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# Using personal exposure measurements of particulate matter to estimate health impacts associated with cooking in peri-urban Accra, Ghana☆

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ABSTRACT

This study assessed personal exposure to $PM_{2.5}$ and the associated potential health outcomes in Accra, Ghana. The Household Air Pollution Tool model was employed to estimate health benefits attributable to various fuel use scenarios using user-derived and publicly available inputs, including the Global Burden of Disease data presented by the Institute for Health Metrics and Evaluation. This study assessed personal exposure for four fuel user groups: LPG-only, LPG and charcoal, charcoal only, and wood use alone or in combination with any other fuel. Ambient $PM_{2.5}$ concentrations were also assessed during the study period. The wood user group demonstrated significantly higher $PM_{2.5}$ exposure than the other three user groups, which all had average $PM_{2.5}$ personal exposure similar to the average ambient $PM_{2.5}$ concentration. The results of the exposure assessment imply that ambient particulate matter may drive the majority of $PM_{2.5}$ exposure in peri-urban LPG and charcoal using households in Accra and therefore for the majority of homes in Accra (~80% are non-wood users in urban Ghana), reductions in $PM_{2.5}$ exposure and associated health gains may require reducing ambient PM. From a study by Zhou et al., in Accra biomass burning accounted for 39–62% of total $PM_{2.5}$ mass in the kitchen in different neighborhoods. Road dust and vehicle emissions comprised 12–33% of $PM_{2.5}$ mass. This means that even if direct PM emissions are low from LPG and charcoal burning homes, homes using wood fuel to meet their household energy needs contribute to ambient PM, which influences the $PM_{2.5}$ exposure of their non-wood using neighbors.


## Introduction

Approximately 3 billion people globally rely on dirty solid fuels to cook and heat their homes. Most households use inefficient stoves, such as three-stone fires, which incompletely combust solid fuels, releasing toxic substances (Bonjour et al., 2013). Adverse health effects have been well documented in studies of cookstoves and the associated kitchen and household air pollution (KAP and HAP, respectively). Exposure to HAP is now identified as the most important environmental risk factor for ill health in developing countries, resulting in an estimated 3.8 million premature deaths per year worldwide (WHO). DALYs sum the years of life lost due to premature death in the population and the years of life lived with disability for people living with a disease or resulting condition.

Further studies show that clean cooking interventions can reduce the risk of diseases related to household air pollution by creating access to improved cooking technologies, such as cleaner burning fuels or stoves that increase the completeness of solid fuel combustion. A methodology has been developed to standardize the quantification of health benefits from clean cooking interventions that reduce exposure to HAP (Pillarisetti, Mehta, & Smith, 2016). Under this new method, estimates of avoided premature death and disability are made by inputting personal exposure (PE) measurements before and after an intervention into the Household Air Pollution Intervention Tool (HAPIT) model, developed at the University of California, Berkeley. HAPIT outputs deaths and DALYs averted from an intervention, yielding a potentially tradeable commodity of aDALYs (averted disability-adjusted life years) (Pillarisetti et al., 2016).

In the Greater Accra region, 3.5% of people depend on wood and 45.4% depend on charcoal to meet their daily cooking needs. The introduction of clean and fuel-efficient cooking technologies to regions dependent on solid fuels is necessary to alleviate the associated negative health, environmental, and social impacts. In fact, the Ghanaian government has previously implemented programs to promote LPG use, and in the 2010 census, 41.4% of households in the Greater Accra area reported LPG as their primary fuel (Agbemabiese, Nkomo, & Sokona, 2012;

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Kemausuor, Obeng, Brew-Hammond, & Duker, 2011). Numerous other technologies have been designed and introduced in the region in an effort to provide access to cleaner cooking solutions for those still using solid fuels (Agbemabiese et al., 2012; Kemausuor et al., 2011). Performance of such cooking technologies has largely been determined in controlled testing environments. However, results from such controlled tests are often not indicative of real-world performance because they provide no information on user acceptability, making actual impacts difficult to extrapolate. Assessing cooking technologies in real-world settings is critical for understanding true performance, estimating the related impacts, and gauging adoptability of promising stoves. Here, we assessesed real-world exposure and usage patterns associated with different cooking technologies to better understand their potential health implications.

## Methods

### *Study overview*

Personal exposure to particulate matter under 2.5 μm ($PM_{2.5}$) was monitored for modeling health outcomes to produce an estimate of aDALYs under a scaled-up LPG program. $PM_{2.5}$ was selected for monitoring because it serves as a proxy for the complex mixture that makes up air pollution and is associated with a variety of adverse health effects (e.g. (Naeher et al., 2007)). The study also collected information on stove usage.

Peri-urban households were selected to represent Ghana's large, urbanizing population. Although these households have certain distinguishing characteristics, such as being located on the perimeter of the city and engaging in some agricultural practices, they do not have a distinct census classification. Rather they fall within the urban category in the Ghanaian national census, making their numbers difficult to estimate. Nationally, 50.9% of the population (24.7 million people) is classified as urban, while 90.5% of Greater Accra (3.6 million people) is listed as urban (Ghana Statistical Service (2010 Ghanaian Census, Citation: Ghana Statistical Service, 2012)). Households were selected to represent a cross-section of the expected fuel mixtures used for cooking in the region, based on surveys conducted before the start of measurements and from previous census results. Groups were identified as: 1. Exclusive LPG users; 2. LPG and charcoal users; 3. Exclusive charcoal users; 4. Any wood use

Due to budget constraints, a total sample size of 60 was selected with 15 households targeted for each of the four study groups.

Participant availability, geographic and seasonal considerations, and equipment failures resulted in 45 households/individuals being successfully sampled. Seven households were sampled from the LPG-only group, 18 from the LPG and charcoal group, 11 from the charcoal only group, and nine from any wood use group. Due to differences in fuel use reported during initial participant selection, and measured and reported fuel during the same period, some households were recatagorized during analysis.

During the monitoring period, three consecutive daily household visits allowed the following:

- Continuous 48-hour measurements of PE to $PM_{2.5}$ collected using gravimetric equipment in all households.
- 48-hour real-time measurements of PE to $PM_{2.5}$ collected using light scattering monitors in 50% of households.
- 48-hour stove usage of up to two of the most commonly used stoves in each home.
- Daily surveys of participant time-activity.

Over the entire study period, outdoor ambient $PM_{2.5}$ was measured by the Ghana Environmental Protection Agency (Ghana EPA) near study households to determine the influence of ambient air pollution on PE.

### *Inclusion and exclusion criteria*

During household selection, the following inclusion criteria were used: the participant (1) was over 18 years of age, (2) was not pregnant, and (3) did not smoke cigarettes. Additional survey data was collected to understand the socioeconomic make-up of the selection pool. None of this information was used to screen participants from the overall potential pool.

### *Recruitment, consent, and stove types*

Participant selection was challenging due to the difficulty of finding LPG-exclusive homes. A few homes declined to particpate due to scepticism about the study. A participant selection survey was administered in order to find a cross-section of socio-economically comparable homes in the same areas with the desired fuel(s) used. Representatives from Berkeley Air Monitoring Group (Berkeley Air) conducted an intensive in-country training for a field team of 6 and stayed through the first week of sampling to ensure a smooth study start up and to provide supervision and expert troubleshooting. The fieldwork occurred over a four-week span, which commenced on July 23rd and finished on August 18th, 2017. Stove types varied across the households in the study catchment area and included: three-stone fires; built-in, u-shaped mud stoves without chimneys; charcoal pot stoves (both cast aluminum and ceramic-lined sheet metal models); 1–4 burner LPG stoves; and in two homes, drum stoves (typically installed outdoors, for smoking fish) (Table 1).

### *Data collection device descriptions and protocols*

#### *Stove use monitoring*

Stove Use Monitoring Sensors (SUMs) were deployed to assess usage of various cooking appliances throughout this study. The device used as a Stove Use Monitor was the commercially available iButton (model DS1922T, Maxim Integrated, CA), with a maximum temperature of 125 °C. iButtons were synced to local time and set to log an instantaneous temperature every ten minutes.

SUMs placement was guided by best practices described by Ruiz-Mercado, Canuz, and Smith (2012) and Mukhopadhyay et al. (2012). On traditional wood stoves, the SUMs were bundled in metal tape with insulating silicone pads and placed on the side of one of the stones in the three-stone fires, or next to a wall on the U-shaped mud stoves. For LPG stoves, the iButton was placed in between burners on the surface of the stove with a piece of silicone insulation and metal tape. For charcoal pot stoves, SUMs were placed on a handle or ear of the stove, again with insulation and metal tape.

#### *Personal exposure monitoring*

$PM_{2.5}$ was measured using both the gold standard gravimetric method (Ultrasonic Portable Air Sampler (UPAS), Access Sensor Technologies, Fort Collins, CO) and a real-time light scattering method, using a particle and temperature sensor (PATS+, Berkeley Air Monitoring Group, Berkeley, CA). The UPAS is a small, time-integrated monitor with a $PM_{2.5}$ cyclone, which secures over a cassette holding a standard 37-mm air sampling filter. All study participants' personal exposure was measured gravimetrically, and a subset (50%) were collocated with PATS+. $PM_{2.5}$ mass deposition of the UPAS filters was determined gravimetrically by weighing the PTFE filters before and after sampling in a constant humidity and temperature room on an electronic microbalance with 1 μg resolution (Mettler Toledo, OH).

Participants were outfitted with an apron designed to hold the UPAS and PATS+ on the center of the chest, with inlets exposed to the outside air near the breathing zone. The aprons were designed and

**Table 1**
Specifications and photos of stove type.

| Stove Model and Specifications | Stove Image |
|---|---|
| **LPG stove (1-4 burners)** |  |
| **U-Shaped Adobe Stove without chimney**<br>• Clay<br>**Three-stone fire**<br>• Stones or bricks |   |
| **Charcoal pots (traditional on left and Toyola improved on right)**<br>• Clay and/or metal |   |

manufactured in Accra with local feedback from Ghanaian women with regard to the form factor. Participants were instructed to wear the apron all day for the 48-hour monitoring period, except during bathing and sleeping, when they were instructed to hang the apron somewhere near them. Participant compliance with these instructions was not checked directly with motion sensors, but a series of questions was administered during the time-activity survey to check when women were wearing the aprons (Fig. 1).

Environmental and contextual information that might impact indoor air quality was also collected during the study, including kitchen volume, ventilation, and reports of other sources of household air pollution emitted during the monitoring period.

*Ambient air pollution monitoring*

Ambient $PM_{2.5}$ air pollution levels were determined by 24-hour gravimetric $PM_{2.5}$ sampling in the vicinity of participating households using an AirMetrics MiniVol $PM_{2.5}$ sampler. The $PM_{2.5}$ was collected on 47 mm diameter Teflon filters with 2 μm pore size containing built-in PMP support rings (Pall Corporation). The integrated MiniVol pump was set to a flow rate of 5 L/min each week. It was installed in locations where it would be safe and would not be disturbed, such as on the roof of a home, in a tree, or on a pole. All analysis and maintenance including instrument calibration, filter weighing, and mass concentration calculations was performed by the Ghana EPA. The MiniVol collected four back-to-back 24-hour samples each week of the study, however, due to instrument failure, only 7 samples were used in the analysis.

*Survey methods*

Participant and time activity surveys were administered with the goal of collecting participant demographics, as well as data on reported cooking behaviors and other daily activities that may have influenced the technical measurements. Surveys were designed in Open Data Kit (ODK), a digital questionnaire application for mobile devices. Questions were both open and closed type and also included enumerator observations. The ODK application was installed on password-protected tablets, which the teams used to record answers, and take various photographs of participants, cooking locations, households, and instrument placement.

During the first monitoring day in each household, surveys included general questions to assess household organization, typical stove usage


**Fig. 1.** A study participant wearing a personal exposure monitoring apron, fitted with co-located UPAS and PATS+ instruments. Study participants who were photographed gave their consent to do so in the study consent form, which was administered and signed prior to participation.

practices, cooking behaviors, and kitchen and stove locations. On the second and third day in each study household, survey questions were related to specific time activity throughout the previous day, exposure to other sources of smoke, and specific stove usage events, including stove and fuel types used.

*Data management*

Quality assurance checks were implemented throughout the study to ensure data completeness.

- The field manager checked all data forms at the end of each day. Any missing, incorrect, or inconsistent entries were referred directly back to the field surveyors to clarify. Once complete, data was entered into an Excel spreadsheet.
- The data validation specialist checked the data uploaded into Dropbox on a weekly basis, and any missing, incorrect, or inconsistent data were referred back to the field manager for clarification.
- Accuracy of data entry was checked on a randomly selected 10% sample of the data entry forms.

## Analysis

*Calculating $PM_{2.5}$ mass concentration from pump and filter*

The default pump run time for gravimetric samples was taken from the start and stop times as recorded on the sampling forms, which was compared to the pump's integrated timer. Filter samples with run times greater than 56 h (n = 0) or less than 40 h (n = 15) were discarded in order to avoid samples unrepresentative of a full two-day activity cycle.

Filter mass deposition was determined based on the difference between an initial, pre-sample filter mass and a final, post-sample filter mass. A blank adjustment of −33 μg, based on an average of 4 field blanks, was applied to all filters to account for changes in mass related to handling rather than particle deposition during sampling. The UPAS used here was a beta version with new filter handling procedures still in development, and thus some additional uncertainty compared to more common pump and filter methods may have been introduced during this study.

*SUMS cooking event identification algorithm*

Cooking events were identified from the iButton temperature traces using SUMSARIZER (sumsarizer.com), an online analysis tool developed specifically for the cookstove community. The data files were uploaded to the web server, where segments from each data file were randomly selected for the user to manually identify perceived cooking events. Based on this user-provided input, a machine learning algorithm then applied the patterns identified by the user to the rest of the data files. As the SUMSARIZER developers note, the algorithm works best at identifying cooking events accurately for similar cookstoves or similar temperature traces. The data in this project was thus analyzed in four separate batches, based on stove types monitored (traditional charcoal stoves, improved charcoal stoves, three stone fires, and LPG stoves). Identified cooking events were then analyzed in R (RStudio, Inc.). Cooking events under 10 min in duration were removed from the analysis, and cooking events within 30 min of each other were grouped into single events.

*Sample exclusion*

Sample loss (n = 15) was due to technical UPAS failures or irreconcilable transcription errors. These failures resulted in a final sample size of 7 households from the LPG-only group, 18 from the LPG and charcoal group, 11 from the charcoal only group, and 9 from the mixed fuel with wood use group.

The UPAS failures occurred mostly near the start of the study, before robust methods were developed for powering the device. The internal battery of the UPAS generally lasts about 30 h when operating continuously at 1 L per minute. To reach the 48-hour sample duration, battery packs were connected to the UPASs during the home visits, 24 h after the sampling start. However, some of the battery packs proved to have lower battery capacity than listed, or to turn off sporadically. After sufficiently capacious and reliable battery packs were sourced, the incidence of UPAS failures was reduced. In future work, intermittent sampling (i.e. 30 s on/30 s off) may provide a more straightforward solution to sampling logistic challenges, since no additional battery pack would be needed, although a validation data set comparing performance between the intermittent and continuous sampling approaches would be required. While every sample included a UPAS, not every UPAS was co-located with a PATS+.

*Imputed health effects and HAPIT*

Exposure data from different classes of interventions was input into the most recent version of the Household Air Pollution Intervention Tool (HAPIT) to estimate averted Disability Adjusted Life Years (aDALYs) and deaths. The underlying calculations behind the HAPIT model are explained elsewhere. Briefly, HAPIT utilizes (1) integrated exposure-response curves described by Burnett et al. (2014) and (2) Ghana-specific burden of disease information from the Institute of Health Metrics and Evaluation (IHME) to estimate the health impact of a change in household air pollution exposures in terms of DALYs and premature deaths averted. For this study, HAPIT was customized to output estimates under multiple intervention scenarios. The currently available version of HAPIT utilizes data from the 2013 IHME Global Burden of Disease efforts.

HAPIT utilizes user-input mean and standard deviation of exposures to recreate distributions for scenarios representing exposures before and after the introduction of an intervention. 1000 pairs of pre- and post-intervention exposures are drawn from the recreated distributions, and averted ill-health is estimated for each pair. The mean averted ill-health and range of potential averted deaths and aDALYs are reported in both tabular and graphical form.

HAPIT also calculates the remaining ill-health that could be avoided if 100% penetration of a truly clean cooking option, such as gas or electric cooking, was fully achieved.

## Results

*Participant demographics*

Data from 45 participants was ultimately used for the study. The mean age of primary cooks was reported at 38 years of age. The youngest group was the LPG-only group (32 years), and the eldest was the any wood use group (46 years). Average household size was 5 members, with an average of 3 members in the LPG-only group, 4 members in the LPG and charcoal group, 6 members in the charcoal only group, and 5 members in the any wood use group. 80% of participants reported their status as married, while the remaining reported being single (13%), divorced (4%), or widowed (2%).

*Stove ownership*

Forty percent of all participants had an LPG stove as their primary stove. Of those remaining, the charcoal pot stove was the most common (27%), followed by the improved charcoal pot stove (20%), and finally the three-stone fire. 58% of participants reported regularly using a secondary stove. Of those participants, the most commonly used secondary stove was an LPG stove (n = 6), followed by the charcoal pot stove (n = 5), and finally the three-stone fire (n = 4) and the improved charcoal pot stove (n = 4).

### Cooking behaviour

Fig. 2 shows usage times for the four study groups. The LPG-only group showed the lowest daily mean cooking time among the groups (54 min per day), while the LPG and charcoal group had the highest mean cooking time per day (121 min per day). The any wood use group had a daily mean cooking time of 106 min, but with much higher variability (standard deviation of 155 min). This variability could be due to differences in cooking practices with the same stove and/or due to difficulties in pinpointing wood fire cooking times. Strictly quantifying the measurement uncertainty in cooking times was not possible since this would have required a reference set of data such as direct observations of cooking events, which were not conducted as we did not want to disrupt or affect normal behaviour by the participant.

The LPG-only group had stoves on for the least amount of time per day, on average. The LPG and charcoal group are seen to use each of their stoves slightly more than the LPG-only group and charcoal only groups use their stoves, respectively, suggesting that the stove stacking increases overall cooking energy use, likely based on the types of foods cooked with each (Fig. 2). There is also the possibility that stove-use time is influenced by the efficiency of various stove types, those which may be more efficient could reduce cooking times by simply allowing participants to finish their tasks more quickly. 88% of LPG-only households used their stoves at least once during the 48-hour monitoring period. For the any wood use group, 67% did.

### Personal exposure of the cooks

Fig. 3 and Table 2 show personal $PM_{2.5}$ exposure results by user group. A statistically significant 69% difference between the any wood use group and the LPG-only group was observed. Significant differences were also observed between the any wood use group and both the LPG and charcoal and the charcoal only groups, with differences of 61% and 62% respectively. No statistical differences were observed between the charcoal only and LPG user groups, not surprisingly, considering charcoal PM emissions are generally low compared to wood combustion emissions (Jetter et al., 2012; MacCarty, Still, & Ogle, 2010). Important to note, is that sample sizes were smaller than anticipated due to data loss, reducing the statistical power to demonstrate differences between groups.

### Other sources of smoke exposure

Other types of smoke exposure were reported by participants during their 48-h study periods. Trash burning and use of mosquito coils were the most common other sources of exposure (n = 12). Interestingly, any wood use group had no reported trash burning. There were no reported charcoal production or participant smoking exposures. However, three participants reported being around others who smoked. There was a limited amount of crop residue burning (n = 1), kerosene lamps (n = 1), candles (n = 1), and smoke from vehicles (n = 1).

### Ambient air pollution

The average ambient $PM_{2.5}$ air pollution from the seven collected 48-h samples was 26.5 ± 14.9 μg/m$^3$. Ambient $PM_{2.5}$ in the region has been characterized by the Ghana EPA and in previous works (Ofosu, Hopke, Aboh, & Bamford, 2012; Zhou et al., 2013) and is affected by weather and seasonality, regional sources and atmospheric transport, secondary formation, and point sources in the vicinity (i.e. production by the nearby charcoal factory, trash burning, vehicular traffic, etc.).

### Estimated health benefits

We modeled three scenarios using HAPIT to estimate the benefits of a "full" transition to LPG for cooking in and around Accra. Scenarios were determined based on the distribution of households stacking stoves and fuels observed during fieldwork and broadly categorized as mixed fuels with wood, charcoal, and charcoal and LPG. The total number of each of these households was determined from Ghana census data for the Greater Accra region. For each class of households, we estimated the number of households in Accra using that type of fuel mix and assumed their exposures decreased to those of the cleanest group measured – the LPG-only households. Scenarios and HAPIT inputs are described in Table 3.

Because exposure reductions for scenarios 2 and 3 were small relative to scenario 1, with substantial overlap in exposure distributions, only results for scenario 1 – the transition of any wood use to LPG – are shown in Table 4.

## Discussion

Personal exposure to $PM_{2.5}$ was found to be significantly lower for the three study groups using combinations of LPG and charcoal compared to the any wood use group as a home cooking fuel. The personal exposures of those three groups not using wood were quite similar to the locally measured ambient background $PM_{2.5}$ (26.5 μg/m$^3$).

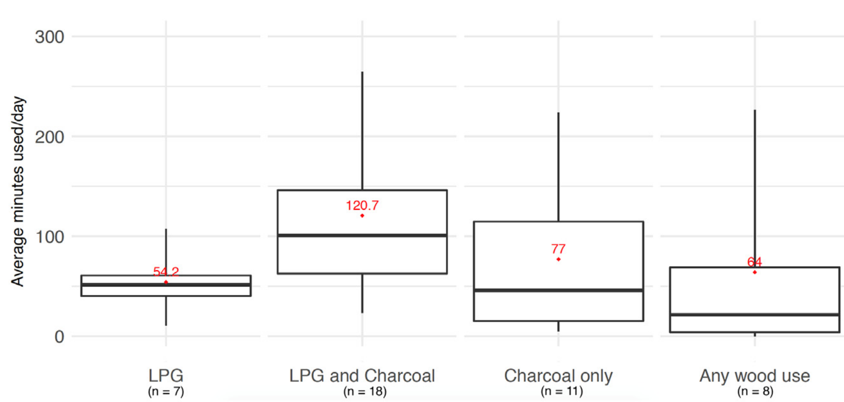


**Fig. 2.** Box plot showing daily average cooking time in the 4 study groups. Cooking times were summed for all stoves used in homes. The red text above the dot shows the group mean. Medians are the central line, the box ends represent the 25th and 75th percentiles, whiskers the 5th and 95th percentiles.

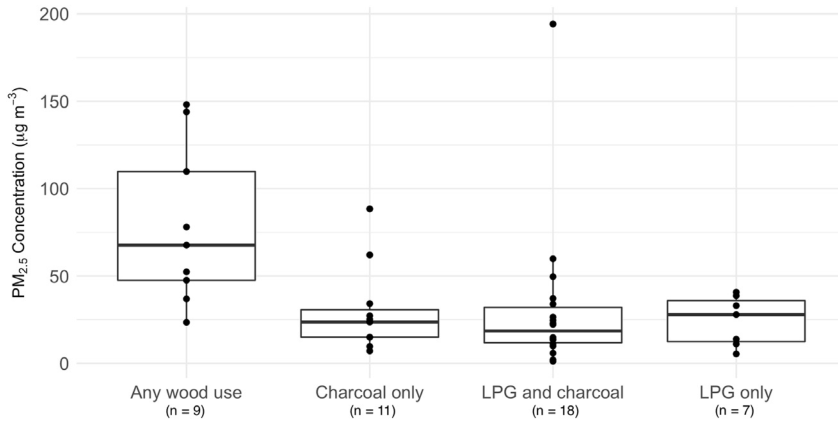


**Fig. 3.** 48 hour gravimetric measurements (UPAS) of personal exposure of study participants to $PM_{2.5}$ in the four study groups. Medians are the central line, the box ends represent the 25th and 75th percentiles, whiskers the 5th and 95th percentiles and data points are represented with dots.

This suggests that in these samples, the personal exposure was primarily driven by ambient concentrations, and further reduction in personal exposure would require reductions to the ambient $PM_{2.5}$.

While the ambient levels measured during the study period were low, typical historic ambient PM concentrations observed across Accra have generally been higher, but are also highly variable based on locality and season. Zhou et al. (2013) measured ambient $PM_{2.5}$ concentrations in four neighborhoods in the Greater Accra area from 2006 to 2007 and found averages from 63 to 104 μg/m$^3$ in the two 'poorer' neighborhoods, to 21–55 μg/m$^3$ in the two 'affluent' neighborhoods. A range of 15–42% of that ambient $PM_{2.5}$ was attributed to biomass combustion using source apportionment, so it could be expected that in the intervening period, with increased LPG adoption, the ambient contributions from those sources could have decreased substantially. While the relative source contributions may have shifted over the last 10 years, the long-term monitoring performed by the Ghana EPA suggests that overall ambient concentrations have not changed substantially from 2006 to 2015.

The importance of seasonality is highlighted in Table 1 in Appendix A, showing average concentrations collected by the Ghana EPA (from 2006 to 2015), grouped by relevant time periods; annual, Harmattan season (December through February windy season), and July through August (the months in which the study took place). Annual regional averages of 96.4 ± 77.8 μg/m$^3$ are substantially lower than the Harmattan season concentrations (139.8 ± 111.3 μg/m$^3$). However, the Harmattan increase will likely be challenging to combat, as regulations could not easily mitigate the associated long-range transport of the biogenic and anthropogenic PM. In the July–August period, however, average concentrations varied substantially by locality. For example, Asylum Down and Dansoman were quite low at 40.7 ± 16.0 and 44.7 ± 24.4 μg/m$^3$ respectively, while Weija and Labadi appear to be more impacted by local sources with concentrations of 108.9 ± 73.9 and 136.0 ± 78.9 μg/m$^3$. Unfortunately, this suggests that an LPG-only household could still be exposed to 2.5–4.5 times higher PM concentrations than what was measured in this study, leaving significantly more un-averted death and disability, even in the event of a complete transition from wood to charcoal or LPG. Local point sources thus have a clear and substantial impact on ambient concentrations and could be reduced through regulation and behavior change. One such change has recently come online, with vehicle emissions testing programs being piloted around the country, while other viable targets remain, including industrial emissions, commercial cooking, public transport systems to reduce the number of vehicles on the road, and paving road surfaces (Zhou et al., 2013).

Although the data collected by Zhou et al. (2013) is now 10 years old, it provides the most relevant available source-specific comparison. Using the observed contributions of biomass smoke to the ambient air quality, removal of this source would correspond to between 7 and 37 μg/m$^3$ reduction in $PM_{2.5}$ exposure, depending on the socioeconomic area, further evidence that the reduction in biomass combustion could have significant impacts on ambient $PM_{2.5}$ and associated personal exposure and health.

Stove usage results were also noteworthy in that the LPG-only group had the lowest cooking time (54 min per day on average), especially in contrast to the LPG and charcoal group (121 min). There could be various reasons for this difference, including socioeconomic status, buying prepared food outside the home, small family sizes for the LPG-only group. It is also not clear why the LPG and charcoal group continued to use charcoal, but it could be due to the cost or behavioral preferences. Although not the focus of this study, it is likely that discouraging the use of charcoal would bring health benefits in the form of CO exposure reductions, and would reduce pressure on Ghana's dwindling forest resources.

**Table 2**
Personal exposure to $PM_{2.5}$ results of the four study groups.

| | LPG-only | LPG and charcoal | Charcoal only | Any wood use |
|---|---|---|---|---|
| Mean (μg/m$^3$) | 24 | 31 | 30 | 79 |
| SD (μg/m$^3$) | 14 | 44 | 24 | 46 |
| COV | 58% | 141% | 81% | 58% |
| Median (μg/m$^3$) | 28 | 19 | 24 | 68 |
| Min (μg/m$^3$) | 5.4 | 1.2 | 7.1 | 23 |
| Max (μg/m$^3$) | 44.7 | 198.3 | 92.4 | 152.2 |
| N | 7 | 18 | 11 | 9 |
| | P-values based on paired students *t*-test | | | |
| Versus LPG and charcoal | 0.58 | | | |
| Versus charcoal | 0.58 | 1.0 | | |
| Versus any wood use | 0.01 | 0.01 | 0.01 | |
| | Percent difference | | | |
| Versus LPG and charcoal | −21% | | | |
| Versus charcoal | −19% | 3% | | |
| Versus any wood use | −69% | −61% | −62% | |

**Table 3**
Modeled HAPIT scenarios and inputs.

| # | Scenario | %$^+$ | # of HH$^-$ | Baseline exposure (μg/m$^3$, SD) | LPG exposure (μg/m$^3$, SD) | People per HH$^-$ |
|---|---|---|---|---|---|---|
| 1 | Wood to LPG | 19 | 152,400 | 79 (46) | 24 (14) | 5 |
| 2 | Charcoal only to LPG | 27 | 216,500 | 30 (24) | | |
| 3 | LPG and charcoal to LPG-only | 37 | 297,000 | 31 (44) | | |

**Table 4**
Modeled health benefits of a transition away from wood fuels to LPG in the Greater Accra Region. Results shown are modeled over a 5-year timeframe, with each year of exposure reduction resulting in 5 years of benefit.

| Cause | Measure | Mean averted | Min averted | Max averted | Total avoidable | Percent not avoided |
|---|---|---|---|---|---|---|
| ALRI | Averted deaths | 57 | 40 | 69 | 90 | 37 |
| COPD | Averted deaths | 22 | 12 | 29 | 37 | 41 |
| IHD | Averted deaths | 128 | 95 | 225 | 310 | 59 |
| LC | Averted deaths | 4 | 1 | 5 | 6 | 37 |
| Stroke | Averted deaths | 430 | 135 | 532 | 760 | 43 |
| ALRI | Averted DALYs | 4922 | 3457 | 5896 | 7752 | 37 |
| COPD | Averted DALYs | 932 | 523 | 1253 | 1614 | 42 |
| IHD | Averted DALYs | 3006 | 2225 | 5261 | 7252 | 59 |
| LC | Averted DALYs | 90 | 36 | 116 | 153 | 41 |
| Stroke | Averted DALYs | 9384 | 2942 | 11,618 | 16,583 | 43 |

## Next steps

This collaborative project helped build local capacity for carrying out household energy monitoring studies with personal exposure and stove usage measurements, using well-established methods and protocols. The skills developed by the Ghana EPA and Ghana Atomic Energy Commission will aid in monitoring and evaluating of the government programs to expand the use of LPG, including the introduction of a national LPG cylinder recirculation program.

In addition to this added capacity, it is important to disseminate the results of this work to the study participants community, as the results will help inform residents of the dangers of household air pollution and perhaps produce behavior change to cleaner fuels and cookstoves. The path to information dissemination may include community forums in Accra and Amasaman, radio interviews, or other types of press, such as infographics in newspapers or leaflets.

One of the key outcomes of this study is the documentation of the role that ambient air quality played as the driver of personal exposure to PM for three of the study groups. The importance of household energy as a source of urban and regional air pollution has been established in multiple locations prior to this study. Conclusions from this Accra study further illuminate the relationship between ambient air quality, personal exposures, and health impacts, and suggest the limitations of household-level interventions, such as exclusively market-based initiatives. The policy implications point towards an important role for regional or national programs in dramatically reducing ill-health from cooking with solid fuels, due to their ability to more effectively impact ambient air quality, but this continues to be an important area for further study.

## Appendix A

**Table 1**
Ambient $PM_{2.5}$, estimated by using PM10 data collected by the Ghana EPA (from 2006 to 2015), grouped together for the entire year, for the Harmattan season (December to March), and for the sampling period used in this study, July–August.

| | Annual data (μg/m$^3$) | | | Harmattan data (μg/m$^3$) | | | July–August data (μg/m$^3$) | | |
|---|---|---|---|---|---|---|---|---|---|
| Site | Mean | Median | Std dev | Mean | Median | Std dev | Mean | Median | Std dev |
| Kaneshie First Light | 94.0 | 80.7 | 75.3 | 125.0 | 103.1 | 111.5 | 83.6 | 68.9 | 57.7 |
| Tetteh Quarshie Interchange | 103.9 | 84.7 | 109.6 | 142.4 | 104.8 | 140.3 | 76.8 | 62.7 | 57.9 |
| Achimota Interchange | 99.0 | 75.4 | 87.4 | 145.7 | 103.7 | 121.7 | 81.2 | 51.5 | 80.9 |
| Labadi | 128.0 | 102.8 | 131.9 | 165.9 | 135.2 | 140.0 | 108.9 | 97.6 | 73.9 |
| Mallam | 109.3 | 86.4 | 91.5 | 164.6 | 124.3 | 147.4 | 88.6 | 73.9 | 58.5 |
| Graphic | 109.4 | 102.6 | 73.2 | 126.2 | 102.2 | 103.5 | 99.9 | 97.2 | 57.4 |
| Weija | 155.3 | 145.5 | 83.1 | 174.1 | 145.5 | 89.2 | 136.0 | 107.0 | 78.9 |
| Kasoa | 105.5 | 94.1 | 67.5 | 151.2 | 136.9 | 101.8 | 97.6 | 89.9 | 51.6 |
| Tantra Hill | 101.0 | 77.0 | 63.0 | 151.2 | 179.7 | 64.8 | NA | NA | NA |
| John Teye | 148.0 | 136.9 | 92.2 | 188.3 | 265.3 | 140.9 | NA | NA | NA |
| East Legon | 70.4 | 51.9 | 74.1 | 117.7 | 74.9 | 112.6 | 64.4 | 47.6 | 73.3 |
| Dansoman | 58.9 | 41.7 | 67.7 | 101.1 | 60.0 | 113.0 | 44.7 | 38.6 | 24.4 |
| Asylum Down | 57.4 | 42.4 | 62.2 | 97.8 | 65.4 | 100.4 | 40.7 | 36.9 | 16.0 |
| North Industrial Area | 69.8 | 50.1 | 66.5 | 135.9 | 87.3 | 112.0 | 45.0 | 42.8 | 24.3 |
| South Industrial Area | 61.5 | 50.3 | 49.2 | 96.8 | 72.4 | 78.0 | 52.0 | 48.4 | 30.2 |
| Odorkor | 75.5 | 53.3 | 79.9 | 141.1 | 85.3 | 132.4 | 56.3 | 53.2 | 23.1 |
| **Mean** | **96.4** | **79.3** | **77.8** | **139.8** | **117.0** | **111.3** | **76.3** | **65.4** | **49.4** |

Bold values indicate mean and median of ambient $PM_{2.5}$

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