed time horizon *T* is zero. There are thus two substantive problems with the approach: 1) It is incompatible with a world in which wealth is changing over time (which for equity purposes requires a non-constant discount factor), and 2) the assumed time horizon has a dramatic effect on the calculation of GWP, with no *a priori* rationale justifying the selection of a specific time horizon.

To address this issue, our approach derives the present value of radiative forcing associated with different pollutants. The formula for this calculation is shown in equation A22:

$$GWP_{j\epsilon K} = \left. \sum_{t=1}^{\infty} \frac{1}{(1+\delta_s)^{t-1}} \cdot RF_{j,t} \middle/ \sum_{t=1}^{\infty} \frac{1}{(1+\delta_s)^{t-1}} \cdot RF_{CO2,t} \right. \quad \text{(A22)}$$

where radiative forcing in future years is discounted relative to the present using an appropriate social discount rate δ_d, and still is normalized by the forcing from CO_2 (as shown in the denominator of A22). To obtain this time-discounted GWP, we simply calculate the time path of radiative forcing for pollutant *j* as a function of time *t* ($RF_{j,t}$ in W/m²). For our purposes, we limit our time horizon to 100 years. We then substitute this pollutant-specific, time-normalized GWP into equation A21.

The final step is to compute the change in forcing following adoption of a different stove-fuel combination, and to value that change. This calculation is shown by equation A23.

$$Carb = c^{CO2} \cdot \chi \cdot \left(fuelu_0 \cdot GWP_{i,m} \cdot \mu_m \cdot \varepsilon f_0 - fuelu_i \cdot GWP_{i,m} \cdot \mu_{i,m} \cdot \varepsilon f_i\right) \quad \text{(A23)}$$

In this expression, the CO_2-equivalent warming from stove *i* and fuel *m* ($GWP_{i,m}$ in g CO_2-eq/MJ useful energy) is multiplied by the energy content of the fuel being used (μ_m in MJ/kg fuel). This product is then multiplied by the fuel efficiency of the stove (εf_i) to account for differences in the thermal efficiency with which useful energy is derived from the fuel in a particular stove. This effective global warming potential (in g CO_2-eq/kg fuel) is then multiplied by the amount of fuel used per month ($fuelu_i$ in kg of fuel/month) to yield the g CO_2-eq/month. The terms for the traditional and improved ICS equivalent emissions are then scaled by the ICS usage rate, and the change in emissions if finally multiplied by the social cost of carbon (c^{CO2}, in /g CO_2).

9. Other environmental benefits

The other major category of social benefits is that related to the environmental services lost due to non-sustainable harvesting of biomass, or in the case of sustainable harvesting, the cost of tree replacement (*Bio*). The first type of such costs, associated with non-sustainable harvesting, is very difficult to generalize, and there are few high quality studies that measure such non-market values well. We can estimate the second category as the product of the cost of timber farming c^f (in /kg of wood produced) multiplied by the change in renewably-harvested biomass (as previously estimated). This is clearly a lower bound for other environmental values since it does not include the value of avoided deforestation or forest degradation (except insofar as this contributes to global warming).

$$Bio = c^f \cdot \chi \cdot (1-\psi) \cdot (fuelu_0 - fuelu_i) \quad \text{(A24)}$$

Total net benefits

To obtain the total net benefits (*NB*), we then subtract the sum of the costs from the sum of the benefits as shown below:

$$NB = \sum Benefits - Costs = (Morb\ +\ Mort\ +\ Timesav\ +\ Carb\ +\ Bio) \\ -(Cap\ +\ Prog\ +\ O\&M\ +\ Fuel\ +\ Learn). \quad \text{(A25)}$$

B. Parameterization of the model: Summary of data sources

Table B1. Stove costs (c_i^c, in)

Description	Location	Value	Source
Wood-burning ICS			
Rocket / Malena	Bolivia	30-40	World Bank (2011)
Ceramic	India	19-31	World Bank (2011)
Generic wood	Uganda	15	World Bank (2011)
Jiko kisasa / rocket mud	Kenya	1-6.5	World Bank (2011)
Efficiency	Bangladesh	5.80	Miller & Mobarak (2011)
Chimney	Bangladesh	11	Miller & Mobarak (2011)
Mud chimney	India	12.50	Hanna et al (2012)
Greenway Smart Stove		19.5	
AFEE-1		40-45	
Apon chulah		29-32.5	GACC catalog
Berkeley-Darfur "Cool Mesh"		18-35	GACC catalog
Berkeley-Darfur V.14		8-10	GACC catalog
Bharatlaxmi			GACC catalog
BioLite HomeStove		40-70	GACC catalog
Chitetezo / Canarumwe / Upesi Digital		2-4	GACC catalog
Concrete village stove		12-14	GACC catalog
DK-T5		20-30	GACC catalog
EzyStove		25-75	GACC catalog
FIRENZEL		43-53	GACC catalog
Firewood Stove		18-25	GACC catalog
GreenGenStove Model THX02		8-12	GACC catalog
Green Stove		30-40	GACC catalog
Himalayan clean cook stove		2-9	GACC catalog
Insulating Pottery Rocket Stove		6	GACC catalog
Jiko Chap Chap		29	GACC catalog
Jiko Kenya		34.5-40	GACC catalog
Jiko Poa		15	GACC catalog
Jiko Smart Wood		20-22	GACC catalog
Kuna Yala Stove		40-60	GACC catalog
Kunimbili		16.1-17.2	GACC catalog
KuniTatu - Three Stick Stove		11-13	GACC catalog
Kushal-2		25-40	GACC catalog
Mbaula Green		39-49	GACC catalog
Mwoto Quad2		10.8-16	GACC catalog
Mwoto Quad3.2		15	GACC catalog
Mwoto TLUD		14	GACC catalog
Natural Draft Top Lit Up Draft Stove (TLUD)		20	GACC catalog
Okelo Kuc Rural Stove		2-6	GACC catalog
PCS - 1		33	GACC catalog
Peko Pe		12-15	GACC catalog
Philips HD4008		31	GACC catalog
Prakti-MFS		38	GACC catalog
Prime Cylindrical		30	GACC catalog
Prime Square		30	GACC catalog
Quick Mami		30-50	GACC catalog
Rocket stove		15-23	GACC catalog
Rua		16-20	GACC catalog

Sampada		38-43	GACC catalog
Save80 Standard		20-55	GACC catalog
Save80 Wing Model		17-47	GACC catalog
SCODE Push-n-Pull stove		35-50	GACC catalog
Shakti Chula V.1		35	GACC catalog
Shakti Chula V.2		25.8-28	GACC catalog
Side Feed Fan Stove		20	GACC catalog
Small Natural Draft Sunken Pot Rocket Stove		20	GACC catalog
Square John		30-50	GACC catalog
TERI SPF143- forced draft mud stove		20	GACC catalog
Top Load Fan Stove		20	GACC catalog
Troika TLUD stove		16-20	GACC catalog
Unnotho Chulla		15	GACC catalog
VERC Grihalaxmi		2-4	GACC catalog
Zoom Dura		45	GACC catalog
Zoom Relief		25	GACC catalog
Zoom Versa		45	GACC catalog
Statistics – Mean (sd)		**24.8 (13.6)**	
Charcoal ICS			
Air Blower CCS 922A		12-20	GACC catalogue
Air Blower CCS 922B		4-7	GACC catalogue
Apon Chulah	Bangladesh	29-32.5	GACC catalogue
Briketi EcoStove	Uganda	9-11	GACC catalogue
Briketi EcoStove v2	Uganda	12-15	GACC catalogue
Canamake Ivuguruye	Rwanda	5.7-6.5	GACC catalogue
CCSD9		12-15	GACC catalogue
Charcoal stove	China	20	GACC catalogue
CookClean CookMate		6-20	GACC catalogue
EcoRecho		11-25	GACC catalogue
EzyChar		25-95	GACC catalogue
Firewood Stove		18-25	GACC catalogue
Himalayan clean cook stove		2-9	GACC catalogue
Jiko Africa		35.7	GACC catalogue
JikoJoy		20	GACC catalogue
jikokoa		40	GACC catalogue
Jiko Smart Charcoal		14-17	GACC catalogue
Kunimbili		16.1-17.2	GACC catalogue
KuniTatu - Three Stick Stove		11-13	GACC catalogue
Mbabula		25-50	GACC catalogue
Mbaula Green		39-49	GACC catalogue
Moto Stoves		25-32	GACC catalogue
Obama Stove		6	GACC catalogue
Okelo Kuc		7.25-15	GACC catalogue
Original Gyapa		7	GACC catalogue
Peko Pe		12-15	GACC catalogue
Portico Premium Stove		33-50	GACC catalogue
Prakti Single Burner Charcoal Stove		40-50	GACC catalogue
Rapidita		10-15	GACC catalogue
Recho Plop Plop+		13-25	GACC catalogue
Rua		16-20	GACC catalogue
SCODE charcoal stove all metal		28-35	GACC catalogue
SCODE Push-n-Pull stove		35-50	GACC catalogue

SCODE SP-FL micro gasifier Concrete body		50-80	GACC catalogue
SCODE SP-FL micro gasifier portable		50-80	GACC catalogue
Shakti Chula V.1		32.5-35	GACC catalogue
Shakti Chula V.2		25.8-28	GACC catalogue
Shakti Chula V.3		58-63	GACC catalogue
SmartHome Stove		11	GACC catalogue
Zoom Versa		45	GACC catalogue
StoveTec wood charcoal stove	Various	10-12	Worldbank (2011)
Generic charcoal stove	Uganda	11	Worldbank (2011)
Recho Mirak stove	Haiti	3-4	Worldbank (2011)
Statistics – Mean (sd)		**24.7 (17.4)**	
Liquid petroleum gas			
A1-m single stove	Ghana	40-48	GACC catalogue
NOMENA LPG Cookstove	Ghana	200-500	GACC catalogue
F2-m_Single stove	Ghana	40-48	GACC catalogue
LPG/NG 2B gas stove		19.79-21.99	GACC catalogue
LPG/NG 2B SS		26.99-29.99	GACC catalogue
LPG/NG 2B SS gas stove		26.99-29.99	GACC catalogue
LPG/NG 4B gas stove.		36.99-40.99	GACC catalogue
LPG/NG 4B SS		53.99-59.99	GACC catalogue
LPG Stove Télia n°2	Burkina Faso	45-55	GACC catalogue
M1-m-G Stove	Ghana	40-42	GACC catalogue
Moto Safi BG-02C	China	27.6-34	GACC catalogue
Moto Safi BG-04C	China	45-55	GACC catalogue
Statistics – Mean (sd)[1]		**39.2 (11.3)**	
Electric			
G-coil	India	15	Jeuland et al (2015)
Generic electric stove	S Africa	18.3	Howells et al (2006)
Generic electric stove	Tanzania	49.8	Wiskerke et al (2010)
Prestige induction	India	70	GACC catalogue
Statistics – Mean (sd)		**38.3 (26.3)**	

Notes: For computation of statistics, we use the median value for stoves with ranges of costs.
[1] Statistic excludes the NOMENA stove, which is a high cost outlier.

Table B2. Program cost (c^p, in /hh-yr)

Description	Location	Value	Source
Project estimates			
World Bank Energy Access Proj.	Ethiopia	0.97	World Bank project docs
World Bank Sustainable Energy Proj.	Rwanda	4.50	World Bank project docs
World Bank Household Energy & Universal Access Proj.	Mali	2.66	World Bank project docs
Patsari stove	Mexico	8.0	Baillis et al (2009)
TRAction project	India	8.9	Duke project documents
Statistics – Mean (sd)		**4.0 (3.0)**	
Expert estimates			
LPG	AfrD	0.45	Mehta & Shapar (2004)
LPG	AfrE	0.23	Mehta & Shapar (2004)
LPG	AmrB	1.26	Mehta & Shapar (2004)
LPG	AmrD	0.51	Mehta & Shapar (2004)
LPG	SearD	0.22	Mehta & Shapar (2004)
LPG	SearB	0.15	Mehta & Shapar (2004)
ICS	AfrD	1.17	Mehta & Shapar (2004)
ICS	AfrE	0.72	Mehta & Shapar (2004)
ICS	AmrB	3.85	Mehta & Shapar (2004)
ICS	AmrD	1.43	Mehta & Shapar (2004)
ICS	SearD	0.65	Mehta & Shapar (2004)
ICS	SearB	0.43	Mehta & Shapar (2004)
Statistics – Mean (sd)		**0.8 (0.9)**	

Table B3. Maintenance cost (c_i^m, in /yr)

Description	Location	Value	Source
Wood-burning ICS			
AFEE	Philippines	7.16	50% dep. assumption
Apon chulah	India	3.63	50% dep. assumption
Patsari	India	3.33	50% dep. assumption
Statistics – Mean (sd)		**4.7 (2.1)**	
Charcoal ICS			
Briketi	Uganda	1.00	50% dep. assumption
Canamake	Rwanda	0.75	50% dep. assumption
Charcoal stove	China	3.33	50% dep. assumption
Statistics – Mean (sd)		**1.7 (1.4)**	
LPG			
LPG	Nepal	0.53	Pokharel (2004)
NG 4B SS	Mexico	4.29	50% dep. assumption
NG 4B	Mexico	4.00	50% dep. assumption
NG 2B	Mexico	2.00	50% dep. assumption
NG 2B gas	Mexico	2.10	50% dep. assumption
NG 2B SS	Mexico	2.00	50% dep. assumption
LPG (Pokharel)	Nepal	1.47	50% dep. assumption
LPG stove Telia	Burkina Fasa	4.17	50% dep. assumption
Statistics – Mean (sd)		**2.6 (1.4)**	
Electric – no estimates			
G-coil	India	7.0	Maintenance program cost
Statistics (overall)		**2.6 (1.8)**	

Table B4. Lifespan of stove (T_i, in years)

Description	Location	Value	Source
Wood-burning ICS			
Adarsh Cook Stove	India	3	GACC catalogue
AFEE- 1	Philippines	3	GACC catalogue
Apon Chulah	Bangladesh	4	GACC catalogue
Berkeley-Darfur Stove	India	5	GACC catalogue
BioLite HomeStove	China	5	GACC catalogue
Burkina Mixte		2	GACC catalogue
Chitetezo / Canarumwe / Upesi Digital	Africa	4	GACC catalogue
Concrete village stove		2	GACC catalogue
DK-T5		1	GACC catalogue
Econochar	Various	3	GACC catalogue
EzyStove		3	GACC catalogue
Firenzel		8	GACC catalogue
Firewood Jambar	Senegal	2	GACC catalogue
Fixed One-Pot Rocket Mud	Africa	2	GACC catalogue
Foladi Duo	Afganistan	2	GACC catalogue
Greenstove	India	3	GACC catalogue
Hifadhi	Kenya	5	GACC catalogue
Himalayan Clean Stove	Nepal	3	GACC catalogue
Inkawasi TAWA	Peru	5	GACC catalogue
Insulating Pottery Rocket Stove		8	GACC catalogue
Jiko Kenya	Kenya	2	GACC catalogue
Jiko Kisasa	Kenya	4	GACC catalogue
Jiko Smart Wood	Kenya	5	GACC catalogue
Kunimbili		4	GACC catalogue
KuniTatu - Three Stick Stove		2	GACC catalogue
Kushal-2		3	GACC catalogue
Mbaula Green		4	GACC catalogue
Mwoto Quad2		1	GACC catalogue
Natural Draft Top Lit Up Draft Stove (TLUD)		3	GACC catalogue
Okelo Kuc Rural Stove		3	GACC catalogue
Peko Pe		10	GACC catalogue
Prakti-MFS		5	GACC catalogue
Prime Cylindrical		2	GACC catalogue
Prime Square		2	GACC catalogue
RamTara Stove		3	GACC catalogue
Rocket Stove		3	GACC catalogue
Rua		3	GACC catalogue
SCODE Push-n-Pull stove		6	GACC catalogue
Shakti Chula V.2		5	GACC catalogue
Small Natural Draft Sunken Pot Rocket Stove		3	GACC catalogue
Square John		10	GACC catalogue
TERI SPF143- forced draft mud stove		2	GACC catalogue
Top Load Fan Stove		3	GACC catalogue
Troika TLUD stove		2	GACC catalogue
Zoom Dura		5	GACC catalogue
Zoom Plancha	China	5	GACC catalogue
Zoom Relief		2	GACC catalogue
Zoom Versa		5	GACC catalogue
Tulip Clay	Benin	1	GACC catalogue
Statistics – Mean (sd)		**3.7 (2.1)**	

Charcoal ICS			
Apon Chulah	Bangladesh	4	GACC catalogue
Briketi EcoStove	Uganda	5	GACC catalogue
Briketi EcoStove v2	Uganda	5	GACC catalogue
Canamake Ivuguruye	Rwanda	4	GACC catalogue
Charcoal stove	China	3	GACC catalogue
Burkina Mixte	Burkina Faso	2	GACC catalogue
Charcoal Jambar	Africa	2	GACC catalogue
Charcoal Stove	China	3	GACC catalogue
CookClean CookMate	Ghana	4	GACC catalogue
EcoRecho	Haiti	1	GACC catalogue
Hifadhi	Kenya	5	GACC catalogue
Improved Canamake	Rwanda	4	GACC catalogue
Ã‰clair		2	GACC catalogue
EzyChar		3	GACC catalogue
Firewood Stove		15	GACC catalogue
Himalayan clean cook stove		3	GACC catalogue
Jiko Africa		2	GACC catalogue
JikoJoy		5	GACC catalogue
jikokoa		2	GACC catalogue
Jiko Smart Charcoal		5	GACC catalogue
Kunimbili		4	GACC catalogue
KuniTatu - Three Stick Stove		2	GACC catalogue
Mbaula Green		4	GACC catalogue
MBS 9		15	GACC catalogue
Multimarmite		2	GACC catalogue
Nansu Unfired Clay		1	GACC catalogue
Obama Stove		3	GACC catalogue
Okelo Kuc		3	GACC catalogue
Original Gyapa		3	GACC catalogue
Peko Pe		10	GACC catalogue
Portico Premium Stove		3	GACC catalogue
Prakti Single Burner Charcoal Stove		4	GACC catalogue
Rahisi Stove (Prototype)		10	GACC catalogue
Rapidita		4	GACC catalogue
Recho Plop Plop+		2	GACC catalogue
Rocket Works Cha-ZaMa Charcoal Stove		1	GACC catalogue
Rua		3	GACC catalogue
Sakkanal		2	GACC catalogue
SCODE charcoal stove all metal		7	GACC catalogue
SCODE Push-n-Pull stove		6	GACC catalogue
SCODE SP-FL micro gasifier Concrete body		5	GACC catalogue
SCODE SP-FL micro gasifier portable		5	GACC catalogue
Shakti Chula V.1		10	GACC catalogue
Shakti Chula V.2		5	GACC catalogue
Shakti Chula V.3		8	GACC catalogue
SmartHome Stove		2	GACC catalogue
Zoom Stove		3	GACC catalogue
Zoom Versa		5	GACC catalogue
Statistics – Mean (sd)		**4.4 (3.12)**	
LPG			
A1-m single stove	Ghana	4	GACC catalogue
NOMENA LPG Cookstove	Ghana	5	GACC catalogue
F2-m_Single stove	Ghana	4	GACC catalogue

LPG Stove Télia n°2	Burkina Faso	6	GACC catalogue
Moto Safi BG-02C	China	8	GACC catalogue
NG 4B SS	Mexico	7	GACC catalogue
NG 4B	Mexico	5	GACC catalogue
NG 2B SS gas	Mexico	7	GACC catalogue
NG 2B gas	Mexico	5	GACC catalogue
NG 2B SS	Mexico	7	GACC catalogue
Statistics – Mean (sd)		**5.8 (1.4)**	
Electric – no data			

Table B5. Usage rate (χ)

Description	Location	Value	Source
ICS(wood)	Rwanda	0.8	Ghislaine (2013)
ICS(wood)	Guatemala	0.5	Ruiz-Mercado et al (2011)
ICS(wood)	India	0.4	Hanna et al (2012)
ICS(wood)	India	0.2	TRACtion
ICS(wood)		0.6	Frapolli (2010)
ICS(wood)		0.45	Adrianzen (2010)
ICS(electric)	India	0.16	TRACtion

Table B6. Average daily cooking time with traditional stove ($cook_0$, in hr/day)

Description	Location	Value	Source
Traditional stove	Kenya	5.0	Silk (2012)
Traditional mud chulha	Uttar Pradesh, India	3.1	Brooks et al. (2015)
Traditional mud angeti	Uttarakhand, India	3.7	Brooks et al. (2015)
Biomass ICS	India	2.14	Mukhopadhyay et al (2012)
Biomass ICS	India	1.24	Mukhopadhyay et al (2012)
Traditional stove	Nepal	2.4	Pant (2008)
Traditional stove	Nepal	3.3	Thakuri (2009)
Traditional stove	Kenya	2.8	Ezzati & Kammen
Statistics – Mean (sd)		**3.9 (1.0)**	

Table B7. Time efficiency of ICS relative to traditional stove (te_i, as a ratio)

Description	Item	Value	Source
Wood-burning ICS			
		0.59	MacCarthy et al (2010)
		1.52	MacCarthy et al (2010)
		1.05	MacCarthy et al (2010)
		0.57	MacCarthy et al (2010)
		0.57	MacCarthy et al (2010)
		0.92	MacCarthy et al (2010)
		0.80	MacCarthy et al (2010)
		1.15	MacCarthy et al (2010)
		0.32	MacCarthy et al (2010)
		0.77	MacCarthy et al (2010)
		0.79	MacCarthy et al (2010)
		0.88	MacCarthy et al (2010)
		0.65	MacCarthy et al (2010)
		0.81	MacCarthy et al (2010)
		0.61	MacCarthy et al (2010)
		0.86	Hutton (2007)
		0.80	Pant (2010)
		0.93	Thakuri (2009)
Statistics – Mean (sd)		**0.80 (0.17)**	
Charcoal ICS			
		0.50	MacCarthy et al (2010)
		0.74	MacCarthy et al (2010)
		0.79	MacCarthy et al (2010)
Statistics – Mean (sd)		**0.68 (0.16)**	
LPG			
		0.60	MacCarthy et al (2010)
		0.83	MacCarthy et al (2010)
Generic LPG	Rice	0.89	Hougan et al (2014)
Generic LPG	Beans	0.96	Hougan et al (2014)
Generic LPG	Dry corn	1.12	Hougan et al (2014)
Oryx LPG	Rice	0.77	Hougan et al (2014)
Oryx LPG	Beans	0.60	Hougan et al (2014)
Oryx LPG	Dry corn	0.93	Hougan et al (2014)
		0.53	Anozeia (2007)
Statistics – Mean (sd)		**0.8 (0.2)**	
Electric			
Generic Electric	Rice	0.95	Hougan et al (2014)
Generic Electric	Beans	0.96	Hougan et al (2014)
Generic Electric	Dry corn	1.06	Hougan et al (2014)
		0.60	Anozeia (2007)
Statistics – Mean (sd)		**0.99 (0.065)**	

Table B8. Thermal efficiency of stove (ϵf_i, in %)

Description	Details	Value	Source
Traditional biomass stove			
Generic traditional stove		7%	Wiskerke et al (2010)
Three stone stove	Water boiling test	21.4%	Zhang et al (2000)
Three stone stove	Water boiling test	17.6%	Smith et al (2000)
Three stone stove	Water boiling test	18.1%	Smith et al (2000)
Three stone stove	Water boiling test	18.2%	Smith et al (2000)

Statistics – Mean (sd)		**16.5 (5.5)**	
<u>Wood-burning ICS</u>			
ARTI Bhayalaxmi	IWA high power efficiency	17	GACC catalog
ARTI Bhayalaxmi	Cold start efficiency	7	GACC catalog
ARTI Bhayalaxmi	Hot start efficiency	17	GACC catalog
ARTI Laxmi	IWA high power efficiency	18.15	GACC catalog
ARTI Laxmi	Cold start efficiency	13.5	GACC catalog
ARTI Laxmi	Hot start efficiency	18.15	GACC catalog
Onil	IWA high power efficiency	12.8	GACC catalog
Onil	Cold start efficiency	10.7	GACC catalog
Onil	Hot start efficiency	14.8	GACC catalog
Patsari	IWA high power efficiency	17	GACC catalog
Patsari	Cold start efficiency	7	GACC catalog
Patsari	Hot start efficiency	17	GACC catalog
PCS-1	Average thermal efficiency	36.5	GACC catalog
Philips HD4008	IWA high power efficiency	32.95	GACC catalog
Philips HD4008	Cold start efficiency	33.65	GACC catalog
Philips HD4008	Hot start efficiency	34.2	GACC catalog
Apon Chulah	Average thermal efficiency	30.5	GACC catalog
Statistics – Mean (sd)		**19.9 (9.8)**	
<u>Charcoal ICS</u>			
Apon Chulah	Average thermal efficiency	30.5	GACC catalog
Canamake	IWA high power efficiency	37.1	GACC catalog
Charcoal Stove	Average thermal efficiency	47.0	GACC catalog
Generic stove	Average thermal efficiency	44.0	Zhang et al (2000)
CookClean CookMate	IWA high power efficiency	25.7	GACC catalog
CookClean CookMate	Cold start efficiency	24.4	GACC catalog
CookClean CookMate	Hot start efficiency	27.0	GACC catalog
CookClean CookMate	Simmer efficiency	24.8	GACC catalog
New Lao Stove	IWA high power efficiency	24.3	GACC catalog
New Lao Stove	Cold start efficiency	17.0	GACC catalog
New Lao Stove	Hot start efficiency	31.6	GACC catalog
Obama Stove	IWA high power efficiency	34.0	GACC catalog
Okelo Kuc	IWA high power efficiency	25.6	GACC catalog
Okelo Kuc	Cold start efficiency	19.7	GACC catalog
Okelo Kuc	Hot start efficiency	31.5	GACC catalog
Okelo Kuc	Heating stove thermal efficiency	34.3	GACC catalog
Okelo Kuc	Simmer efficiency	43.0	GACC catalog
Toyola	IWA high power efficiency	26.8	GACC catalog
Toyola	Cold start efficiency	22.6	GACC catalog
Toyola	Hot start efficiency	30.9	GACC catalog
Statistics – Mean (sd)		**30.1 (8.0)**	
<u>LPG</u>			
LPG	Thermal efficiency	42	Zhang et al (2000)
LPG Stove Télia n°2	IWA high power efficiency	49.25	GACC catalog
LPG Stove Télia n°2	Simmer efficiency	61.63	GACC catalog
Anard	Thermal efficiency	64	GACC catalog
Statistics – Mean (sd)		**54.2 (10.4)**	
<u>Electric – no data</u>			

Table B9. Energy conversion factor for stove (μ_i)

Description	Details	Value	Source
Wood		16	IOR Energy[1]
Charcoal		33	FAO (1983)
LPG		49	IOR Energy[1]
Electricity		3.6	IOR Energy[1]

[1] http://web.archive.org/web/20100825042309/http://www.ior.com.au/ecflist.html

Table B10. Amount of fuel used for cooking; traditional stove ($fuelckg_0$, in kg/day)

Description	Location	Value	Source
Traditional	Bangladesh	3.6	Chowdhury (2012)
Traditional	Nepal	2.8	Johnson et al (2013)
Traditional	Peru	6.1	Johnson et al (2013)
Traditional	Nepal	11.2	Johnson et al (2013)
Unsure	Nepal	2.4	Amacher (1996)
Unsure	Nepal	12.2	Amacher (1996)
Traditional	Kenya	14.3	Ballis (2003)
Chulha	Uttar Pradesh, India	9.2	Brooks et al. (2015)
Angeti	Uttarakhand, India	9.97	Brooks et al. (2015)
ICS	Bangladesh	3.2	Chowdhury (2012)
ICS	Nepal	2.5	Johnson et al (2013)
ICS	Peru	3.8	Johnson et al (2013)
ICS	Nepal	7.5	Johnson et al (2013)
ICS	India	16.9	Smith et al (2007)
ICS	Kenya	6.9	Ballis (2003)
ICS	Kenya	11.9	Ballis (2003)
Statistics – Mean (sd)[1]		**8.0 (4.4)**	

[1] For traditional stoves only.

Table B11. Percentage of people buying wood (f)

Description	Location	Value	Source
Survey measure	Uttarakhand, India	23%	TRACtion project
Survey measure	Uttar Pradesh, India	47%	TRACtion project

Table B12. Average daily wood fuel collection time ($collt_0$, in hr/day)

Description	Location	Value	Source
Survey measure	India	5.22	Hanna et al (2012)
Survey measure	Kenya	1.99	Silk (2012)
Survey measure	Nepal	1.03	Nepal et al (2011)
Author-calculated	Nepal	0.36	Amacher (1996)
Author-calculated	Nepal	0.37	Amacher (1996)
Survey measure	Nepal	2.50	Kumar & Hotchkiss (1998)
Survey measure	Pakistan	6.00	Jan (2012)
Survey measure	India	1.9	Saksena et al (1995)
Estimated	S Asia	0.69	Hutton (2006)
Estimated	SS Africa	0.79	Hutton (2006)
Survey measure	Uttarakhand	1.83	TRACtion
Survey measure	Uttar Pradesh	2.5	TRACtion
Statistics – Mean (sd)		**2.1 (2.0)**	

Table B13. Shadow value of time (fraction of wage) (κ^t)

Description	Location	Value	Source
Time spent obtaining cholera vaccines	Mozambique	0.35	Jeuland et al. (2010)
Value of time spent traveling – recent estimate	UK	0.33	Accent/Hague (1999), as cited in Mackie et al. (2002)
Value of time spent traveling – high estimate	UK	0.43	MVA, ITS, TSU (1987), as cited in Mackie et al. (2002)
Transport choices	UK	0.22	Quarmby (1967)
Transport choices	UK	0.45	Lisco (1968)
Choice of driving route	US	0.40	Thomas (1968)
Urban commuting choices	UK	0.22	Stopher (1969)
Choice of public transport alternatives	UK	0.3	Lee & Dalvie (1969)
Time spent collecting water	Kenya	1.2	Whittington et al. (1990)
Statistics – Mean (sd)		**0.43 (0.30)**	

Table B14. Minimum wage rates (W, in US2015 per hr)

Country	Value
Afganistan	0.44
Algeria	1.10
Angola	0.88
Bangladesh	0.08
Belize	1.60
Benin	0.48
Bhutan	0.32
Bolivia	1.03
Botswana	0.18
Cameroon	0.41
Central African	0.40
Chad	0.64
China	1.13
Colombia	1.55
DR Congo	0.14
Guatemala	1.18
India	0.18
Indonesia	0.41
Kenya	0.22
Laos	0.26
Lesotho	0.41
Madagascar	0.24
Malawi	0.12
Mali	0.26
Mauritius	0.39
Mexico	0.62
Nepal	0.29
Nicaragua	0.47
Niger	0.34
Nigeria	0.51
Pakistan	0.62
Philippines	0.62
Sierra Leone	0.64
Swaziland	0.30
Timor	0.47
Vietnam	0.28
Zambia	0.33
Statistics – Mean (sd)	**0.53 (0.38)**

Notes: Values obtained from https://en.wikipedia.org/wiki/List_of_minimum_wages_by_country.

Table B15. Average daily fuel preparation time for ICS stove (*prep*, in hr/day)

Description	Location	Value	Source
Survey measure	Uttar Pradesh, India	0.7	TRACtion project

Table B16. Cost of fuel (p_i)

Descrption	Location	Value	Source
Firewood (/kg)			
	India	0.05	Pokharel (2004)
	Nepal	0.009	Amacher (1996)
	Nigeria	0.03	Anozie (2007)
	India	0.06	Farsi & Flippini (2007)
	Uttarakhand	0.092	TRACtion
	Uttar Pradesh	0.067	TRACtion
Statistics – Mean (sd)		**0.051 (0.029)**	
Charcoal (/kg)			
	Pakistan	0.13	Battarai (1998)
	India	0.31	Battarai (1998)
	Philippines	0.15	Battarai (1998)
	Malawi and Kenya	0.13	Barnes & Openshaw (2010)
	Ethiopia	0.23	LSMS (2011)
	Tanzania	0.31	LSMS (2011)
Statistics – Mean (sd)		**0.21 (0.085)**	
LPG (/kg)			
	India	0.57	Pokharel (2004)
	Nigeria	1.17	Anozie (2007)
	India	0.34	Farsi & Flippini (2007)
Statistics – Mean (sd)		**0.69 (0.43)**	
Electric			
	Bangladesh	0.061	See notes
	Bhutan	0.031	See notes
	Phnom Penh	0.183	See notes
	China	0.091	See notes
	Bogota	0.181	See notes
	Ethopia	0.070	See notes
	India	0.070	See notes
	Indonesia	0.088	See notes
	Malaysia	0.109	See notes
	Mynamar	0.036	See notes
	Nigeria	0.096	See notes
	Pakistan	0.085	See notes
	Paraguay	0.080	See notes
	Philippines	0.361	See notes
	South Africa	0.120	See notes
	Thailand	0.095	See notes
	Vietnam	0.081	See notes
	Nigeria	0.030	Anozie (2007)
	India	0.108	Pokharel (2004)
	Nigeria	0.030	Anozie (2007)
Statistics – Mean (sd)		**0.10 (0.075)**	

Notes: For electricity prices, unless otherwise noted, source is https://en.wikipedia.org/wiki/Electricity_pricing.

Table B17. Learning hours (l, in hours)

By assumption (no data)

Table B18. Incidence/prevalence of disease (IR_k, in cases per 100 persons-yr)

Description	Location	Value	Source
Acute lower respiratory illness			
Child ALRI	Thailand	0.058	Hasan et al (2014)
Low estimate – child ARI	Developing	0.205	Rudan et al (2004)
High estimate – child ARI	Developing	0.710	Rudan et al (2004)
Low estimate – child ALRI	Guatemala	0.070	Kulsum (2005)
High estimate – child ALRI	Guatemala	0.145	Kulsum (2005)
	Global	0.300	WHO (2004)
	Nepal	0.670	Pant (2008)
	Nepal	0.870	Thakuri (2009)
	India	0.498	Smith & Mehta (2000)
	China	0.175	Smith & Mehta (2000)
	Other Asia & Pacific	0.255	Smith & Mehta (2000)
	Sub-Saharan Africa	0.638	Smith & Mehta (2000)
	Latin America	0.127	Smith & Mehta (2000)
	Mid-East & N. Africa	0.214	Smith & Mehta (2000)
	LDC Total	0.326	Smith & Mehta (2000)
Statistics – Mean (sd)		0.351 (0.26)	
COPD			
Prevalence		0.012-0.077	Bousquet et al. (2007)
Statistics – Mean (sd)	Non S. Asia	4.1 (1.3)	GHE (2014)
Statistics – Mean (sd)	S. Asia	4.3 (4.7)	GHE (2014)
Lung cancer			
Prevalence	Global	0.023	Ferlay et al (2010)
Statistics – Mean (sd)	Non S. Asia	0.014 (0.005)	GHE (2014)
Statistics – Mean (sd)	S. Asia	0.023 (0.016)	GHE (2014)
IHD			
Statistics – Mean (sd)	Non S. Asia	1.0 (0.62)	GHE (2014)
Statistics – Mean (sd)	S. Asia	0.73 (0.17)	GHE (2014)

Table B19. Mortality rate due to disease (MR_k, in deaths/10000 people-yr)

Description	Location	Value	Source
Acute lower respiratory illness			
Statistics – Mean (sd)	Non S. Asia	15.4 (16.0)	WHO (2010)
Statistics – Mean (sd)	S. Asia	10.2 (5.44)	WHO (2010)
COPD			
Estimate	Africa	1.81	Yeung et al. (2004)
Estimate	SEAsia	4.0	Yeung et al. (2004)
Estimate	Western Pacific	8.0	Yeung et al. (2004)
Statistics – Mean (sd)	Non S. Asia	1.6 (1.4)	WHO (2010)
Statistics – Mean (sd)	S. Asia	4.8 (2.6)	WHO (2010)
Lung cancer			
Statistics – Mean (sd)	Non S. Asia	1.27 (1.73)	WHO (2010)
Statistics – Mean (sd)	S. Asia	0.77 (0.29)	WHO (2010)
IHD			
Statistics – Mean (sd)	Non S. Asia	10.7 (12.2)	WHO (2010)
Statistics – Mean (sd)	S. Asia	8.1 (4.7)	WHO (2010)

Notes: Statistics from the WHO are pulled from the country-level Global Burden of Disease Estimates: http://www.who.int/healthinfo/mortality_data/en/.

Table B20. Cost-of-illness of disease (COI_k, in /case of illness)

Description	Location	Value	Source
Acute lower respiratory illness			
Direct (per visit)	South Africa	5968	Sinha et al (2012)
Outpatient (per visit)	India	3-10	Peasah et al (2015)
Inpatient (per visit)	India	156	Peasah et al (2015)
Direct	Nepal	61.40	Pant et al. (2008)
Direct	Nepal	14.70	Thakuri (2009)
Direct	DCP project	2-22	Jamison et al.
Direct	Global CBA	0.25-23	Hutton et al. (2007)
Direct		7	Monto & Lehmann
Statistics – Mean (sd)[1]	**LDCs only**	**38.5 (55.3)**	
COPD			
Direct + indirect (per yr)	Spain	1,076	Morera (1992)
Direct-stage 1 (per yr)	USA	1,681	Hilleman et al (2000)
Direct-stage 2 (per yr)	USA	5,037	Hilleman et al (2000)
Direct-stage 3 (per yr)	USA	10,812	Hilleman et al (2000)
Direct (per yr)	Netherlands	876	Rutten van Molken et al (2000)
Direct-stage 1 (per yr)	Italy	169	Dal Negro et al (2002)
Direct-stage 2 (per yr)	Italy	3,367	Dal Negro et al (2002)
Direct-stage 3 (per yr)	Italy	4,389	Dal Negro et al (2002)
Direct + indirect (per yr)	Sweden	1,440	Jansson et al (2002)
Direct-stage 1 (per yr)	Spain	1,329	Miravitlies et al (2002)
Direct-stage 2 (per yr)	Spain	1,840	Miravitlies et al (2002)
Direct-stage 3 (per yr)	Spain	2,618	Miravitlies et al (2002)
Direct (per yr)	Spain	1,020	Masa et al (2004)
Direct (per visit)	Vietnam	651	Pham et al (2014)
Direct (per visit)	Laos	105	Chu et al (2009)
Direct + indirect (per visit)	Laos	257	Chu et al (2009)
Direct chronic bronchitis	Nepal	36.8	Pant (2008)
Direct COPD	DCP project	31.7	Jamison et al.
Direct COPD	Global CBA	85.0	Hutton et al.
Statistics – Mean (sd)[1]	**LDCs only**	**103 (92)**	
Lung cancer			
Direct (per visit)	Laos	114	Chu et al (2009)
Direct + indirect (per visit)	Laos	382	Chu et al (2009)
Direct (per visit)	Vietnam	3203	Pham et al (2014)
Direct (per visit)	Vietnam	339	Pham et al (2014)
Direct - low est (per yr)	Mexico	13456	Arrieta et al (2015)
Direct - high est (per yr)	Mexico	144555	Arrieta et al (2015)
Statistics – Mean (sd)[1]	**LDCs only**	**1010 (1467)**	
IHD			
Direct (per visit)	Vietnam	1,832	Pham et al (2014)
Direct (per yr)	India	376	Mukherjee & Koul (2014)
Not specified if direct only or not (per yr)	AFR-D	47	Bloom et al (2012)
	AFR-E	43	Bloom et al (2012)
	SEAR-B	59	Bloom et al (2012)
	SEAR-D	32	Bloom et al (2012)
Statistics – Mean (sd)[1]	**LDCs only**	**1010 (1467)**	

Notes:
[1] Statistics are computed for the less-developed countries only.

Table B21. Social cost of carbon emissions (c^{CO2}, in /ton CO_2-equivalent)

Curves derived from simulation data from EPA; plotting average 5th, 50th, and 95th percentiles across models

Description	Location	Median value	Source
2.5% discount rate; median social cost	Simulation	38.4	EPA social cost of carbon
3% discount rate; median social cost	Simulation	25.0	EPA social cost of carbon
5% discount rate; median social cost	Simulation	6.8	EPA social cost of carbon

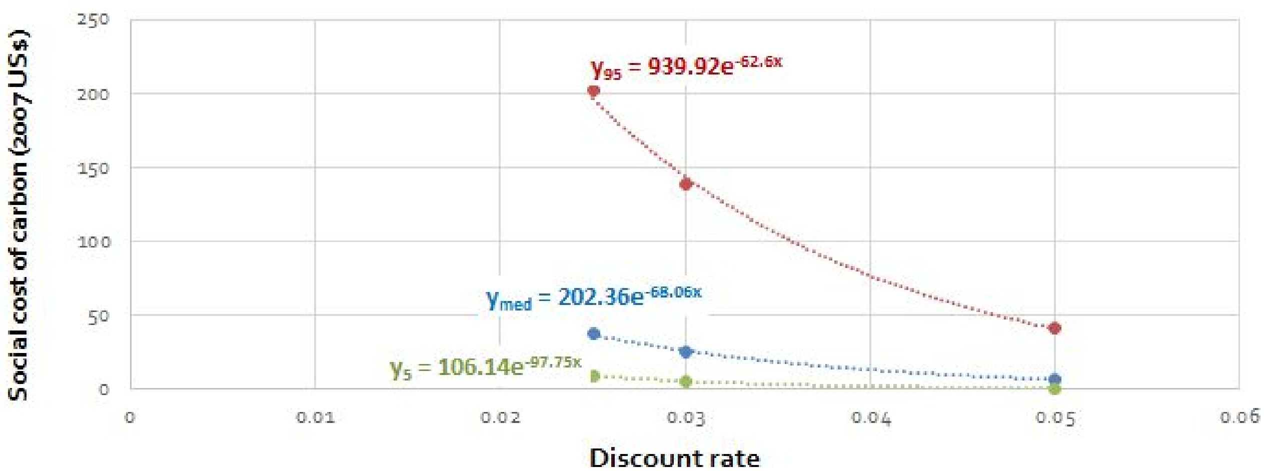

Table B22. Biomass harvesting that is non-renewable (ψ, in %)

Description	Location	Value
	Angola	29.5
	Argentina	19.2
	Bangladesh	52.1
	Benin	4.9
	Bhutan	56
	Bolivia	8
	Botswana	4.1
	Brazil	11
	Burkina Faso	35.2
	Burundi	56.3
	Cambodia	12.4
	Cameroon	2
	Central African Republic	14.6
	Chad	20
	Chile	25.2
	China	22.2
	Colombia	7.9
	Congo	5.5
	Costa Rica	22.1
	Côte d'Ivoire	17.1
	Cuba	2
	DR Congo	1.5
	Dominican Republic	33
	Ecuador	0.1
	El Salvador	27.6
	Equatorial Guinea	0
	Eritrea	66.8
	Ethiopia	59.9
	Gambia	41.5
	Ghana	11.3
	Guatemala	6
	Guinea	15.1
	Guinea-Bissau	21.7
	Guyana	3.9
	Haiti	66.6
	Honduras	0
	India	23.7
	Indonesia	30.1
	Jamaica	17.1
	Kenya	61.1
	Lao PDR	10.3
	Lesotho	53
	Liberia	3.4
	Madagascar	12.4
	Malawi	12.2
	Mali	19
	Mauritania	30.3
	Mexico	26.7
	Mozambique	26
	Myanmar	3.4
	Namibia	35.8
	Nepal	52.8
	Nicaragua	4.4

	Niger	21.5
	Nigeria	3.2
	Pakistan	79.6
	Panama	1.5
	Papua N. G.	20.5
	Paraguay	20.1
	Peru	25.9
	Philippines	20.1
	Rwanda	64.7
	Senegal	28.5
	Sierra Leone	12.4
	Singapore	75.6
	Somalia	46
	South Africa	24.8
	Sri Lanka	20.1
	Sudan	40.2
	Suriname	8.6
	Swaziland	1.4
	Thailand	5.1
	Togo	34.8
	Trinidad & Tobago	0.1
	Uganda	54.6
	Tanzania	9.2
	Venezuela	10
	Viet Nam	16.8
	Zambia	21.9
	Zimbabwe	2.2
Statistics – Mean (sd)	Asia	**30.4 (23.7)**
Statistics – Mean (sd)	Non-Asia	**21.4 (18.9)**

Notes: Data from Bailis et al. (2015)

Table B23. Household size (*hhsize*)

Description	Location	Value	Source
Rural household size	India	4.90	Indian census
Urban household size	India	4.60	Indian census
Average household size	Burkina Faso	5.94	UN data
Average household size	Uganda	4.85	UN data
Average household size	Senegal	9.16	UN data
Average household size	Botswana	4.15	UN data
Average household size	Ghana	4.51	UN data
Average household size	Bahamas	3.48	UN Pop Division 2011
Average household size	Bolivia (Plurinational State of)	3.82	UN Pop Division 2011
Average household size	Bulgaria	2.45	UN Pop Division 2011
Average household size	Cape Verde	4.22	UN Pop Division 2011
Average household size	Costa Rica	3.48	UN Pop Division 2011
Average household size	Dominican Republic	3.75	UN Pop Division 2011
Average household size	Ghana	4.62	UN Pop Division 2011
Average household size	Iran (Islamic Republic of)	3.56	UN Pop Division 2011
Average household size	Jamaica	3.08	UN Pop Division 2011
Average household size	Mexico	4.11	UN Pop Division 2011
Average household size	Nauru	6.08	UN Pop Division 2011
Average household size	Uruguay	2.92	UN Pop Division 2011
Average household size	Zambia	4.89	UN Pop Division 2011
Average household size	Bangladesh	4.88	DHS
Average household size	Benin	5.06	DHS
Average household size	Bolivia (Plurinational State of)	3.97	DHS
Average household size	Burkina Faso	5.69	DHS
Average household size	Burundi	4.93	DHS
Average household size	Cambodia	4.91	DHS
Average household size	Cameroon	5.11	DHS
Average household size	Comoros	5.47	DHS
Average household size	Congo-Brazzaville	4.42	DHS
Average household size	DR Congo	5.28	DHS
Average household size	Cote d'Ivoire	5.28	DHS
Average household size	Egypt	4.86	DHS
Average household size	Ethiopia	4.65	DHS
Average household size	Ghana	3.95	DHS
Average household size	Guinea	6.34	DHS
Average household size	Guyana	4.06	DHS
Average household size	Haiti	4.53	DHS
Average household size	Honduras	4.71	DHS
Average household size	Indonesia	4.23	DHS
Average household size	Kenya	4.25	DHS
Average household size	Kyrgyz	4.45	DHS
Average household size	Lesotho	4.74	DHS
Average household size	Liberia	5.17	DHS
Average household size	Madagascar	4.81	DHS
Average household size	Malawi	4.79	DHS
Average household size	Mozambique	4.51	DHS
Average household size	Nepal	4.60	DHS
Average household size	Niger	5.95	DHS
Average household size	Nigeria	4.64	DHS
Average household size	Pakistan	7.28	DHS
Average household size	Philippines	4.86	DHS
Average household size	Rwanda	4.51	DHS
Average household size	Sao Tome	3.80	DHS

Average household size	Senegal	9.78	DHS
Average household size	Sierra Leone	5.96	DHS
Average household size	Tajikistan	6.03	DHS
Average household size	Tanzania	5.24	DHS
Average household size	Timor	5.92	DHS
Average household size	Uganda	4.98	DHS
Average household size	Zimbabwe	4.30	DHS
Statistics – Mean (sd)		4.86 (1.22)	
Average # < 5 yrs old (rural)	India	0.493	Indian census
Average # < 5 yrs old (urban)	India	0.371	Indian census
Average # < 5 yrs old	Burkina Faso	1.033	UN data
Average # < 5 yrs old	Uganda	0.901	UN data
Average # < 5 yrs old	Senegal	1.34	UN data
Average # < 5 yrs old	Botswana	0.483	UN data
Average # < 5 yrs old	Ghana	0.623	UN data
Average # < 5 yrs old	Bahamas	0.263	UN Pop Division 2011
Average # < 5 yrs old	Bolivia (Plurinational State of)	0.443	UN Pop Division 2011
Average # < 5 yrs old	Bulgaria	0.126	UN Pop Division 2011
Average # < 5 yrs old	Cape Verde	0.400	UN Pop Division 2011
Average # < 5 yrs old	Costa Rica	0.290	UN Pop Division 2011
Average # < 5 yrs old	Dominican Republic	0.393	UN Pop Division 2011
Average # < 5 yrs old	Ghana	0.657	UN Pop Division 2011
Average # < 5 yrs old	Iran (Islamic Republic of)	0.297	UN Pop Division 2011
Average # < 5 yrs old	Jamaica	0.290	UN Pop Division 2011
Average # < 5 yrs old	Mexico	0.389	UN Pop Division 2011
Average # < 5 yrs old	Nauru	0.602	UN Pop Division 2011
Average # < 5 yrs old	Uruguay	0.213	UN Pop Division 2011
Average # < 5 yrs old	Zambia	0.952	UN Pop Division 2011
Average # < 5 yrs old	Bangladesh	0.59	DHS
Average # < 5 yrs old	Benin	1.00	DHS
Average # < 5 yrs old	Bolivia (Plurinational State of)	0.55	DHS
Average # < 5 yrs old	Burkina Faso	1.17	DHS
Average # < 5 yrs old	Burundi	1.04	DHS
Average # < 5 yrs old	Cambodia	0.64	DHS
Average # < 5 yrs old	Cameroon	0.97	DHS
Average # < 5 yrs old	Comoros	0.87	DHS
Average # < 5 yrs old	Congo-Brazzaville	0.92	DHS
Average # < 5 yrs old	DR Congo	1.20	DHS
Average # < 5 yrs old	Cote d'Ivoire	0.99	DHS
Average # < 5 yrs old	Egypt	0.66	DHS
Average # < 5 yrs old	Ethiopia	0.82	DHS
Average # < 5 yrs old	Ghana	0.63	DHS
Average # < 5 yrs old	Guinea	1.18	DHS
Average # < 5 yrs old	Guyana	0.51	DHS
Average # < 5 yrs old	Haiti	0.66	DHS
Average # < 5 yrs old	Honduras	0.64	DHS
Average # < 5 yrs old	Indonesia	0.50	DHS
Average # < 5 yrs old	Kenya	0.79	DHS
Average # < 5 yrs old	Kyrgyz	0.67	DHS
Average # < 5 yrs old	Lesotho	0.57	DHS
Average # < 5 yrs old	Liberia	1.03	DHS
Average # < 5 yrs old	Madagascar	0.88	DHS
Average # < 5 yrs old	Malawi	0.96	DHS
Average # < 5 yrs old	Mozambique	0.89	DHS

Average # < 5 yrs old	Nepal	0.58	DHS
Average # < 5 yrs old	Niger	1.42	DHS
Average # < 5 yrs old	Nigeria	0.91	DHS
Average # < 5 yrs old	Pakistan	1.10	DHS
Average # < 5 yrs old	Philippines	0.63	DHS
Average # < 5 yrs old	Rwanda	0.84	DHS
Average # < 5 yrs old	Sao Tome	0.69	DHS
Average # < 5 yrs old	Senegal	1.94	DHS
Average # < 5 yrs old	Sierra Leone	1.18	DHS
Average # < 5 yrs old	Tajikistan	0.90	DHS
Average # < 5 yrs old	Tanzania	1.01	DHS
Average # < 5 yrs old	Timor	1.04	DHS
Average # < 5 yrs old	Uganda	1.07	DHS
Average # < 5 yrs old	Zimbabwe	0.72	DHS
Statistics – Mean (sd)		0.77 (0.34)	

Notes: UN Data is available here: http://data.un.org/Explorer.aspx?d=POP&f=tableCode%3a22

Table B24. % of households using solid fuels (*sfu*)

Description	Location	Value	Source
	Rwanda	80	Ghislaine (2013)
	Guatemala	50	Ruiz-Mercado et al (2011)
	India	40	Hanna et al (2012)
	Bangladesh	91	
	Bhutan	40	
	India	58	
	Indonesia	55	
	Nepal	82	
	Pakistan	64	
	Sri Lanka	75	
	Timor-Leste	92	
	Afghanistan	85	
	Algeria	5	
	Angola	55	
	Azerbaijan	7	
	Belize	12	
	Benin	91	
	Bolivia	29	
	Botswana	37	
	Burkina Faso	92	
	Burundi	95	
	Cambodia	89	
	Cameroon	75	
	Central African Republic	95	
	Chad	88	
	China	46	
	Comoros	71	
	Congo	77	
	Cote d'Ivoire	78	
	Democratic Republic of Congo	93	
	Eritrea	60	
	Ethiopia	95	
	Gambia	91	
	Ghana	84	

	Guatemala	57	
	Guinea	95	
	Guinea-Bissau	95	
	Haiti	91	
	Kenya	80	
	Kiribati	80	
	DPR of Korea	91	
	Kyrgyzstan	34	
	Lao PDR	95	
	Lesotho	61	
	Liberia	95	
	Madagascar	95	
	Malawi	95	
	Mali	95	
	Mauritania	58	
	Micronesia	41	
	Mongolia	72	
	Mozambique	95	
	Myanmar	92	
	Nicaragua	54	
	Niger	95	
	Nigeria	74	
	Papua New Guinea	73	
	Philippines	50	
	Rwanda	95	
	Senegal	51	
	Sierra Leone	95	
	Solomon Islands	90	
	Somalia	95	
	Sudan (former)	79	
	Swaziland	55	
	Togo	94	
	Tonga	43	
	Uganda	95	
	Tanzania	94	
	Vanuatu	84	
	Viet Nam	56	
	Zambia	83	
	Zimbabwe	66	
Statistics – Mean (sd)	**Asia**	**69.6 (18.5)**	**UN Data only**
Statistics – Mean (sd)	**Non-Asia**	**74.0 (24.2)**	**UN Data only**

Notes: All country-specific with no source listed is from the UN and can be obtained here: https://data.un.org/
Summary statistics are only from UN data.

Table B25. Value of a statistical life (VSL)

Description - method	Location	Value	Source
Stated preference	Mozambique	11,700	Jeuland et al. (2008)
Revealed preference	Kenya	500	Kremer et al. (2009)
Stated preference	Bangladesh	12,075	Maskery et al. (2008)
Stated preference	China (Urban & rural)	78,163	Hammitt and Zhou (2006)
Wage-risk	India (Urban)	263,575	Simon, Cropper, Alberini and Arora (1999)
Wage-risk	India (Urban)	910,000	Shanmugam (2000)
Wage-risk	India (Urban)	1,885,000	Shanmugam (2001)
Stated preference	India (Urban)	9,068	Bhattacharya, Abernini, and Cropper (2007)
Wage-risk	India (Urban)	877,500	Shanmugam (1997)
Wage-risk	China (Urban)	52,650	Guo and Hammitt (2009)
Stated preference	China (Urban)	28,470	Wang and Mullahy (2006)
Stated preference	Thailand	182,000	Gibson et al. (2007)
Stated preference	Malaysia	397,800	Melhuish, Ross, Goodge et al (2005)
Statistics – Mean (sd): Poor and rural		**25600 (35400)**	
Statistics – Mean (sd): Overall		**362200 (556500)**	

Notes:

Table B26. Cost of tree replacement (c^f)

By assumption.

Table B27. Particulate emissions for stove fuel combinations ($\varepsilon_{PM2.5,i,m}$, in 24-hr µg/m³ $PM_{2.5}$)

Description	Location	Value	Source
Traditional biomass			
Kitchen levels	Guatemala	1650	Bruce et al (2004)
Child exposure	Guatemala	536	Bruce et al (2004)
Kitchen levels	Ghana	650	Pennise et al (2009)
Cooking area	Rwanda	910	Ghislaine (2013)
Kitchen levels	China	270	Chowhury et al (2013)
Kitchen levels	China	450	Chowhury et al (2013)
Personal exposure	Peru	116	Fitzgerald et al (2012)
Personal exposure	Peru	126	Fitzgerald et al (2012)
Kitchen levels	Peru	207	Fitzgerald et al (2012)
Kitchen levels	Peru	173	Fitzgerald et al (2012)
Kitchen levels	Mexico	1250	Smith et al (2007)
Kitchen levels	India	520	Smith et al (2007)
Kitchen levels	India	1020	Smith et al (2007)
Kitchen levels	Guatemala	1930	Albalak et al (2001)
Kitchen levels	Guatemala	528	Naeher et al (2001)
Mother exposure	Guatemala	481	Naeher et al (2001)
Child exposure	Guatemala	279	Naeher et al (2001)
Cooking area	Nigeria	1414	Oluwole et al (2013)
Statistics – Mean (sd)		**695 (515)**	
Biomass ICS			
Kitchen levels	Guatemala	728	Bruce et al (2004)
Child exposure	Guatemala	505	Bruce et al (2004)
Kitchen levels	Guatemala	403	Bruce et al (2004)
Child exposure	Guatemala	374	Bruce et al (2004)
Kitchen levels	Ghana	320	Pennise et al (2009)
Cooking area	Rwanda	558	Ghislaine (2013)
Kitchen levels	China	220	Chowhury et al (2013)
Kitchen levels	China	100	Chowhury et al (2013)
Personal exposure	Peru	34.2	Fitzgerald et al (2012)
Personal exposure	Peru	29.15	Fitzgerald et al (2012)
Kitchen levels	Peru	42.35	Fitzgerald et al (2012)
Kitchen levels	Peru	25.55	Fitzgerald et al (2012)
Kitchen levels	Mexico	470	Smith et al (2007)
Kitchen levels	India	165	Smith et al (2007)
Kitchen levels	India	170	Smith et al (2007)
Kitchen levels	Guatemala	330	Albalak et al (2001)
Kitchen levels	Guatemala	96.5	Naeher et al (2001)
Mother	Guatemala	257.2	Naeher et al (2001)
Child exposure	Guatemala	169.7	Naeher et al (2001)
Cooking area	Nigeria	130.3	Oluwole et al. (2013)
Statistics – Mean (sd)		**303 (224)**	
Charcoal ICS[1]			
Water boiling test	Laboratory	251000	MacCarthy et al (2010)
Water boiling test	Laboratory	260000	MacCarthy et al (2010)
Water boiling test	Laboratory	71000	MacCarthy et al (2010)
Water boiling test	Laboratory	44000	MacCarthy et al (2010)
Reductions relative to biomass stoves		**54-84%**	
LPG			
Kitchen levels	Ethiopia	220	Pennise et al (2009)
Kitchen levels	Ethiopia	110	Pennise et al (2009)
Kitchen levels	Ethiopia	80	Pennise et al (2009)

Kitchen levels	India	219	Balakrishnan et al (2013)
Child exposure	Guatemala	68.5	Naeher et al (2001)
Mother's exposure	Guatemala	117	Naeher et al (2001)
Kitchen levels	Guatemala	19	Naeher et al (2001)
ICS (biogas)	China	90	Chowhury et al (2013)
ICS (biogas)	China	110	Chowhury et al (2013)
Statistics – Mean (sd)		**133 (119)**	
Electric – no emissions			

[1] As data on 24-hour emissions are scarce, we impute the value of 24-hour PM emissions by using the proportion of PM emissions in the study against stove-fuel combination where we have data for their 24-hour PM emissions. For example, MacCarthy et al (2005) measured emissions for multiple stove-fuel combination and thus we can obtain a ratio of emissions for these to ICS(wood) using their data. This ratio can then be multiplied against 24-hour PM emissions for ICS(wood) where more data is available from other studies.

Table B28. Other emissions factors for traditional biomass stoves ($\varepsilon_{j,trad,biomass}$)

Description	Value	Source
CO_2 (g/MJ fuel)		
Accacia-trad mud	506.3	Smith et al (2000)
Acacia 3R	502.8	Smith et al (2000)
Euc 3R	566.1	Smith et al (2000)
Wood-metal no flue	545.0	Zhang et al (2000)
Brush-metal no flue	458.0	Zhang et al (2000)
Statistics – Mean (sd)	**515.6 (41.8)**	
CO (g/MJ fuel)		
Accacia-trad mud	24.2	Smith et al (2000)
Acacia 3R	23.7	Smith et al (2000)
Euc 3R	22.2	Smith et al (2000)
Wood-metal no flue	14.6	Zhang et al (2000)
Brush-metal no flue	36.6	Zhang et al (2000)
Statistics – Mean (sd)	**24.2 (7.9)**	
CH_4 (g/MJ fuel)		
Accacia-trad mud	1.43	Smith et al (2000)
Acacia 3R	3.44	Smith et al (2000)
Euc 3R	1.04	Smith et al (2000)
Wood-metal no flue	0.66	Zhang et al (2000)
Brush-metal no flue	1.95	Zhang et al (2000)
Statistics – Mean (sd)	**1.71 (1.08)**	
N_2O (g/MJ fuel)		
Accacia-trad mud	0.034	Smith et al (2000)
Acacia 3R	0.065	Smith et al (2000)
Euc 3R	0.027	Smith et al (2000)
Wood-metal no flue	0.266	Zhang et al (2000)
Brush-metal no flue	0.606	Zhang et al (2000)
Statistics – Mean (sd)	**0.114 (0.056)**	
BC (g/MJ fuel)		
3R	0.306	MacCarthy et al (2008)
3R	0.278	Bond et al (2013)
Statistics – Mean (sd)	**0.29 (0.020)**	
OC (g/MJ fuel)		
3R	0.25	Roden et al (2008)
Traditional	1.09	Roden et al (2008)
Traditional	1.07	Roden et al (2008)
Statistics – Mean (sd)	**0.80 (0.48)**	

Table B29. Other emissions factors for improved biomass stoves ($\varepsilon_{j,ICS,biomass}$)

Description	Value	Source
CO_2 (g/MJ fuel)		
Accacia IVM	355	Smith et al (2000)
Accacia IMET	353.9	Smith et al (2000)
Accacia IVC	308.2	Smith et al (2000)
Wood imp	388	Zhang et al (2000)
Statistics – Mean (sd)	**351.3 (32.8)**	
CO (g/MJ fuel)		
Accacia IVM	35.45	Smith et al (2000)
Accacia IMET	16.39	Smith et al (2000)
Accacia IVC	18.08	Smith et al (2000)
Wood imp	17.2	Zhang et al (2000)
Statistics – Mean (sd)	**21.8 (9.1)**	
CH_4 (g/MJ fuel)		
Accacia IVM	3.04	Smith et al (2000)
Accacia IMET	1.06	Smith et al (2000)
Accacia IVC	0.78	Smith et al (2000)
Wood imp	0.83	Zhang et al (2000)
Statistics – Mean (sd)	**1.4 (1.1)**	
N_2O (g/MJ fuel)		
Accacia IVM	0.0543	Smith et al (2000)
Accacia IMET	0.0713	Smith et al (2000)
Accacia IVC	0.0468	Smith et al (2000)
Wood imp	0.136	Zhang et al (2000)
Statistics – Mean (sd)	**0.077 (0.041)**	
BC (g/MJ fuel)		
Rocket	0.315	MacCarthy et al (2008)
Karve	0.076	MacCarthy et al (2008)
Fan	0.016	MacCarthy et al (2008)
Wood ICS	0.158	Bond et al (2013)
Statistics – Mean (sd)	**0.14 (0.13)**	
OC (g/MJ fuel)		
Wood Fan stove	0.31	Roden et al (2008)
Wood Fan stove	0.18	Roden et al (2008)
Wood Fan stove	0.02	Roden et al (2008)
Gasifer	0.11	Roden et al (2008)
Improved ICS	0.07	Roden et al (2008)
Gasifer	0.19	Roden et al (2008)
Fan stove	0.16	Roden et al (2008)
Eco estufa	0.68	Roden et al (2008)
Eco estufa	0.54	Roden et al (2008)
Eco estufa	0.14	Roden et al (2008)
Eco estufa	0.74	Roden et al (2008)
Eco estufa	0.77	Roden et al (2008)
Eco estufa	0.33	Roden et al (2008)
Eco estufa	0.34	Roden et al (2008)
Eco lenka	1.54	Roden et al (2008)
Eco lenka	2.01	Roden et al (2008)
Eco lenka	0.06	Roden et al (2008)
Eco lenka	0.39	Roden et al (2008)
Justa	0.18	Roden et al (2008)
Statistics – Mean (sd)	**0.46 (0.52)**	

Table B30. Other emissions factors for improved charcoal stoves ($\varepsilon_{j,ICS,charcoal}$)

Description	Value	Source
CO_2 (g/MJ fuel)		
Coal briq metal flue	643	Zhang et al (2000)
Honeycomb coal metal flue	742	Zhang et al (2000)
Honeycomb coal ICS no flue	303	Zhang et al (2000)
Statistics – Mean (sd)	**562.7 (230.3)**	
CO (g/MJ fuel)		
Coal briq metal flue	18.1	Zhang et al (2000)
Honeycomb coal metal flue	25.6	Zhang et al (2000)
Honeycomb coal ICS no flue	6.52	Zhang et al (2000)
Statistics – Mean (sd)	**16.7 (9.6)**	
CH_4 (g/MJ fuel)		
Coal briq metal flue	2.65	Zhang et al (2000)
Honeycomb coal metal flue	1.08	Zhang et al (2000)
Honeycomb coal ICS no flue	0	Zhang et al (2000)
Statistics – Mean (sd)	**1.24 (1.33)**	
N_2O (g/MJ fuel)		
Coal briq metal flue	0.0389	Zhang et al (2000)
Honeycomb coal metal flue	0.119	Zhang et al (2000)
Honeycomb coal ICS no flue	0.0489	Zhang et al (2000)
Statistics – Mean (sd)	**0.069 (0.044)**	
BC (g/MJ fuel)		
Charcoal Jiko	0.022	MacCarthy et al (2008)
Bituminous coal	0.0052	Zhi et al (2008)
Statistics – Mean (sd)	**0.014 (0.012)**	
OC (g/MJ fuel)		
Charcoal Jiko	0.35	Zhi et al (2008)
Hard coal in brick kiln	0.44	Bond et al (2004)
Statistics – Mean (sd)	**0.396 (0.069)**	

Table B32. Other emissions factors for LPG stoves ($\varepsilon_{j,ICS,gas}$)

Description	Value	Source
$\underline{CO_2}$ (g/MJ fuel)		
Biogas	142	Smith et al (2000)
LPG	125.6	Smith et al (2000)
LPG-trad	140	Zhang et al (2000)
LPG-IR	153	Zhang et al (2000)
Statistics – Mean (sd)	**140.2 (11.3)**	
<u>CO</u> (g/MJ fuel)		
Biogas	0.1918	Smith et al (2000)
LPG	0.6076	Smith et al (2000)
LPG-trad	0.0996	Zhang et al (2000)
LPG-IR	1.03	Zhang et al (2000)
Statistics – Mean (sd)	**0.482 (0.427)**	
$\underline{CH_4}$ (g/MJ fuel)		
Biogas	0.0989	Smith et al (2000)
LPG	0.00203	Smith et al (2000)
LPG-trad	0.0231	Zhang et al (2000)
LPG-IR	0.0158	Zhang et al (2000)
Statistics – Mean (sd)	**0.035 (0.044)**	
$\underline{N_2O}$ (g/MJ fuel)		
Biogas	0.43	Smith et al (2000)
LPG	0.27	Smith et al (2000)
LPG-trad	0.15	Zhang et al (2000)
LPG-IR	0.00	Zhang et al (2000)
Statistics – Mean (sd)	**0.214 (0.181)**	
<u>BC</u> (g/MJ fuel)		
LPG	0.0037	MacCarthy et al (2008)
LPG	0.0025	Bond et al (2004)
Statistics – Mean (sd)	**0.003 (0.004)**	
<u>OC</u> (g/MJ fuel)		
LPG	0.00193	Bond et al (2004) & Zhang et al. (2000)

Table B33. Other emissions factors for electric stoves ($\varepsilon_{j,ICS,electric}$)

Description	Value
CO2 (g/kW-hr)[1]	
Angola	386
Bangladesh	625
Benin	683
Colombia	157
Guatemala	418
India	999
Indonesia	722
Ivory Coast	408
Kazakhstan	1293
Kenya	393
Nepal	13
Nigeria	372
Pakistan	482
Peru	148
Sri Lanka	384
Statistics – Mean (sd)	**499 (330)**
CO (g/kW-hr) – no data	
CH4 (g/kW-hr)[1]	
Angola	13.41
Bangladesh	23.50
Benin	9.77
Colombia	0.57
Guatemala	20.68
India	16.64
Indonesia	20.41
Ivory Coast	9.80
Kazakhstan	18.88
Kenya	13.42
Nepal	0.93
Nigeria	14.40
Pakistan	31.46
Peru	5.34
Sri Lanka	27.17
Statistics – Mean (sd)	**15.1 (9.0)**
N2O (g/kW-hr)[1]	
Angola	2.68
Bangladesh	2.74
Benin	9.55
Colombia	1.01
Guatemala	5.93
India	19.59
Indonesia	8.55
Ivory Coast	1.03
Kazakhstan	21.5
Kenya	2.68
Nepal	0.19
Nigeria	1.89
Pakistan	5.49
Peru	1.35
Sri Lanka	5.43
Statistics – Mean (sd)	**5.97 (6.54)**
BC (g/kW-hr)[2]	

Natural Gas Combustion	0.029
Bituminous Combustion	0.003
Sub-Bituminous Combustion	0.244
Distillate Oil Combustion	0.022
Process Gas Combustion	0.093
OC (g/kW-hr) [2]	
Natural Gas Combustion	0.019
Bituminous Combustion	0.005
Sub-Bituminous Combustion	0.183
Distillate Oil Combustion	0.054
Process Gas Combustion	0.192

Notes: [1] From EIA, based on electricity mix in different countries
[2] Calculations, based on data from EPA and EIA: http://www3.epa.gov/blackcarbon/2012report/Chapter4.pdf; http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1.