The potential for improved cookstoves to reduce carbon dioxide emissions

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ABSTRACT

This paper presents an analysis of the cost of reducing carbon dioxide emissions through the introduction of improved cookstoves. The analysis constructs mitigation cost curves for three types of woodfuel user in 75 countries that account for 95 percent of all emissions from cooking with wood. Each curve is based on a Monte Carlo simulation of the costs and benefits of households switching to improved cookstoves, using a range of values for the most important variables in the calculation (woodfuel consumption and cost, stove cost and lifespan, level of adoption and emission reduction). The simulation results are then used to produce cost curves at the country and global level, using expansion coefficients based on national woodfuel statistics and census results.

The analysis shows that the cost of an improved cookstove would be recovered by savings in woodfuel costs in about 215 million households. After taking into account households already using improved stoves, the net number of households that should switch to improved stoves is 155 million, which would result in an emission reduction of 95 $MtCO_2$. If emission reductions are also valued (i.e. given a carbon price), more households should switch and the net emission reduction potential increases, reaching 165 $MtCO_2$ at a carbon price of USD 20/tCO_2. While these amounts are relatively small compared to total global emissions, improved cookstoves could make an important contribution to emission reductions in some countries, especially in Africa. It is also worth noting that the benefit-cost ratio of investing in improved cookstoves is relatively high, ranging from 2.9 to 3.5 at a carbon price of zero and USD 20/tCO_2 respectively.

Keywords: cookstoves; climate change; valuation; cost-benefit analysis; Monte Carlo simulation

INTRODUCTION

Globally, about 2.4 billion people or one-third of the World’s population use woodfuel as their main source of fuel for cooking (FAO, 2014a) and current consumption for cooking - about 1.35 billion cubic metres - is expected to remain about the same for at least the next 20 years (Cushion *et al*, 2010). However, although this is one of the most significant socioeconomic benefits derived from forests, it also has several negative externalities, such as the impacts of indoor air pollution on human health, the greenhouse gas emissions from woodfuel use and the degradation of forest resources that may occur if woodfuel harvesting is unsustainable.

At present, emissions of carbon dioxide (CO_2) from woodfuel use are not included in global accounting of greenhouse gas emissions in order to avoid double-counting. Instead, because woodfuel harvesting reduces the stock of forest biomass, emissions from woodfuel use are implicitly included in the estimates of emissions from land use change. However, as an indicator of the contribution of woodfuel use to emissions, it is still appropriate to compare these emissions with the total, as any reduction in woodfuel use should result in an increase in forest carbon stocks.

Table 1 makes such a comparison, using data presented in the Global Carbon Atlas (derived from Boden *et al*, 2013) and the FAOSTAT Forestry database (FAO, 2014b).[1] This shows that CO_2 emissions from woodfuel use in 2010 amounted to 2,462 million tonnes ($MtCO_2$), which was equal to about seven percent of total global emissions from all sources. Furthermore, this amount was similar to the global net emissions from land use change.

At the regional level, the majority of emissions from woodfuel use occur in Africa (33%) and Asia and Oceania (41%), although about 10-20 percent of these emissions may be from uses other than cooking (Broadhead *et al*, 2001). Very few emissions in Europe and North America are likely to be from the use of woodfuel for cooking and a significant proportion of the emissions in Latin America come from the use of charcoal in the Brazilian steel industry. Thus, global emissions specifically from the use of woodfuel for cooking probably amount to about 1.8 billion tCO_2. The table also shows the significance of emissions from woodfuel use in Africa, where these are equal to about one-third of all emissions on the continent or two-thirds of the emissions from land use change.

Table 1 Emissions of carbon dioxide from woodfuel use compared to total carbon emissions in 2010 (in $MtCO_2$)

Region	Type of emission			Emissions from woodfuel use			Woodfuel emissions as share of the total
	Fossil fuels	Land use change	Total	Fuelwood	Charcoal	Total	
Africa	1,171	1,256	2,427	590	226	817	34%
Asia and Oceania	16,529	630	17,159	952	66	1,018	8%
Europe	6,009	-720	5,289	195	4	199	4%
North America	5,933	-116	5,817	50	7	57	1%
Latin America and Caribbean	1,691	1,365	3,056	297	74	371	12%
World	31,332	2,415	33,747	2,084	378	2,462	7%

Sources: Boden et al (2013) and FAOSTAT (2014). Note: emissions from charcoal include those from its use and manufacturing (roughly one-third and two-thirds of the total respectively).

Improving the technology that households use for cooking is one way that the negative impacts of cooking with woodfuel can be reduced, but the success of projects to introduce improved cookstoves has been mixed. For example, the earliest comprehensive review of cookstove projects (Manibog, 1984) reported that the number of stoves distributed in the previous decade was far less than originally planned and that up to half of the stoves distributed were either not used or used only infrequently. A decade later, Barnes *et al* (1993) produced similar findings from a review of the 160 stove programmes operating at that time. Common failures in these early stove programmes were the cost of stoves compared to their alternatives (often a simple three-stone fire), poor stove design and a lack of training in the use of new stoves. More importantly, these programmes (often run by governments) tended to be top-down and centralised, with little input from users and little or no use of local materials and artisans that could be used to replace or repair new stoves when they failed.

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[1] FAOSTAT woodfuel production data is presented in cubic metres. This was converted to CO_2 emissions by first multiplying by 0.75 (to convert from cubic metres to metric tonnes), then multiplying the result by 1.7472, which is the default factor for woodfuel CO_2 emissions (tCO_2 per tonne of wood burned) shown in the Guidelines for National Greenhouse Gas Inventories issued by the Intergovernmental Panel on Climate Change (IPCC, 2006).

In recent years, interest in improved cookstoves has increased again with, for example, the United Nations Foundation aiming to support the introduction of 100 million improved cookstoves by 2020 through the Global Alliance for Clean Cookstoves (UN Foundation, 2014). In addition, a review of cookstove programmes since the mid-1990s (Gifford, 2010) has shown that many of these new programmes have learned from previous efforts. For example, while some of the larger programmes are still implemented by governments, about half are now run by non-governmental organisations (NGOs) and two-thirds of the 100 programmes started in the last decade were still operating in 2010.

The success of these more recent programmes has been attributed to more involvement of local people in the manufacturing and design of stoves, which has increased their availability and acceptance by users. Better training in the use of improved cookstoves and improved monitoring have also led to more sustainable results. With respect to financing, many poor households still find it difficult to purchase an improved cookstove, but a number of new and innovative ways of helping people to acquire an improved cookstove have been introduced, often linked to the sale of CO_2 emission reductions on carbon markets.

Given the renewed interest in the use of improved cookstoves and current concerns about climate change, this paper aims to examine the potential for such devices to reduce global CO_2 emissions. Considering that many of the social and technical barriers to adoption are now well known, it focuses on the costs and benefits of improved cookstoves and the construction of mitigation cost curves to show the emissions reductions that would be economically feasible across a range of different carbon prices. Using data on woodfuel use collected for the latest FAO State of the World's Forests report (FAO, 2104a), it also identifies countries where the potential for emissions reductions are highest and where cookstove programmes might focus their attention in the future.

METHODOLOGY

The overall approach to this analysis is similar to the methodology described by Jeuland and Pattanayak (2012). It first compares the annual cost of household energy use (for cooking) with and without an improved cookstove, using a range of input values derived from the data sources. The difference in costs between the two alternatives are then divided by the CO_2 emission reduction expected from using an improved cookstove to arrive at a cost of the emission reduction (in USD/tCO_2).

These calculations are made at the level of an individual household in each country and are repeated using a Monte Carlo simulation (with 500 iterations) that randomly selects input values in each calculation from a specified range for each variable. The simulation is performed in each country for three types of woodfuel user (charcoal users, urban and rural fuelwood users), then the individual results are multiplied by an expansion coefficient[2] and summed across all three types of user to produce a mitigation cost curve for each country.

The analysis only examines the cost of switching to an improved cookstove using the same type of woodfuel and it does not examine the cost of switching to an alternative type of

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[2] The expansion coefficient for each type of woodfuel user is the number of those types of user in the country divided by 500.

energy (e.g. a solar or biogas cookstove). In addition, it does not include any other benefits from the use of improved cookstoves, such as the health benefits that might be achieved from reductions in indoor air pollution or any climate benefits from reductions in other greenhouse gases emitted from woodfuel use. Thus, the mitigation costs presented here are slightly higher than might be expected if these other benefits were included in the calculations. In total, the analysis examines 75 countries accounting for 95% of the 534 million households in the World using woodfuel to cook,[3] so these results are a slight underestimate of the total mitigation potential at the global level.

For the purpose of calculating costs, the analysis assumes that charcoal users and urban fuelwood users purchase their fuelwood and charcoal, while rural fuelwood users collect their fuelwood unless its market price is less than their opportunity cost of time (in which case they would also purchase fuelwood). It also assumes that there would be an additional delivery and extension cost associated with the distribution of improved cookstoves in rural areas whereas, for other users, the cost of switching to an improved cookstove would be only the cost of the cookstove. Thus, the calculation of costs for rural fuelwood users is slightly more complicated than for the other two types of woodfuel user.

The cost of switching to an improved cookstove

For each household, the annual cost of switching to an improved cookstove is calculated using the seven equations described below.

$$\text{Eq. 1: } E_1 = C \cdot P \mid C \sim U([C_{min}, C_{max}]),\ P \sim U([P_{min}, P_{max}])$$

$$\text{Eq. 2: } E_2 = C \cdot T \cdot N \mid C \sim U([C_{min}, C_{max}]),\ T \sim U([T_{min}, T_{max}]),\ N \sim U([0, N_{pov}, N_{max}])$$

$$\text{Eq. 3: } E_3 = \min(E_1, E_2)$$

Equation 1 shows that, if woodfuel is purchased, the annual cost of woodfuel without an improved cookstove (E_1) is calculated as the annual consumption of woodfuel in tonnes (C) multiplied by price per tonne (P), where the values of C and P are randomly selected from a range of consumption levels and prices (based on the data sources and distributed uniformly).

Equation 2 is used to calculate the annual cost of woodfuel without an improved stove if it is collected (E_2). This is equal to annual consumption (C), multiplied by the number of years needed to collect one tonne of woodfuel (T) and the opportunity cost of time (i.e. the annual income - N - that would be earned from using this time for other activities).

As before, the amount of consumption is randomly selected from a uniform range of values and so is the collection time. However, for the opportunity cost of time, the range of values

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[3] The countries included in the analysis are: Angola; Argentina; Bangladesh; Benin; Bolivia; Brazil; Burkina Faso; Burundi; Cambodia; Cameroon; Central African Republic; Chad; Chile; China; Colombia; Congo; Côte d'Ivoire; Dominican Republic; DPR Korea; DR Congo; Ecuador; El Salvador; Equatorial Guinea; Ethiopia; Gabon; Gambia; Ghana; Guatemala; Guinea; Guinea-Bissau; Honduras; India; Indonesia; Kenya; Lao PDR; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Mexico; Morocco; Mozambique; Myanmar; Namibia; Nepal; Nicaragua; Niger; Nigeria; Pakistan; Panama; Papua New Guinea; Paraguay; Peru; Philippines; Rwanda; Samoa; Senegal; Sierra Leone; Solomon Islands; Somalia; South Africa; Sri Lanka; Sudan (former); Swaziland; Thailand; Togo; Uganda; United Republic of Tanzania; Vanuatu; Venezuela; Viet Nam; Zambia; and Zimbabwe.

used for selecting one to use in the analysis is divided into two parts. The lower end of the distribution $[0, N_{pov}]$ is based on the international poverty line of USD 1.25 in each country and the proportion of the population falling below this amount. For the upper part of the distribution $[N_{pov}, N_{max}]$, the upper limit for the distribution is set so that the average level of income across the whole distribution is equal to the average per capita value added in agriculture (after an allowance for returns to capital).[4] The value used in each iteration is selected uniformly from one of the two parts of the distribution, depending on the value of the random number generated (i.e. whether it is more or less than the proportion of the population living below the poverty line).

Equation 1 is used to calculate the annual cost of woodfuel without an improved cookstove for charcoal users and urban fuelwood users. For rural woodfuel users, the minimum result from the two alternative calculations is used (Equation 3).

With an improved cookstove, the annual cost of cooking with woodfuel is calculated in two parts: the cost of the woodfuel used plus the cost of the cookstove.

$$\text{Eq. 4: } E_4 = E_1 \cdot (1-(R \cdot A)) \mid R \sim U([R_{min}, R_{max}]),\ A \sim U([A_{min}, A_{max}])$$

$$\text{Eq. 5: } E_5 = E_3 \cdot (1-(R \cdot A)) \mid R \sim U([R_{min}, R_{max}]),\ A \sim U([A_{min}, A_{max}])$$

Equations 4 and 5 show the cost of woodfuel used with an improved cookstove (E_4 or E_5), which is the original cost of woodfuel multiplied by one minus the reduction in woodfuel needed when an improved cookstove is used. The reduction factor (R) is multiplied by an adoption rate (A) to take into account that some households may not use their improved cookstove or may not use it all the time. As before, the reduction factor and adoption rates are selected from a uniformly distributed range of values drawn from the literature on cookstoves. Equation 4 applies to charcoal users and urban fuelwood users, while Equation 5 is applied to rural fuelwood users.

$$\text{Eq. 6: } I_1 = S/D \mid S \sim U([S_{min}, S_{max}]),\ D \sim U([D_{min}, D_{max}])$$

$$\text{Eq. 7: } I_2 = (S+X+(2T_{cost} \cdot T_{max} \cdot \sqrt{RN}))/D \mid S \sim U([S_{min}, S_{max}]),\ D \sim U([D_{min}, D_{max}]),\ RN \sim U([0, 1])$$

Equations 6 and 7 are used to calculate the average annual cost of an improved cookstove. For charcoal users and urban fuelwood users, Equation 6 shows that the annual cost (I_1) is calculated as the cost of the stove (S) divided by its durability (D) or the number of years it is expected to remain useable, where S and D are selected from a range of values based on the experiences of current cookstove projects. Considering that the average life of a cookstove is generally only a few years, discounting was not used in the annual cost calculation, because this would not affect the results very much and it avoids the difficulty of selecting an appropriate discount rate.

Equation 7 shows the calculation used for rural fuelwood users. This is similar to the previous equation, except that an extension cost (X) and a transport cost is added to the cookstove cost (S), then the sum of these three items is divided by durability (D). The transport cost is

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[4] For comparability with the income measure derived from value-added, the poverty line used in each country was converted from the international measure (USD 1.25 at purchasing power parity or PPP) to a value in US Dollars at market exchange rates and, in countries where reliable estimates of per capita value-added in agriculture could not be obtained, gross domestic product (GDP) per capita was used.

calculated as the cost per kilometre of transporting a stove (T_{cost}) multiplied by two (for a round trip) then multiplied by transport distance. The transport distance is calculated as the maximum transport distance (T_{max}) multiplied by the square root of a randomly generated number between zero and one (RN). This latter part of the equation ($T_{max} \cdot \sqrt{RN}$) is the formula for the distance from the centre of a disk (of radius T_{max}) to a randomly selected point on that disk (Wallin, 2014).

The extension cost is based on local labour costs and assumptions about how much time it would take to distribute cookstoves and train rural users in their use. The transport cost is based on local fuel prices and the maximum transport distance assumes that cookstoves would be manufactured and distributed from decentralised locations in countries.

Based on the above equations, the annual cost of switching to an improved cookstove is simply calculated as $E_4+I_1-E_1$ for charcoal users and urban fuelwood users, or $E_5+I_2-E_3$ for rural fuelwood users.

The carbon dioxide emissions reduction from switching to an improved cookstove

The CO_2 emissions from cooking with and without an improved cookstove are based on the amount of woodfuel used in the two alternative situations.

$$\text{Eq. 8: } CD_1 = C \cdot M \mid C \sim U([C_{min}, C_{max}])$$

$$\text{Eq. 9: } CD_2 = CD_1 \cdot (1-(R \cdot A)) \mid R \sim U([R_{min}, R_{max}]),\ A \sim U([A_{min}, A_{max}])$$

Equation 8 is similar to Equation 1 above and shows that the CO_2 emissions from woodfuel use without an improved cookstove (CD_1) are equal to the annual consumption of woodfuel in tonnes (C) multiplied by an emissions factor (M) for the tonnes of CO_2 emitted per tonne of woodfuel used. For the latter, standard emissions factors from the Intergovernmental Panel on Climate Change (IPPC, 2006) are used, namely a value of 3.100 for charcoal and 1.7472 for fuelwood. In each iteration, the value of C used in the calculation is the same as that selected for calculating the woodfuel cost.

Equation 9 matches Equations 4 and 5 and shows that the CO_2 emissions from an improved cookstove (CD_2) are equal to the original emissions multiplied by a reduction factor adjusted for adoption. The variables selected for each iteration - R and A - are the same as those selected for the calculation of woodfuel costs.

Combining the results of Equations 8 and 9, the emissions reduction from switching to an improved cookstove is simply CD_1-CD_2 in each iteration of the analysis.

Calculation of the mitigation cost curve

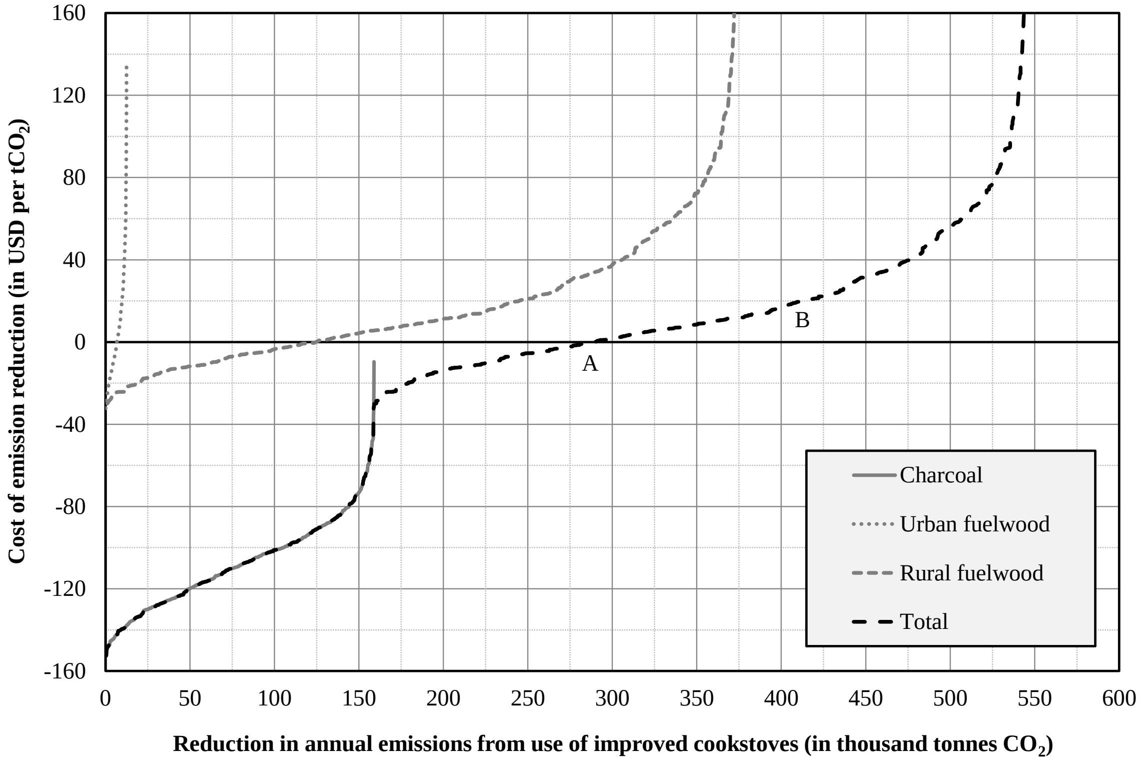
Based on the above equations, the cost of an emissions reduction (in USD/tCO_2) in each iteration of the model is calculated as the cost of switching to an improved cookstove, divided by the emissions reduction expected from this switch, which is:

$$\text{for charcoal users and urban fuelwood users: } \quad \frac{(E_4+I_1-E_1)}{(CD_1-CD_2)}$$

for rural fuelwood users: $$\frac{(E_5+I_2-E_3)}{(CD_1-CD_2)}$$

For each of the three types of woodfuel user, the Monte Carlo simulation gives 500 paired results showing, in each case, an expected emission reduction (in tCO_2/year) and associated mitigation cost (in USD/tCO_2) for a household switching to an improved cookstove. To produce a mitigation curve at the country level, each emission reduction is multiplied by the expansion coefficient for that type of user in that country and the results are sorted by cost and then aggregated. The three cost curves are then summed to produce a mitigation cost curve for the country, which can also be added to the results for other countries to produce regional or global mitigation cost curves.

Figure 1 Mitigation cost curve for the introduction of improved cookstoves in Angola



As an example, Figure 1 above presents the results obtained for Angola. The solid grey line at the bottom of the figure is the cost of switching to improved cookstoves for households using charcoal. In this case, the results show that the savings from reduced expenditure on charcoal more than pay for the cost of buying an improved cookstove (i.e. the net cost of switching to an improved cookstove is negative throughout its range). The other two grey lines show the cost of switching for fuelwood users. In both cases, using an improved cookstove would save money in some households, but result in a net cost for many.

The black, broken line in the figure is the total mitigation cost curve obtained by aggregating the three grey curves. At first, this follows the curve for charcoal, then it moves to the right at cost levels where households using fuelwood should also switch to an improved cookstove. Point A in the figure shows that annual emissions could be reduced by 280,000 tCO_2 if all of the households that would save money from an improved cookstove chose to switch to one.

This is about 1 million households (or 50% of households cooking with wood in Angola) and the majority of these would be charcoal users.

In addition to calculating the optimal number of improved cookstoves that should be used at any given emission cost or carbon price, the simulation model can also provide useful information for the design of investments in emissions reductions. For example, at a carbon price of USD 20/tCO_2, it would be optimal for 1.45 million households in Angola to use improved cookstoves, with an expected emission reduction of 410,000 tCO_2 per year (Point B in Figure 1). If this emission reduction could be sold, the USD 8.2 million generated each year could subsidise about 75-80% of the cost of supplying the 1.45 million improved cookstoves required. However, due to the fact that a lot of switching would benefit users financially (through lower fuel costs), the figure above suggests it would be more cost-effective to focus any subsidy on fuelwood users and, for charcoal users, to promote switching by other means (e.g. provision of micro-credit, information and awareness raising or training local artisans to manufacture and sell improved cookstoves as a business venture). Such insights are useful for planning future cookstove programmes.

DATA SOURCES

Most of the woodfuel data used in this analysis was taken from international statistical databases or the results of large-scale household surveys. In addition, a literature survey of woodfuel studies, cookstove project websites and project documents was also used to gather information about the costs and benefits of improved cookstoves.

Woodfuel consumption, price, collection time and cost

Statistics about the number of households using woodfuel to cook were obtained from national censuses and large-scale household surveys (for more details, see FAO, 2014a). Figures were obtained for the most recent year over the period 2000 - 2011 and were adjusted for population growth and changes in total woodfuel consumption in each country, to give estimates for 2011. The division of households into charcoal users and urban or rural fuelwood users was also based on these survey results.

Average household consumption was calculated by dividing total consumption of fuelwood or charcoal in 2011 (from FAOSTAT) by the number of households using each type of fuel.[5] Household consumption can vary due to factors such as household size, income and proximity to supply sources, but information about variability is not readily available. Therefore, as a proxy, the average deviation in per capita consumption between countries in each continent was used in the analysis as the range of household consumption levels from which input variables were selected. For Africa, the range was +/- 42% for charcoal and +/- 57% for fuelwood, for Asia and Oceania the ranges were +/- 70% and +/- 45% and for Latin America and the Caribbean the range was +/- 53% for both types of fuel. Although these ranges are quite large, it is likely that there is considerable variation between individual households in woodfuel consumption levels.

For woodfuel prices, international trade statistics (from FAOSTAT) were used to calculate unit prices for each country, by dividing total trade value by total volume. However, while

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[5] Household fuelwood consumption might be different in urban and rural households, but it was only possible to calculate an average for all households, so this might be a source of some error in the analysis.

international trade volumes are quite large for charcoal and it is feasible to calculate a cost per metric tonne (MT) in such a way, international trade in fuelwood is relatively small and this approach cannot be used. Therefore, for fuelwood, an opportunity cost was calculated by subtracting the cost of labour (used to produce one metric tonne of charcoal) from charcoal prices and dividing the result by the amount of wood required to make one metric tonne of charcoal.

The above calculations gave average prices for charcoal of USD 212/MT in African countries, USD 453/MT in Asia and Oceania and USD 251/MT in Latin America and the Caribbean. For fuelwood, the results were USD 56/m^3 in Africa, USD 64/m^3 in Asia, USD 45/m^3 in Oceania and USD 25/m^3 in Latin America and the Caribbean.[6] While these prices may seem high, they are generally similar to the limited local market price information that is available. It should also be noted that woodfuel is often sold to consumers in small volumes with a high profit margin, so these figures are unlikely to be unrealistically high.

Average prices in each country were also limited by an upper boundary fixed at two times the regional average.[7] For the range of values within a country, a uniform distribution of +/- 20% was used, because urban woodfuel prices are unlikely to vary significantly within a country.

For fuelwood collection time, data was obtained from a literature review of journal articles, book chapters, conference proceedings and project reports. From this, 74 studies were obtained where productivity had been measured (61 studies of fuelwood and 13 of charcoal). These measurements were all converted to standard units (amount of time taken to produce one metric tonne of woodfuel or charcoal).[8]

Proximity to forest resources has a strong influence on fuelwood collection time. However, due to the high level of variability in the data, correlation between forest cover and fuelwood collection time was quite weak and it was not possible to produce credible estimates of collection time for every country.[9] Therefore, an average fuelwood collection time was calculated for each region and used for all countries in the respective region. Similarly, the average deviation in the data within each region was used as the range of values in the simulation for each country. This resulted in the following fuelwood collection times: 0.0732 MT/year +/- 35% in African countries; 0.0931 +/- 50% in Asia and Oceania; and 0.0698 +/- 15% in Latin America and the Caribbean.

To calculate the cost of fuelwood collection time, the most recent statistics about the proportion of people living on less than USD 1.25/day and per capita value added in agriculture were taken from World Bank databases (World Bank, 2014a).

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[6] In Latin America and the Caribbean, this calculation resulted in negative fuelwood prices in many countries (due to low charcoal prices and high labour costs), so a minimum price of USD 25/m^3 was used.

[7] This limit was applied to countries with very little trade in charcoal, where unrealistically high prices were sometimes calculated.

[8] For charcoal production, the time taken to collect fuelwood to make the charcoal was excluded from the calculation, to give an estimate of the time it takes to make charcoal. The average of the 13 observations - 0.095 years/MT - was used to calculate the opportunity cost of fuelwood, as described previously.

[9] Although, at a broad scale, the data did match expectations with, for example, generally longer collection times in arid countries with low forest cover and shorter times in places with high forest cover.

Costs and benefits of improved cookstoves

Information about the costs and durability of improved cookstoves and their benefits (in terms of reduced woodfuel consumption and emissions) was collected from a literature review. A major data source was the project database of the Global Alliance for Clean Cookstoves (GACC, 2014a), which contains the details of many current cookstove projects. Other sources of information included books and book chapters, journal articles and the websites of organisations selling or promoting cookstoves. In total, 51 useful data sources were identified, giving between 60-140 observations of the different variables of interest (cookstove cost, durability, etc.).

In the case of costs, most information was available for Africa, where an improved cookstove may cost as little as USD 1-2 (for a simple home-made fuelwood stove, made from local materials) to USD 40 or more (depending on size). Based on the data, a range of USD 5-20 (for charcoal stoves) and USD 5-40 (for fuelwood stoves) was used the average range of stove costs for the whole continent. For Asia and Oceania, a similar range of stove costs was found and a range of USD 10-35 and USD 5-35 was used for charcoal and fuelwood stoves, respectively. Less information was available for Latin America and the Caribbean, but the small amount of available cost data suggested that stove costs there are quite a lot higher, so a cost range of USD 20-60 per stove was used for both types of stove. Based on these average stove costs for each continent, a range of costs for each country was then derived by adjusting these figures for the relative purchasing power in each country (World Bank, 2014b).

The durability (or expected life) of a cookstove is affected by many variables, such as: the type of fuel used; its size; intensity of use; and the materials used to make it. The literature review produced 40 estimates of durability, with the majority (23) of these falling in the range of 3-5 years. However, many of these estimates were *ex ante* predictions of how long a cookstove should last in a project. Given the possibility of optimism bias in these estimates, the analysis assumed that stoves might last for 3-5 years in Latin America and the Caribbean (where stoves are slightly more expensive and, presumably, more durable) and 2-4 years elsewhere.

For the extension cost associated with distributing cookstoves in rural areas, per capita GDP figures were taken from the World Bank (2014a) and converted into an amount per day as a proxy for daily income. This was then multiplied by 10/30 to get an extension cost per stove (assuming that two people working and travelling for 5 days could distribute 30 stoves). Transport cost per kilometre was calculated as five times the fuel cost (to allow for other vehicle operating costs and depreciation), with local fuel costs taken from World Bank statistics. The maximum transport distance was based on the average area of first or second-level administrative districts in each country (Wikipedia, 2014) and the simple assumption that cookstoves are distributed from the centre of a circular area equal to that size. The latter calculations gave an average transport cost per stove, varying from USD 7.50 in the Democratic Republic of Congo to under USD 1.00 in smaller countries such as Vanuatu, Gambia and Panama.

The literature review was also used to collect estimates of the reduction in woodfuel use and emissions expected from a switch to an improved cookstove. In total, this produced 41 estimates, varying from 7-90% and with an average of 53%. As with the estimates of durability, many of these figures were either projections or were the results of limited tests under controlled conditions. Furthermore, the few results from surveys in the field tended to suggest lower reductions of up to about 35%. Thus, to avoid the possibility of optimism bias, a range of 15-25% was used in the analysis as an estimate of the woodfuel and emission reductions that might be expected from the use of improved cookstoves.

The emission reduction was also multiplied by an adoption rate of 70-90%, based on the literature reviewed in Jeuland and Pattanayak (2012). While this is towards the higher end of their range of values for adoption, it reflects the fact that modern cookstove programmes are generally run more effectively than in the past and, more importantly, many of these programmes expect users to make at least some contribution to the cost of their new cookstoves. In addition, any optimism bias here will be offset by the values for emission reductions used in the analysis, which are quite conservative compared to the results of the literature review.

RESULTS

At the global level, the results of the analysis suggest that about 215 million households should use improved cookstoves at a carbon price of zero, rising to 385 million at a carbon price of USD 20/tCO_2. As a proportion of all households cooking with woodfuel, these figures amount to 43% and 76% respectively.

Figure 2 Number of households where using to an improved cookstove would be economically optimal at different carbon prices (in USD/tCO_2)

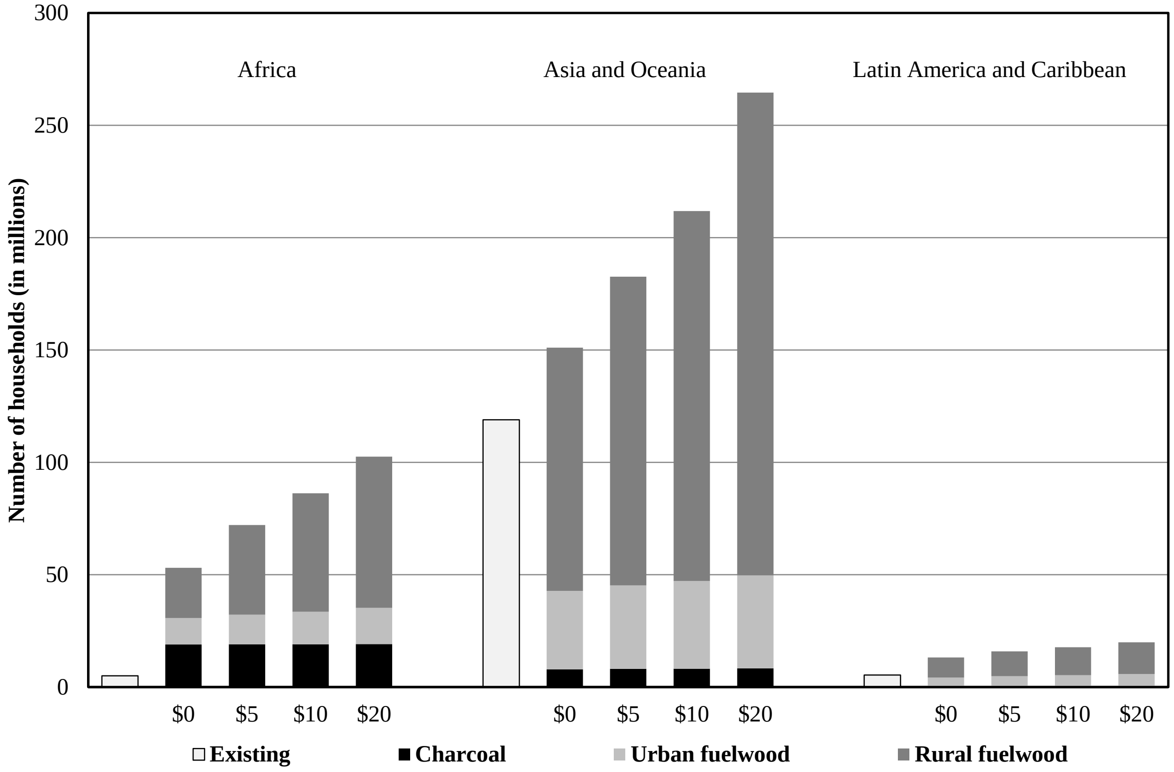

Figure 2 presents these results at the regional level, and shows that using improved cookstoves would be economically optimal in 50-100 million African households and 150-250 million households in Asia and Oceania, plus a relatively small number of households in Latin America and the Caribbean. These large differences between the regions are mainly due to the number of households cooking with woodfuel in each region, although there are also some differences between countries and regions due to the local costs of cookstoves and woodfuel.

The figure also shows two other important points. The first is that switching to an improved cookstove would make economic sense for many households without taking into account the benefit of reduced CO_2 emissions (i.e. the savings in woodfuel costs would exceed the cost of the stove). This is particularly the case for charcoal users and, to a lesser extent, urban fuelwood users. Indeed, as carbon values are introduced into the analysis, almost all the additional households that should switch to improved cookstoves are rural households.

A second factor that should be taken into account is that some households already use improved cookstoves, so the potential for emissions reductions will be less than shown in the figure. Information about the existing number of households already using improved cookstoves was taken from the Global Alliance for Clean Cookstoves database (GACC, 2014b) and is also shown in the figure. Currently, it is estimated that about 130 million households use improved cookstoves, although the vast majority of these are in China (95 million), with another 10 million in India and over 1 million in each of a small number of other countries (Brazil, Mexico, Nigeria, Pakistan, Thailand, Viet Nam and Zambia).

It is possible to calculate the net number of households that should switch to improved cookstoves by simply multiplying the simulation results by a reduction factor. However, this would be too simplistic, because it is likely that most households with an improved cookstove are those where the cost of switching is lowest (i.e. they are at the bottom of the mitigation cost curve). Thus, in graphical terms, the mitigation cost curve should be shifted to the left (rather than reduced in range along the x-axis) to account for the number of households that already use improved cookstoves.

The results of the model were adjusted for this by removing the emission reductions calculated for all of the households with the lowest emission reduction costs in each country, up to the point where the number of households removed matched the number of households that already have an improved cookstove. The result of this adjustment at the global level is shown in Figure 3, where the original gross mitigation cost curve (shown in grey) moves to the left by about 40 $MtCO_2$.

Figure 4 presents these same results at the regional level. Due to the large number of households already using improved cookstoves in Thailand and China,[10] the net mitigation potential from the introduction of improved cookstoves is quite similar in Africa and Asia. In addition, the analysis suggests that it is likely that almost all households using charcoal already use an improved cookstove, except in Africa.

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[10] According to GACC statistics, almost all households in Thailand already use improved cookstoves. In China, the number of households already using improved cookstoves is roughly equal to the number that should switch at a carbon price of USD 20/tCO_2, suggesting that there may also be very limited scope for promoting improved cookstoves there. However, this illustrates that there may be other important benefits that encourage the use of improved cookstoves. It may also be because some of those households using improved cookstoves are cooking with other fuels, in which case this analysis underestimates the remaining potential for woodfuel stove switching in China.

Figure 3 The global mitigation cost curve for the introduction of improved cookstoves, with adjustment for the existing use of improved stoves

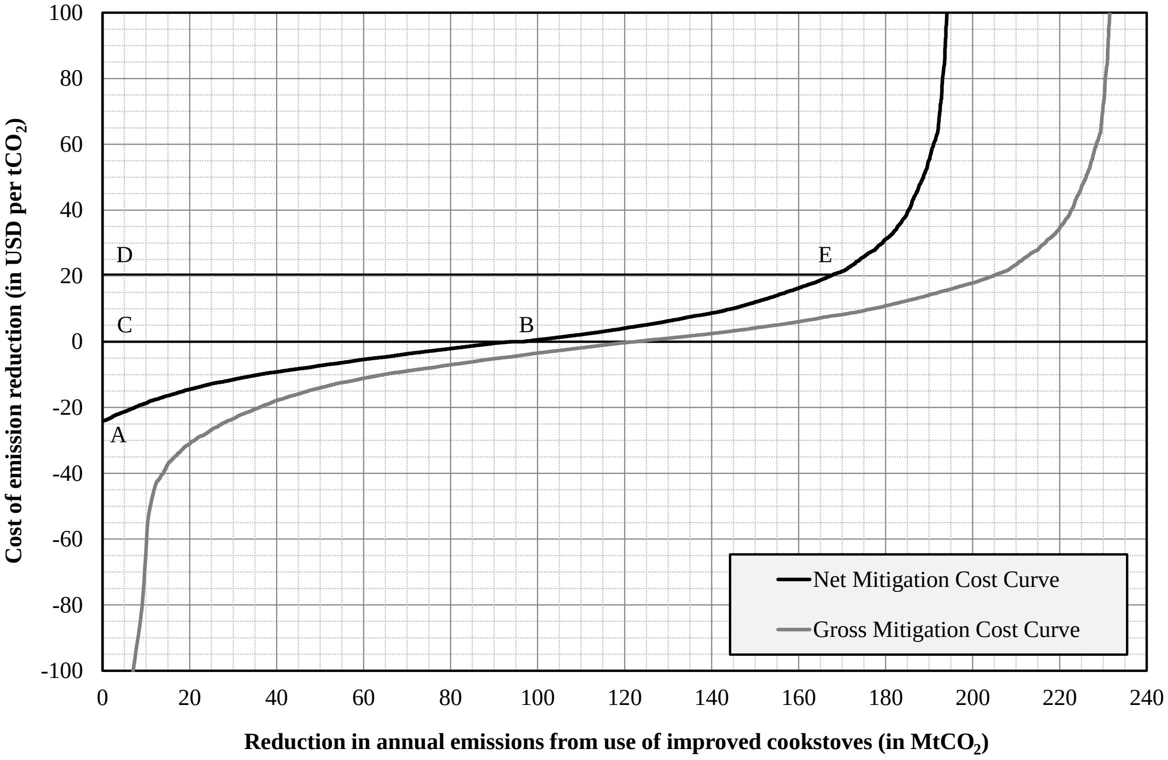
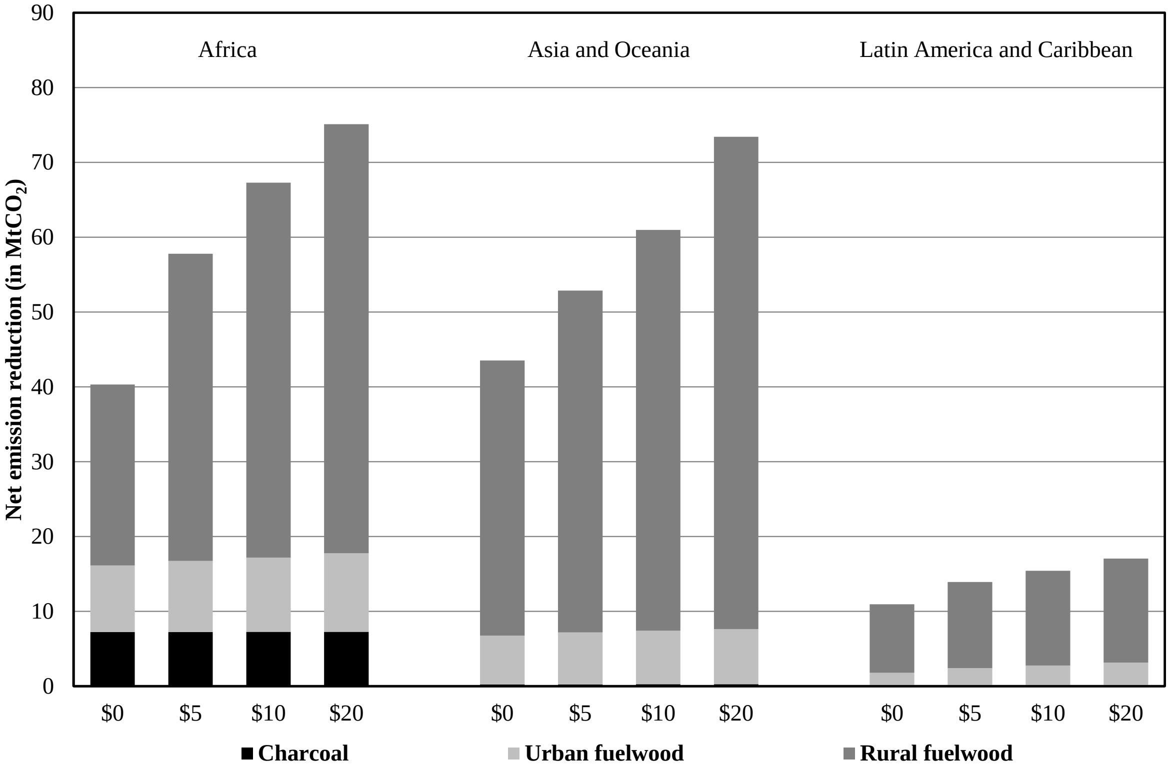


Figure 4 Net emission reduction potential from the introduction of improved cookstoves at different carbon prices (in USD/CO$_2$)



Globally, the net mitigation potential from the introduction of improved cookstoves is about 95 $MtCO_2$ per year at a zero carbon price, rising to 165 $MtCO_2$ at a carbon price of USD 20/tCO_2. These amounts are relatively small compared to total global emissions, for example 165 $MtCO_2$ would amount to just under 0.5% of global emissions in 2010. However, the results for Africa are more significant. The potential emissions reductions there (40-75 $MtCO_2$) are about 1.5-3.0% of current CO_2 emissions, so the introduction of improved cookstoves could make a meaningful contribution to emission reductions on that continent.

One other useful measure that can be calculated from the mitigation cost curve is the benefit-cost ratio. At any point along the curve, the total annual cost of switching to improved cookstoves is calculated as the number of households switching multiplied by the average (annual) stove cost. The net benefit is then the difference between this and the reduction in fuel costs and value of reduced emissions that will be achieved at any chosen carbon price.

Graphically, this net benefit is the area between the mitigation cost curve and the carbon price chosen for the calculation. So, at a zero carbon price, this would be the area ABC in Figure 3, which is also the private net benefit of switching to improved cookstoves. At a carbon price of USD 20/tCO_2, the annual net benefit would be the area AED, comprising the private net benefit of ABC and the social net benefit (or the net benefit from reduced CO_2 emissions) shown as the area CBED. The total benefit of switching is the total stove cost plus the total net benefit of switching and this amount, divided by the total stove cost, gives the benefit-cost ratio.

Table 2 Annual costs and benefits and the benefit-cost ratio for the optimal introduction of improved cookstoves at a carbon price of USD 20/tCO_2

Region	Stove costs (million USD)	Net benefits (million USD)			Benefit-cost ratio
		Private	Social	Total	
Africa	657	1,160	1,285	2,446	4.7
Asia and Oceania	1,071	683	1,208	1,891	2.8
Latin America and Caribbean	163	100	314	414	3.5
World	1,890	1,943	2,807	4,751	3.5

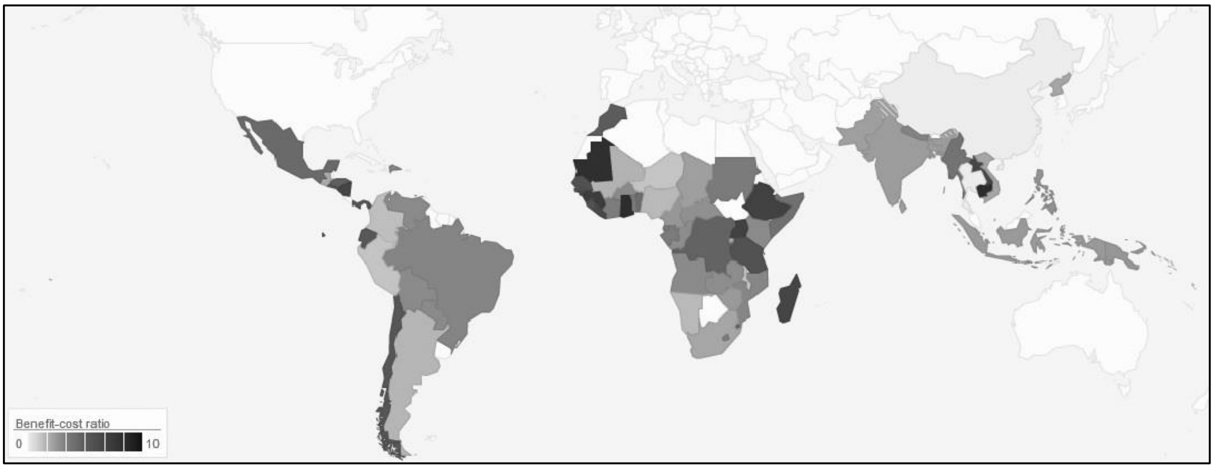
Table 2 shows the total annual costs, benefits and benefit-cost ratio that would be achieved if households switched to improved cookstoves up to the point at which the cost of emission reductions (or carbon price) reached USD 20/tCO_2 (i.e. point E in Figure 3). At this point, 285 million households should switch to improved cookstoves, at an annual cost of USD 1.9 billion. Savings in woodfuel costs would amount to USD 3.8 billion, covering the cost of the stoves and giving an additional private net benefit of USD 1.9 billion. The benefit of reduced CO_2 emissions (at a carbon price of USD 20/tCO_2) would amount to a further USD 2.8 billion.

At this level of implementation, the average global benefit-cost ratio would be 3.5, with every one dollar invested in improved cookstoves yielding a saving in woodfuel costs of roughly two dollars and an additional social benefit (from emission reductions) of about USD 1.50. Even at a zero carbon price, where woodfuel cost savings are the only benefit (i.e. point B in Figure 3), the benefit cost-ratio would still be quite high at 2.9, with a total annual cookstove cost of USD 1 billion and net private benefits of USD 1.9 billion.

At a country level, the countries with the largest potential to reduce emissions by using improved cookstoves are those with the largest numbers of households using woodfuel to cook. The countries that also have relatively high benefit-cost ratios are: Ethiopia; DR Congo; Uganda; Myanmar; Ghana; and Cambodia. Switching to improved cookstoves in these countries (up to a carbon price of USD 20/tCO_2) would reduce annual emissions by 44 $MtCO_2$ (about one-quarter of the global potential at this carbon price), with cost-benefit ratios of 4.5 or more in each of the countries. At the same carbon price, optimal switching to improved cookstoves in India would also reduce emissions there by 42 $MtCO_2$ (although the benefit-cost ratio would only be 2.6).

These seven countries listed above account for about half of the global potential to reduce emissions from cooking (across a wide range of carbon prices) and should be a focus of initiatives to promote improved cookstoves. In addition, there are many other countries where the benefit-cost ratio of switching to improved cookstoves is high (see Figure 5), although the potential for emission reductions is only 1-2 $MtCO_2$ per year (or less) in most of these places.

Figure 5 Benefit-cost ratio from the introduction of improved cookstoves in different countries of the World, calculated with a carbon price of USD 20/tCO_2



DISCUSSION AND CONCLUSIONS

The above analysis has used the best information available about the use of woodfuel for cooking and shown that the introduction of improved cookstoves is an economically attractive option for climate change mitigation in many places. A Monte Carlo simulation approach has been used to represent the variability between households that is likely to exist in many countries and this approach is likely to be a more useful technique than simply using national averages for many of the variables used in these calculations. The one weakness is that there may be correlations between some of these variables, so the range of cost estimates and cost-benefit ratios presented here could be slightly over-stated.[11]

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[11] For example, the random selection of input variables could result in the calculation of a highly negative cost of switching with a combination of high household woodfuel use, high woodfuel prices and a cheap stove lasting for many years. In reality such a combination is very unlikely because high woodfuel prices discourage high consumption and a cheap stove is unlikely to last very long, especially if used a lot. As noted by Jeuland and Pattanayak (2012), this issue can be addressed by adding correlation coefficients into the simulation, although it could be difficult to obtain reliable estimates of such coefficients.

The analysis has not reduced emission reductions to take into account the fraction of non-renewable biomass used for energy. Such an adjustment is always required for cookstove projects aiming to sell carbon credits, so that only the non-renewable part of woodfuel use is counted as an emission reduction. However, this is largely an artefact of the currently agreed procedures used in carbon markets, which do not allow any increases in biomass stocks (as a result of reduced woodfuel use) to be counted towards the issuance of carbon credits. From a more neutral viewpoint, all reductions in woodfuel use should lead to mitigation benefits, including those that result in increased biomass stocks.

The permanence and leakage of emission reductions from the introduction of improved cookstoves may be more important uncertainties in this analysis. The permanence of benefits could be an issue because there have been many examples in the past of households switching back to cooking without using their new stoves. This is why proper training and monitoring is so important on cookstove projects and it is suggested that households should contribute to the cost of new stoves. However, given that the private benefits from switching to improved stoves appear to be high and that many stove projects now focus more on training and monitoring, it seems likely that permanence may not be a major issue.

With respect to leakage, there is a risk that wood no longer used as fuel may not accumulate in biomass stocks but be used for other purposes. This also seems unlikely given that most woodfuel is of little value for other uses and that any leakage into other uses may result in long-term accumulation of carbon stocks in products such as building poles, sawnwood and furniture. Thus, the impact of leakage on net emission reductions may not be very large. More of a concern would the extent to which dead biomass is used as woodfuel. Reductions in the use of this will lead to no emission changes if the unused wood remains on the ground and decays. This is the truly non-renewable part of biomass that should be excluded from calculations of the benefits of cookstove projects and it may be significant in many places.

One final interesting result to note is the significant proportion of households where there is a negative cost of switching to an improved cookstove. Switching for these households is a *“no regrets”* option, where the financial benefits of switching (fuelwood cost savings) exceed the costs. It is not unusual for household investments in energy saving to deliver positive net financial benefits (e.g. from improvements in insulation or purchasing more energy efficient appliances) and experience has shown that promotion campaigns, awareness raising and providing better access to finance can be very cost-effective measures to promote such investments. It seems likely that such measures could also be effective in the case of improved cookstoves in many places (particularly in more developed countries and urban areas) and that agencies promoting improved cookstoves should take this into account in their projects and programmes.

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