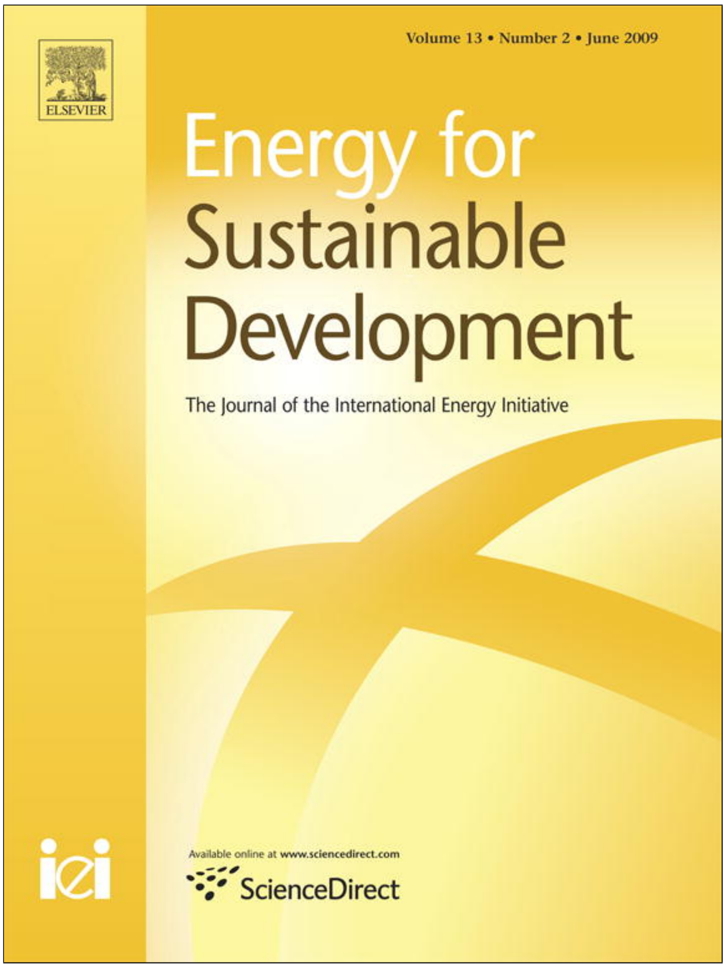
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Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia

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ABSTRACT

This study was undertaken to assess the potential of two types of improved cookstoves to reduce indoor air pollution in African homes. An ethanol stove, the CleanCook, was tested in three locations in Ethiopia: the city of Addis Ababa and the Bonga and Kebribeyah Refugee Camps, while a wood-burning rocket stove, the Gyapa, was evaluated in Accra, Ghana. In both countries, kitchen concentrations of $PM_{2.5}$ and CO, the two pollutants responsible for the bulk of the ill-health associated with indoor smoke, were monitored in a before and after study design without controls. Baseline ('before') measurements were made in households using a traditional stove or open fire. 'After' measurements were performed in the same households, once the improved stove had been introduced. $PM_{2.5}$ was measured using UCB Particle Monitors, which have photoelectric detectors. CO was measured with Onset HOBO Loggers. In Ghana and Kebribeyah Camp, CO was also measured with Gastec diffusion tubes. In Ghana, average 24-hour $PM_{2.5}$ concentrations decreased 52% from 650 μg/m^3 in the 'before' phase to 320 μg/m^3 in the 'after' phase ($p = 0.00$), and average 24-hour kitchen CO concentrations decreased 40% from 12.3 ppm to 7.4 ppm ($p = 0.01$). Including all three subgroups in Ethiopia, average $PM_{2.5}$ concentrations decreased 84% from 1 250 μg/m^3 to 200 μg/m^3 ($p = 0.00$) and average CO concentrations decreased 76% from 38.9 ppm to 9.2 ppm ($p = 0.00$). 24-hour average CO levels in households using both the Gyapa and CleanCook stoves met, or nearly met, the World Health Organization (WHO) 8-hour Air Quality Guideline. $PM_{2.5}$ concentrations were well above both the WHO 24-hour Guideline and Interim Targets. Therefore, despite the significant improvements associated with both of these stoves, further changes in stove or fuel type or household fuel mixing patterns would be required to bring PM to levels that are not considered harmful to health.

Introduction

In Ghana and Ethiopia, women generally cook on simple, inefficient stoves or open fires in poorly vented kitchens. In many cases, stoves are used inside the main living space, though some houses have a separate kitchen and some cooking is done outdoors. For fuel, households use kerosene or biomass sources such as wood or charcoal. Generally, urban households are more likely to use charcoal or kerosene for fuel while rural households and households in refugee camps usually gather fuel wood. Inefficient burning of these fuels leads to very high concentrations of indoor air pollutants such as carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$). Since women and children spend large amounts of time in the kitchen, they are disproportionately affected by the high pollution levels and the health impacts associated with exposure to them.

Globally, the use of dirty biomass fuels to meet families' daily energy needs results in about 1.4 million premature deaths every year. Indoor air pollution (IAP) from biomass fuels has also been linked to increased rates of pneumonia in children and chronic obstructive pulmonary disease among adult women (Smith et al., 2004; Dherani et al., 2008). There is also evidence of links to eye disease, tuberculosis and low birth weight (Pokhrel et al., 2005; Lin et al., 2007; Mishra et al., 2004).

These effects are particularly pronounced in Africa, where the burden of disease is at least two times higher than any other region of the world. Additionally, in Africa, lower respiratory infections (ALRI) account for 11.2% of the total burden of disease on the continent, second only to HIV/AIDS (World Health Organization, 2008). A recent meta-analysis showed that exposure to solid fuels increased risk of

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Fig. 1. CleanCook Stove in Bonga refugee camp.

ALRI by 1.8 (Dherani et al., 2008). Low birth weight and tuberculosis are also among the top ten contributors to the total disease burden in Africa (World Health Organization, 2008).

Recognizing the global impact of IAP, Shell Foundation set out to identify effective programs and technologies being used to address IAP in the key affected regions. Initially, researchers at the University of California-Berkeley (UC Berkeley) were funded to coordinate the development and testing of methods for evaluating changes in IAP associated with improved cookstoves. Under this Household Energy and Health Project, relatively simple monitoring methods were developed and tested in a series of pilot projects in India and Mexico (Smith et al., 2007; Edwards et al., 2007). The stoves tested in these pilot projects showed promise in reducing IAP. The next step was to see whether these gains also applied in Africa with improved wood and/or ethanol stoves.

The Center for Entrepreneurship in International Health and Development (CEIHD) at UC Berkeley was selected to carry out a second round of pilot projects that would assess IAP benefits of improved stoves in Africa, specifically Ghana and Ethiopia. In both cases, CEIHD partnered with a local NGO to implement the monitoring project: Gaia Association in Ethiopia and EnterpriseWorks in Ghana. The Ethiopia project tested an ethanol stove, the CleanCook (Fig. 1), in the city of Addis Ababa and in the Bonga and Kebribeyah Refugee Camps, while the Ghana project tested a wood-burning rocket stove, the Gyapa (Fig. 2), in Accra. The results of these projects are presented in this paper.

Methods

In both countries, kitchen concentrations of $PM_{2.5}$ and CO, the two pollutants responsible for the bulk of the ill-health associated with indoor smoke, were monitored in a before and after study design without controls. Baseline ('before') measurements were made in households using a traditional stove or open fire. 'After' measurements were performed in the same households once the improved stove had been introduced and cooks had adjusted to using it.

In Ghana, baseline measurements were made in 36 households in and around Accra. 34 of these households used a traditional clay wood stove (*mokyia*) for cooking, while the other two used a three-stone open wood fire. In Ethiopia, monitoring was conducted in 33 households. Of the 33, 12 were located in the Kebribeyah Refugee Camp, 12 in the Bonga Refugee Camp and nine in homes in the city of Addis Ababa. Households in the refugee camps initially used three-stone fires or traditional wood-burning stoves. In Addis Ababa households initially used either charcoal or kerosene stoves. Photographs of typical kitchens in Accra, Addis Ababa and the refugee camps are shown in Figs. 3–5.

No instructions were given to the households in Ghana regarding their household activities during the monitoring period. In Ethiopia, households were asked to cook a typical day's worth of food.

Household selection

Field staff identified households in Ghana by visiting neighborhoods in Accra that were known to be heavily dependent on fuel wood

Fig. 2. Gyapa wood stove in Accra.

Fig. 3. Typical kitchen in Accra.

Fig. 4. Typical kitchen in Addis Ababa.

for their household energy needs. A screening questionnaire was used by field staff to ensure that the household was suitable for and amenable to participation in the study.

In both Ethiopian refugee camps, organizations running the camps identified households willing to participate. Since there was no variation in housing structure, stove or fuel used within the refugee camps, there were few confounding factors to account for in identifying participants in these locations. In Addis Ababa, participants were selected randomly from the client networks of two NGOs working in the community — the Good Shepherd Sisters Charities, which focuses on alleviating poverty of women and children and the Former Fuelwood Carriers Association, which works to offer new income generating activities to women who were once solely dependent on the gathering of fuel wood.

Since household selection was not totally random in either case and samples were small, indoor air pollution values may not be entirely representative of the general population. In particular, participants would be considered early adopters since they agreed to try the new stove. The primary objective of this study was, however, to measure changes in IAP after adoption of the new stove. Here, each house acts as its own control due to the before/after study design. Therefore, the 'before' and 'after' measurements within each household can be compared fairly.

Participants received no compensation beyond the new stove and enough fuel to last for the monitoring period although, in the refugee camps, ethanol fuel was provided for free on a long-term basis.

Indoor air pollution sampling

Similar sampling methods were used in both countries, though there was some difference in the sampling period. In Ghana and in two of the Ethiopian locations (Addis Ababa and Bonga Camp), the sampling period was 24 h, whereas in the Ethiopian Kebribeyah Camp, samples were taken over 48 h. A 24-hour sample is considered a representative indoor air sampling time due to the typical daily (24-hour) cycle of cooking and household activity patterns. As a 48-hour sample is essentially two consecutive 24-hour representative samples, the difference in sampling periods is unlikely to have caused any significant bias.

Fine particulate matter was measured in each of the households using a University of California-Berkeley (UCB) Particle Monitor equipped with a photoelectric detector. These monitors measured and logged the $PM_{2.5}$ concentration for every minute of the sampling period (Litton et al., 2004; Edwards et al., 2006; Chowdhury et al., 2007). The UCB monitors were produced and calibrated in the Indoor Air Pollution Laboratory at the University of California-Berkeley using wood smoke prior to their use on the ground. The chamber of the photoelectric detector was cleaned with isopropyl alcohol after every five uses.

Carbon monoxide was measured and concentrations logged every minute of the sampling period in each of the households with a HOBO CO Logger (model #H11-001, Onset Computer Company, Bourne, MA, USA). The loggers used in this study were purchased new and calibrated at UC Berkeley using CO standard gas cylinders of 5 and 60 ppm. Additionally, between the 'before' and 'after' phases of the sampling campaign, a collocation calibration check was run, where the six routinely used loggers were compared to a seventh 'gold standard' logger, which was only used for such collocation calibration checks.

As a backup, in Ghana and Kebribeyah Camp only, CO was measured by a CO diffusion tube (model #810-1DL, Gastec Corporation, Japan). These tubes yielded one average concentration of CO for the entire monitoring period.

The PM and CO monitors were placed on the wall of the kitchen according to the following criteria:

1. Approximately 100 cm from the edge of the combustion zone (this distance away from the stove approximates the edge of the active cooking area);
2. At a height of 125 cm above the floor (this height relates to the approximate breathing zone of a standing woman); and
3. At least 150 cm away (horizontally) from doors and windows, where possible.

All devices were collocated and placed in a position that would minimize the risk of interrupting normal household activities or of the monitor being disturbed or damaged. Detailed kitchen sketches were made during the 'before' sampling so that the sampling location could be duplicated in the 'after' monitoring phase.

Post-monitoring questionnaire

In both countries, post-monitoring questionnaires were administered to the main cook in the household at the end of each monitoring

Fig. 5. Typical refugee camp kitchen in Kebribeyah Camp.

period. The questionnaires were designed to document activities that affected the indoor air pollution levels in the kitchen during the monitoring period such as the type of fuel used, the amount of time spent cooking, and non-stove sources of IAP.

Results

Exposure to an air pollutant is primarily dependent on the pollutant concentration in the air and the length of time that an individual is in the presence of the pollutant. Both short term exposures to relatively high levels and longer term exposures to lower levels of pollutants can have significant and varying health impacts. For this reason, the World Health Organization sets air quality guidelines for a range of time periods or averaging times, depending on the pollutant. Guidelines for CO cover time periods from 15 min to 8 h, while the PM guidelines are for 24 h and one year. Additionally, even for PM, where there is no guideline for periods of less than one day, there are comfort issues associated with very high shorter term peak concentrations. In order to account for both shorter and longer term exposures which affect health, we report the 24-hour average IAP concentration, the highest 15-minute average, and the maximum level recorded.

Ghana IAP

In Ghana, average kitchen concentrations of $PM_{2.5}$ showed a significant 52% reduction after introduction of the improved stove (Student's *t*-Test *p*-value = 0.00). The average $PM_{2.5}$ concentration decreased from 650 μg/m^3 in the 'before' (traditional wood stove) phase to 320 μg/m^3 in the 'after' phase, when households were using the Gyapa wood stove. The average maximum $PM_{2.5}$ concentration dropped by 26% ($p = 0.02$), and the highest 15-minute average $PM_{2.5}$ concentration decreased by 42% ($p = 0.01$) after introduction of the Gyapa (Table 1).

Similarly, average 24-hour kitchen CO concentrations measured by the primary method, the HOBO CO Logger, decreased significantly from 12.3 ppm in the 'before' phase to 7.4 ppm in the 'after' phase, a 40% reduction ($p = 0.01$). The average maximum CO concentrations were not significantly different (124.8 versus 120.7 ppm). The secondary and less accurate CO monitoring method, the CO dosimeter tubes, showed that the average CO concentrations were 27% lower in the 'after' phase, though this result was not statistically significant ($p = 0.18$) (Table 1).

Ghana post-monitoring questionnaire

The post-monitoring questionnaire was used to determine whether factors affecting IAP, such as time spent cooking or use of other IAP sources, stayed relatively constant between the two 24-hour monitoring periods. Results showed that there was no significant difference in the average reported number of people cooked for between the monitoring periods, although the average was slightly lower in the 'after' period (8.3 versus 7.5, $p = 0.54$). Similarly, there was no significant difference in the reported number of hours the stove was lit for cooking (4.4 h before versus 4.1 h after, $p = 0.47$). This implies that differences in indoor air pollution concentrations could not be explained simply by differences in the amount of cooking or stove usage during the monitoring periods.

Non-stove sources of indoor air pollution commonly include smoke from kerosene lamps, cigarettes, incense and mosquito coils. The average reported number of hours kerosene lamps were used decreased from 1.1 h to 0.5 h, which was just significant ($p = 0.04$). No households reported cigarettes smoked or incense or mosquito coils burned within the kitchen. There was also no reported garbage burning or other nearby outdoor air pollution sources during either phase of monitoring. The number of households reporting rain or light rain at some point during the 24-hour sampling period increased from 3 to 8 between monitoring phases. While there was some difference in use of kerosene lamps and rain reported, these reported differences are not large enough to account for much, if any, of the differences in the kitchen IAP concentrations.

The amount of money households reported spending on fuel wood for cooking decreased from 2 500 cedis to 1 700 cedis, a significant, 32% reduction ($p = 0.02$) indicating that less fuel was required to do an equivalent amount of cooking on the Gyapa stove than on the traditional stove.

Table 1
Average $PM_{2.5}$ and CO kitchen concentrations in Ghana for households using traditional clay wood stoves or open fires compared with concentrations after adoption of the Gyapa wood stove.

	Traditional clay wood stove or open fire[a]	Gyapa wood stove[a]	Percent reduction	*t*-Test (*p*-value)
$PM_{2.5}$: 24-hour average (μg/m^3)	650 (490)	320 (240)	52%	0.00
$PM_{2.5}$: maximum (μg/m^3)	42 000 (20 500)	31 300 (18 400)	26%	0.02
$PM_{2.5}$: highest 15-minute average (μg/m^3)	12 500 (9 750)	7 220 (4 790)	42%	0.01
CO: 24-hour Average, HOBO (ppm)	12.3 (9.9)	7.4 (6.1)	40%	0.01
CO: maximum, HOBO (ppm)	124.8 (84.6)	120.7 (125.1)	3.3%	0.86
CO: average, tubes (ppm)	6.8 (5.6)	5.0 (5.0)	27%	0.18

[a] Standard deviations are shown in parentheses.

Ethiopia IAP

In Ethiopia, the average kitchen $PM_{2.5}$ concentrations for all 33 households decreased significantly from 1 250 μg/m^3 in the 'before' phase to 200 μg/m^3 in the 'after' phase ($p = 0.00$), an 84% reduction when households were using the CleanCook stove. The average maximum $PM_{2.5}$ concentrations decreased 71% and the highest 15-minute average decreased 80%. Each of these reductions was highly significant ($p = 0.00$). Average $PM_{2.5}$ levels also decreased significantly for each subgroup in Ethiopia. In Addis Ababa, average levels were reduced from 640 to 230 μg/m^3, a 64% reduction. The average maximum value decreased 57% and the highest 15-minute average decreased 68%. In Bonga Camp, average $PM_{2.5}$ levels decreased 84% from 960 to 150 μg/m^3 with the average maximum value and highest 15-minute average decreasing 70% and 83% respectively. In Kebribeyah Camp, $PM_{2.5}$ levels decreased 94% from 2 170 to 130 μg/m^3. There, the average decline in maximum value was 84% and the average reduction in the highest 15-minute average was 91% (Table 2).

Similarly, the average kitchen CO concentrations for all households were reduced from 38.9 ppm in the 'before' phase to 9.2 ppm in the 'after' phase. This is a significant reduction of 76% ($p = 0.00$). The average of the maximum CO concentrations was also significantly lower in the 'after' monitoring period (273.2 versus 91.0 ppm) and the mean values from diffusion tube measurements in Kebribeyah Camp (37.2 versus 9.7 ppm). Average CO levels went from 24.6 to 5.9 ppm, 22.1 to 5.6 ppm and 70.5 to 14.6 ppm in Addis Ababa, Bonga Camp and Kebribeyah Camp respectively (reductions of 76%, 75% and 79%), while the average maximum level recorded decreased from 158.1 to 80.9 ppm, 130.3 to 48.6 ppm and 509.3 to 140.5 ppm in those locations (reductions of 49%, 63% and 74%) (Table 3).

Ethiopia post-monitoring questionnaire

The post-monitoring questionnaire was administered to the main cook of the household after the monitoring period was completed. The

Table 2
Average $PM_{2.5}$ kitchen concentrations in Ethiopia for households using traditional stoves (wood, charcoal, kerosene or open fire) compared with concentrations after adoption of the CleanCook ethanol stove.

	Traditional stoves (wood, charcoal, kerosene or open fire) (μg/m^3)[b]	CleanCook ethanol stove (μg/m^3)[b]	Percent reduction	*t*-Test (*p*-value)
All				
24/48-hour average	1 250 (1 280)	200 (230)	84%	0.00
Maximum	42 730 (26 960)	12 370 (14 100)	71%	0.00
Highest 15-minute average	22 560 (20 650)	4 470 (7 760)	80%	0.00
Addis Ababa				
24-hour average	640 (640)	230 (220)	64%	0.05
Maximum	2 799 (1 722)	1 183 (862)	57%	0.04
Highest 15-minute average	1 303 (975)	423 (391)	68%	0.02
Bonga Camp				
24-hour average	960 (790)	150 (110)	84%	0.01
Maximum	2 867 (2 361)	857 (788)	70%	0.01
Highest 15-minute average	1 181 (1 077)	204 (188)	83%	0.01
Kebribeyah Camp				
48-hour average	2 170 (1 630)	130 (80)	94%	0.00
Maximum	70 110 (14 050)	11 200 (10 330)	84%	0.00
Highest 15-minute average	42 720 (21 290)	3 640 (3 940)	91%	0.01

[b] Standard deviations are shown in parentheses.

homes that participated in the study used traditional three-stone wood fires, traditional wood stoves, kerosene stoves, and charcoal stoves in the 'before' test. In the 'after' monitoring period, all the households used the CleanCook stove for their primary cooking. However, nine households also used a three-stone fire for secondary cooking during the 'after' period.

The average amount of time the primary and secondary stoves were lit did not change significantly between monitoring periods (6.2 h before versus 5.6 h after, $p = 0.48$). There was also no significant change in the number of households using kerosene lamps (19 households before and 20 after) or burning garbage (13 households before and 7 after) between the two sampling periods. Incidence of cigarette smoking in the homes also did not change significantly (0 households before and 3 after).

Table 3
Average $PM_{2.5}$ kitchen concentrations in Ethiopia for households using traditional stoves (wood, charcoal, kerosene or open fire) compared with concentrations after adoption of the CleanCook ethanol stove.

	Traditional stoves (wood, charcoal, kerosene or open fire) (μg/m^3)[c]	CleanCook ethanol stove (μg/m^3)[c]	Percent reduction	*t*-Test (*p*-value)
All				
24/48-hour average HOBO	38.9 (33.8)	9.2 (7.1)	76%	0.00
Maximum HOBO	273.2 (209.9)	91.0 (73.7)	67%	0.00
48-hour average CO tubes[d]	37.2 (12.7)	9.7 (7.9)	74%	0.00
Addis Ababa				
24-hour average HOBO	24.6 (11.5)	5.9 (4.8)	76%	0.00
Maximum HOBO	158.1 (90.3)	80.8 (87.2)	49%	0.08
Bonga Camp				
24-hour average HOBO	22.1 (19.1)	5.6 (3.7)	75%	0.01
Maximum HOBO	130.3 (83.1)	48.6 (51.6)	63%	0.01
Kebribeyah Camp				
48-hour average HOBO	70.5 (38.6)	14.6 (8.2)	79%	0.00
Maximum HOBO	509.3 (165.5)	140.5 (60.1)	72%	0.00
48-hour average CO tubes[d]	37.2 (12.7)	9.7 (7.9)	74%	0.00

[c] Standard deviations are shown in parentheses.
[d] For Kebribeyah Camp only.

Table 4
Ghana and Ethiopia results compared to WHO guidelines.

	PM before (24/48-hour average)	PM after (24/48-hour average)	CO before (24/48-hour average)	CO after (24/48-hour average)
Ghana	650 μg/m^3	320 μg/m^3	14.1 mg/m^3	8.5 mg/m^3
Ethiopia	1 250 μg/m^3	200 μg/m^3	44.6 mg/m^3	10.5 mg/m^3
WHO Guideline	25 μg/m^3 (24-hour average)		10 mg/m^3 (8-hour average)	
WHO Interim Target-1	75 μg/m^3 (24-hour average)		NA	

The reported number of people cooked for in each household was not significantly different between the 'before' and 'after' phases ($p = 0.71$). The average number of people cooked for was 8.2 during the 'before' period and 8.0 during the 'after' period, indicating a similar amount of cooking between the monitoring phases.

Discussion

$PM_{2.5}$ and CO concentrations decreased significantly after introduction of the improved stoves in both Ghana and Ethiopia. In Ghana, households using the Gyapa wood stove showed average reductions of 52% for $PM_{2.5}$ concentrations and average reductions of 40% for CO concentrations. In Ethiopia, introduction of the CleanCook ethanol stove resulted in average reductions of 84% and 76% for $PM_{2.5}$ and CO, respectively. As would be expected, indoor air quality improvements were greater for the ethanol stove than the improved wood-burning stove. However, 'after' measurements were fairly comparable between the Gyapa and CleanCook stoves with $PM_{2.5}$ levels slightly lower for the CleanCook (200 μg/m^3 vs. 320 μg/m^3) and CO levels slightly lower for the Gyapa (8.5 mg/m^3 vs. 10.5 mg/m$^{3)}$. Of course, the IAP concentrations measured are affected by all local sources. Therefore the use of a three-stone fire for secondary cooking in approximately one fourth of the homes monitored in Ethiopia, as well as higher incidence of other IAP sources, resulted in higher overall concentrations than would be found for use of the CleanCook alone.

The World Health Organization sets air quality guidelines at levels that significantly reduce the health effects of air pollution. The WHO also provides interim targets for countries that have very high levels of air pollution in order to encourage gradual improvements in air quality. As they are set at health-protective levels, these guidelines apply equally to both indoor and outdoor air. However, in homes where biomass fuels and coal are used for cooking and heating, PM levels may be 10–50 times higher than the guideline values (World Health Organization, 2006).

Average CO levels in households using both the Gyapa and CleanCook stoves were similar and met, or nearly met, the World Health Organization 8-hour Air Quality Guideline (though these monitored values are 24-hour averages). For $PM_{2.5}$, concentrations were well above both the WHO 24-hour Guideline for PM of 25 μg/m^3 and the more lenient 75 μg/m^3 Interim Target-1. Therefore, despite the significant improvements associated with both of these stoves, further changes in stove or fuel type or household fuel mixing patterns would be required to bring PM to levels that are not considered harmful to health (Table 4).

While IAP results were similar for the two stoves, it bears noting that the widespread introduction of the CleanCook stove has been limited by the fact that it is produced in Europe and sells for approximately $80 while the locally-produced Gyapa stove with its $10 price tag is a more affordable option for wood-using households. However, Gaia Association, with a local business partner, has plans to begin production of the CleanCook in Addis Ababa during the first half of 2009. This will cut the cost of the stove in half, making it available to more people in Addis Ababa and other areas of Ethiopia. Gaia Association also plans to make the CleanCook more affordable to low-income consumers through use of carbon finance and amortization of a portion of the cost of the stoves in the cost of the ethanol the stoves consume over their ten year lifespan.

The target market for the CleanCook is kerosene users in Addis Ababa. Charcoal is not used widely within the city. While the CleanCook costs significantly more than a kerosene stove, fuel costs are lower for ethanol. During the study period, a liter of ethanol cost $0.30 per liter compared with $0.35 for a liter of subsidized kerosene. Furthermore, the greater fuel efficiency of the ethanol stove results in additional savings.

As these measurements represent only initial IAP reductions, it would also be useful to monitor how stove performance changes over time. Such measurements would indicate the extent to which the improvements seen here are sustained. Other opportunities include documenting ongoing usage of the stoves and fuel savings associated with them. Future research could also evaluate the full set of costs and benefits (for health, environment, household economics, etc.) of each of these stoves.

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