Accepted refereed manuscript of: Tumwesige V, Okello G, Semple S & Smith J (2017) Impact of partial fuel switch on household air pollutants in sub-Sahara Africa, *Environmental Pollution*, 231, pp. 1021-1029. DOI: 10.1016/j.envpol.2017.08.118

Impact of partial fuel switch on household air pollutants in sub-Sahara Africa.

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ABSTRACT

Over 700 million people in Sub-Saharan Africa depend on solid biomass fuel and use simple cookstoves in poorly ventilated kitchens, which results in high indoor concentrations of household air pollutants. Switching from biomass to biogas as a cooking fuel can reduce airborne emissions of fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO), but households often only partially convert to biogas, continuing to use solid biomass fuels for part of their daily cooking needs. There is little evidence of the benefits of partial switching to biogas. This study monitored real-time $PM_{2.5}$ and CO concentrations in 35 households in Cameroon and Uganda where biogas and firewood (or charcoal) were used. The 24 hour mean $PM_{2.5}$ exposure in households that used: (1) firewood and charcoal, (2) both firewood (54% cooking time) and biogas (46% cooking time) and (3) only biogas were 449 μg m^{-3}, 173 μg m^{-3} and 18 μg m^{-3} respectively. The corresponding 24 hour mean CO exposure was 14.2 ppm, 2.7 ppm and 0.5 ppm. The exposure was high and exceeded the World Health Organisation guidelines when firewood and charcoal were used. Partially switching to biogas reduced CO exposure to below the World Health Organisation guidelines, but $PM_{2.5}$ concentrations were only below the recommended limits when household fuel conversion was complete. These results indicate that the partial switching from solid fuels to biogas was not sufficient and results in concentrations of household air pollution that are likely to continue to harm the health of those exposed. Households only achieved concentrations of $PM_{2.5}$ that were below the recommended limits when biogas was used to meet all cooking needs. Therefore, programmes introducing biogas should aim to ensure that household energy needs can be fully achieved using biogas with no requirement to continue using solid fuels.

CAPSULE – When households in Uganda and Cameroon partially switched to biogas, the carbon monoxide exposure was reduced to below the World Health Organisation guidelines, but concentrations of particulate matter with an aerodynamic diameter of 2.5 μm remained above the recommended limits and only fell below this when household fuel conversion to biogas was complete.

1. Introduction

Over 700 million people in Sub-Saharan Africa (SSA) depend on solid biomass fuels to meet cooking and heating energy needs (Lambe et al., 2015; Mortimer et al., 2016; Ozturk and Bilgili, 2015; World Bank, 2012). Access to less polluting fuels is limited for the majority of the population in SSA (Rao and Pachauri, 2017) and so people tend to obtain their household energy from solid biomass fuels, such as wood, agricultural residues and animal wastes such as dung (Amegah and Agyei-Mensah, 2017; Sulaiman et al., 2017). Biomass fuels meet over 85% of rural energy needs in SSA (Lambe et al., 2015; Mehetre et al., 2017; Rahut et al., 2017) compared to 37% in Asia and 25% in Latin America (Davidson, 1992; Dilaver et al., 2014; Mukhopadhyay et al., 2012; Sovacool, 2012). By contrast, in North America and Europe, the consumption of biomass fuel for cooking has been replaced by less polluting fuels, such as liquefied petroleum gas and electricity (Dilaver et al., 2014). The Cameroon and Uganda energy sectors are highly dependent on biomass, with over 91% of the total energy consumed in the country to meet basic energy needs for cooking and water heating coming from biomass.

A traditional three-stone cookstove, burning solid biomass fuel in a poorly ventilated kitchen is the most common method of cooking in SSA (Bruce et al., 2004; Jagger and Jumbe, 2016; Lambe et al., 2015; Po et al., 2011). These inefficient stoves are prearranged in a triangle using three large stones or bricks to hold the cooking pot. Solid biomass is burnt between the stones with generally incomplete combustion occurring and generating high amounts of household air pollutants (HAP). Two of the most frequently measured markers of HAP are fine particulate matter of 2.5 μm aerodynamic diameter ($PM_{2.5}$) and carbon monoxide (CO) (Bonjour et al., 2013; Jetter and Kariher, 2009; Nolte et al., 2001; Northcross et al., 2010, 2015). Globally, inhalation of HAP results in approximately 4 million premature deaths per year (Apple et al., 2010; Keil et al., 2010; Lewis et al., 2017; Mortimer et al., 2016; Olopade et al., 2017).

Household air pollution is also associated with a range of conditions, including acute and chronic respiratory diseases, cardiovascular diseases, low-birth weight and cataracts (Anenberg et al., 2013; Gordon et al., 2014; Ezzati, 2001).

Guidance on appropriate exposure to $PM_{2.5}$ and CO in inhaled air is provided by the World Health Organisation (WHO) (World Health Organization, 2016). To prevent harmful health consequences, the WHO recommends keeping $PM_{2.5}$ concentrations at less than 25 $\mu g\ m^{-3}$ when averaged over a 24 hour period, with the guidance also recommending CO should not exceed 6 ppm over 24 hours (World Health Organization, 2016).

In SSA, appropriate interventions, such as use of biogas as a cooking fuel, gasifier stoves and improved cookstoves can reduce airborne emissions of $PM_{2.5}$ and CO (Dohoo et al., 2012; Maes and Verbist, 2012; Njenga et al., 2016; Semple et al., 2014) compared to biomass fuels such as firewood, charcoal and animal dung (Fullerton et al., 2009; Hankey et al., 2015). Biogas is a mixture of methane and carbon dioxide (Kinyua et al., 2016; Naik et al., 2014) that is produced when organic wastes, such as food leftovers, animal manure, human fecal matter or poultry droppings, are placed under anaerobic conditions and allowed to decompose (Surendra et al., 2014). Biogas can be burnt in a number of appliances such as biogas stoves (Tumwesige et al., 2014). These stoves have a better combustion efficiency with reduced emission of $PM_{2.5}$ and CO compared to a three-stone fire. However, the impacts of introducing biogas in SSA on HAP concentrations, and consequently on human health, have not been studied in SSA. It is well understood that solid fuels have high emissions of $PM_{2.5}$ and CO compared to gaseous fuels such as biogas, but the impacts on HAP of interventions to introduce biogas stoves, where household typically only partially switch to biogas is under-reported in SSA. In this study, households used biogas to prepare breakfast, firewood was used to prepare lunch, heating of bathing water is done on biogas, and smoldering (a method used to keep evening meals warm) was done using firewood. In this paper, we examine the impact of this type of partial switching on exposure to HAP.

2. Materials and methods

2.1 Study population and sampling techniques

Measurements of indoor $PM_{2.5}$ and CO were taken from households in Cameroon and Uganda in areas where biogas digesters had previously been installed.

In Cameroon, Adamawa province was selected. This province borders the central and eastern provinces to the south, the northwest and west provinces to the southwest, Nigeria to the west and the Central African Republic to the east. Adamawa is mountainous with a land area of 64,000 km^2, and the land is sparsely populated. Cattle production is the major agricultural activity. The Fulani is the major ethic group in the province. This province was purposively selected because SNV and Wageningen University, Netherlands had specifically promoted and installed biogas digesters in the area to investigate the effect of subsidies on the uptake and implementation of innovative technology in a development context. Eighteen households were randomly selected from the list of households with and without installed digesters. These households were recruited to the study between April and May 2015 after consent was given by an adult in the household. Nine households used either charcoal or firewood and nine households used biogas for cooking.

“In Uganda, Kikati in Najjembe Sub-County in Buikwe district was purposively selected for the study. This area was selected because it had been specifically targeted by local organizations promoting biogas technology. Kikati is found 51 km along Kampala-Jinja highway. The village has approximately 400 households. Baseline HAP concentrations were sampled between March and May 2014. Consent was given by an adult in the household.
Eighteen households were randomly selected from lists of households with and without digesters and recruited for the study; three of the households were already using biogas and

wood to meet cooking energy demand. Between August and December 2015, HAP was measured in a) five households that switched from wood to biogas for cooking, b) nine households that used wood as a cooking fuel and c) three households that used both biogas and wood as cooking fuels. One household declined to participate in the post-biogas installation measurements.

Measurement devices (see section 2.2 below) were placed in the room designated as the primary cooking space and at a height of approximately 1 m and typically 1.5 m from the cookstove. Measurements of $PM_{2.5}$ and CO were taken over a 24 hour period.

2.2. Data collection

2.2.1. Kitchen description

In all households under study, the kitchen features including the type of stove, fuel use, type of food cooked, duration of cooking, kitchen design, the cooking area, windows, doors, height from floor to roof, walls, seats ventilation (spaces in kitchen walls), kitchen volume, number of windows, door and window size (dimensions) were obtained through measurement, observation and interview with both household head and the principal cook. The kitchen volume ranged from 4.3-10.2 m^3 (average 7.4 m^3). A traditional three-stone cookstove placed less than a metre from the wall was used by all households that used wood prior to adopting biogas for cooking. In all households, meal preparation was done inside the kitchen, which was built out of unbaked or mud bricks located within a 1-5 m radius from the residential house. It was observed that all kitchens had a door which was kept open during meal preparations. Thirteen households had a window on their kitchens compared to 22 without a window. The door and the window in the kitchen were used for ventilation.

2.2.2 Household characteristics and cooking activity

The number of people in the household, weight of firewood and number of people present in the kitchen during cooking were recorded for each household. In all households, an average of three meals was prepared by children between age of 10-16 years and adult females above the age of 18 years. Breakfast was prepared between 07:00-11:00; lunch was prepared between 11:00-15:00 and dinner prepared between 18:00-21:00. Smoulding was the only method used to keep evening meals warm. It was further observed that meals especially breakfast for non-school-going children was served in the kitchen while the women peels fruit and vegetables and prepares sauces, especially from dried beans which require 2-3 hours of cooking.

In Cameroon, men have a special dining area separate from dining area for children and women. In Uganda, men have a special dining seat or table while children and women usually sit on mats laid on the floor. In households where men returned home late, either from work or social events, dinner is served inside the kitchen for children and sometimes women.

2.2.3 Household air pollution measurements

Household air pollution was assessed by measuring the airborne concentration of $PM_{2.5}$ and CO under the prevailing conditions of the kitchen of each household. No burning or ventilation behaviours were controlled. A TSI SidePak AM510 (TSI Inc, CA, USA) was used to measure mass concentration of $PM_{2.5}$. A CO data logger (LASCAR EL-USB-CO) with a measurement range of 0-1000 ppm was used to measure household levels of CO. Both devices measured concentrations every 1 second and recorded the average value every minute.

The collected data were downloaded using proprietary software (TSI TrakPro Ver. 4.5.1.0); average (arithmetic mean) concentrations and maximum concentrations were identified for each home. The $PM_{2.5}$ concentrations collected by the SidePak were corrected by a factor of 0.295 (Jiang et al., 2011) to account for the difference in particle characteristics, including density, size distribution and or index of refraction. The percentage of time when $PM_{2.5}$ measurements exceeded the two thresholds, the WHO 24-hour guidance limit (25 μg m^{-3}) and the US Environmental Protection Agency (US-EPA) 24-hour hazardous level (250 μg m^{-3}), were also recorded for each sampling period. The CO data were downloaded using proprietary software (EasyLog USB Ver. 7.2.0.0) with 24 h arithmetic mean, maximum and percentage of time > 6 ppm derived from the resulting data log.

2.3 Particulate matter and carbon monoxide analysis

The 24 h averages for $PM_{2.5}$ and CO concentration data were generated for each household together with minimum and maximum concentrations. The mean and standard deviations for each household were calculated and statistical tests used to determine if there were significant differences in $PM_{2.5}$ and CO concentrations in kitchens that used biogas for cooking and similar homes using firewood as cooking fuels in both Cameroon and Uganda.

2.4 Statistical analysis

The HAP data were verified and then analysed using MS Excel 2010, (Microsoft Corp). Proportions were compared using the Student's t-test to determine differences between households using various fuel types.

2.5 Ethics approval

Written and verbal consent for participation in this study was obtained from all volunteers. The study was given ethical approval from the College Ethics Review Board of the University of Aberdeen.

3. Results

Table 1 presents the $PM_{2.5}$ concentrations of the 18 households in Adamawa and Kikati which used firewood and charcoal to meet all cooking needs. The average mean $PM_{2.5}$ concentration was 387 µg m^{-3} in households in Adamawa and 511 µg m^{-3} in Kikati. All wood and charcoal burning households in both countries had mean $PM_{2.5}$ concentrations above the WHO guideline of 25 µg m^{-3}. A Student's t-test indicated that there was no statistically significant difference in $PM_{2.5}$ concentration between households using firewood in Adamawa and Kikati ($p=0.29$).

TABLE 1

Table 2 presents the CO concentrations of 16 households in Adamawa and Kikati which used firewood to meet all cooking needs. The average value for the 24 hour mean CO concentration in homes in Kikati was 11.5 ppm, while in Adamawa it was 16.8 ppm. All households in Adamawa and Kikati had mean exposure levels above the WHO guideline of 6 ppm CO. A Student's t-test indicated that there was no statistically significant difference in CO concentrations between households in Adamawa and Kikati ($p=0.31$).

TABLE 2

Figure 1 shows the measured the $PM_{2.5}$ and CO data for one typical wood burning household in Adamawa over a 20 hour period. This typical wood burning household, CHH14 had a mean $PM_{2.5}$ of 666 µg m^{-3}, standard deviation of 1232, the mean CO of 11.5 ppm and standard deviation of 18.9.

Table 3 presents the $PM_{2.5}$ concentrations of five households in Kikati which switched from firewood to biogas as a cooking fuel. The average value for the 24 hour mean $PM_{2.5}$ concentration for the five households before switching to biogas was 444 µg m^{-3}, and this reduced to 173 µg m^{-3} after the switch. A Student's t-test indicated that this difference was not statistically significant ($p = 0.055$).

TABLE 3

In Adamawa, households using biogas only (excluding CHH16) had mean $PM_{2.5}$ concentrations of 18 µg m^{-3}. Household CHH16 had a higher concentration with a mean $PM_{2.5}$ value of 38.6 µg m^{-3}. The high levels in this house were likely to be due to a traditional medical treatment being used during the sampling time which involved smoldering charcoal, so this household was excluded from the analysis.

Table 4 presents the CO concentrations of five households in Kikati which switched from firewood to biogas as a cooking fuel. The average value of the 24 hour mean CO concentration for the five households before switching to biogas was 22 ppm reducing to 2.7 ppm after the switch. A Student's t-test indicated that there was a statistically significant difference in CO concentration in households in Kikati that switched from firewood to biogas for cooking ($p=0.042$).

TABLE 4

In Adamawa, households using biogas only (excluding CHH16) had mean $PM_{2.5}$ concentrations of 18 µg m^{-3} (Table 5). Household CHH16 had a higher concentration with a mean $PM_{2.5}$ value of 38.6 μg m^{-3}. The high levels in this house were likely to be due to a traditional medical treatment being used during the sampling time which involved smoldering charcoal, so this household was excluded from the analysis.

TABLE 5

With the exception of household CHH16, all households in Adamawa using biogas only had a mean CO value of less than 1 ppm (Table 5); this is below the WHO guideline of 6 ppm. Household CHH16 had a higher exposure with mean CO value of 25 ppm.

Figure 2 shows the measured the $PM_{2.5}$ and CO data over a 20 hour period for one typical household (CHH06) in Adamawa that uses biogas for cooking. Household CHH06 had a mean $PM_{2.5}$ of 14 μg m^{-3}, standard deviation of 23, the mean CO of 1.1 ppm and standard deviation of 4.4.

FIGURE 2

Households in Adamawa had a $PM_{2.5}$ value of 464 μg m^{-3} compared to households in Kikati, which had a mean $PM_{2.5}$ value of 154 μg m^{-3}. A Student's t-test indicated that there was no statistically significant difference (in $PM_{2.5}$ concentration when households used both wood and biogas to meeting their cooking needs ($p=0.36$). In both villages, the mean $PM_{2.5}$ remained high in households when a combination of biogas and wood was used to meet cooking needs, this is comparable to results in Table 1. The results in Table 6 demonstrate that improvements in household air quality are not apparent if firewood and biogas are both used for cooking at the same time.

TABLE 6

Figures 3 shows the mean $PM_{2.5}$ in the 18 households in Adamawa.

FIGURE 3

5. Discussion

The results of this study provide real-time $PM_{2.5}$ and CO concentrations in Adamawa and Kikati, villages in Cameroon and Uganda respectively. The study compares the impact of cooking with biogas, firewood, and a mixture of biogas and firewood on indoor air quality in kitchens in households in two countries in SSA. Households collected firewood either in the gardens or from forest cleared for agriculture; they cited reduction in smoke in their kitchens as a motivating factor for switching from firewood to biogas.

5.1 Biomass fuel: before biogas installation

In Adamawa and Kikati, households that used firewood and charcoal had a 24 h average $PM_{2.5}$ concentration of 387 and 511 µg m^{-3} respectively. Data for CO was 11.5 ppm (Adamawa) to 16.8 ppm (Kikati). These HAP concentrations are high and exceed the WHO guideline of 25 µg m^{-3} for $PM_{2.5}$ and 6 ppm for CO concentration suggesting a serious health risk to the women and children who spend most of their time in the kitchen during cooking hours (Devakumar et al., 2014; Thorsson et al., 2014). Comparable $PM_{2.5}$ results are summarised in Table 7 and previously reported by Hankey et al., (2015); Keil et al., (2010); Pennise et al., (2009); Titcombe and Simcik, (2011) among other studies. A number of factors such as fuel type, cooking period, food to be cooked, season, location (e.g. rural, urban) are likely to impact on the concentration of $PM_{2.5}$ in households as shown in studies by Sanbata et al., (2014) in Addis Ababa, Fullerton et al., (2009) in Malawi, Kurmi et al., (2008) in Nepal and Zhou et al., (2011) in Ghana.

It was observed that kitchens in Adamawa and Kikati had poor ventilation, generally with one small window or ventilator. Improving ventilation in these rural household kitchens would decrease concentrations of $PM_{2.5}$ and CO in household air (Smith et al., 2010). Also, Mortimer, et al., (2016) reported that introduction of improved cookstove in households did not reduce the risk of chronic obstractive disease in children below the age of five.

5.2 Partial fuel switch

In households using both biogas and firewood, it was observed during the study, digesters in these households were not producing enough biogas for a full day of cooking. This was attributed to limited availability of organic waste and increased labour requirements for digester maintenance, mainly due to the need to collect extra water for biogas production. Therefore, installation of biogas digesters in these households had limited impact on the use of firewood. It was also observed that households used firewood to cook and steam specific food types, for example, *matooke* in Kikati and *fufu* in Adamawa, but biogas was used to cook vegetables, porridge and boil water for tea or coffee.

Households using both biogas and firewood (Table 6) had a 24 h average $PM_{2.5}$ concentrations of 464 µg m^{-3} (in Adamawa) and 154 µg m^{-3} in Kikati similar to households using firewood only (Tables 1 and 2). On average, households obtained 48% of their cooking time from solid biomass fuels, and 52% from biogas (Tumwesige, 2017). Simple changes to the infrastructure of households, for example improved ventilation in the kitchen or use of efficient cookstoves, coupled with education to help householders make better use of these changes would further reduce HAP concentrations.

5.3 Fuel switching

In Adamawa and Kikati, the drivers for deciding to install a biogas digester were: (i) alternative and sustainable energy source that can reduce smoke in their kitchens; (ii) organic fertilizer for resource recovery, reuse and recycling; and (iii) on-site waste management for effective and sustainable waste disposal. In Kikati, switching from firewood to biogas for cooking saw a reduction in the average 24 hour $PM_{2.5}$ and CO concentrations to 173 µg m^{-3} and 2.7 ppm respectively. The CO levels were reduced to below the WHO guidelines, but the $PM_{2.5}$ levels remained above than the WHO limit (Bruce et al., 2015). In Adamawa, households using biogas only (with the exception of CHH16) had mean $PM_{2.5}$ and CO concentrations of 18 µg m^{-3} and 0.5 ppm. These are below the WHO guidelines for $PM_{2.5}$ and CO of 25 µg m^{-3} and 6 ppm respectively. In the study by Titcombe and Simcik, (2011), the use of liquid petroleum gas was found to produce $PM_{2.5}$ concentrations of 14 µg m^{-3}, comparable those produced by biogas in Adamawa.

The use of biogas for cooking is a positive step towards achieving clean cooking and reductions in HAP concentrations. Our results suggest that use of biogas as a cooking fuel can reduce HAP concentrations and is therefore likely to produce health benefits associated with reduced exposure to fine particulate matter and CO. A study by Dohoo et al., (2012), revealed that women reported fewer respiratory symptoms after the installation of biogas digesters. Households in Adamawa and Kikati had a significant reduction in $PM_{2.5}$ and CO exposure. This could lead to reduced risk of pneumonia, blood pressure and heart problems (Gordon et al., 2014; Semple et al., 2014, 2016). Households in Adamawa and Kikati still used other fuels, such as kerosene, for lighting in the evenings; switching to use of solar lamps could further reduce HAP concentrations.

A purposive sampling method was used to select the study areas, so results are limited to study areas with similar characteristics. Studies areas were in rural locations without contamination from vehicles and industries. The household kitchen volume varied from 4.3-10.2 m^3, this is cited as a limitation of the study, comparable kitchen volumes would have been ideal.

Further limitations of this study include a lack of comparative data for indoor $PM_{2.5}$ and CO concentrations in households in other SSA countries switching from biomass fuels to biogas for cooking. In Adamawa, biogas digesters had been in use for a longer period before the study was under taken than in Kikati. In Kikati, the average 24 hour $PM_{2.5}$ concentration was 173 µg m^{-3} compared to only 18 µg m^{-3} in Adamawa. Households in Adamawa had more experience in maintaining biogas digesters than those in Kitaki, where digesters had been installed only 5 months before the study was undertaken.

The duration of sampling was another limitation. Measurements were done over a 24 hour period, this could have lad to behavior change in homes under study. Barnes et al. (2011) provided evidence that behavioural change interventions within biomass burning households had the potential to reduce HAP.

Data on exposure to $PM_{2.5}$ and CO was measured after biogas digesters were installed in Adamawa; these household were matched with those without biogas digesters. To allow direct comparison, it would have been better to measure $PM_{2.5}$ and CO prior to biogas installation and again once the installation has been completed. In Kikati, indoor air quality was measured in households both before and after installation of the biogas digesters allowing direct comparison. Availability of funds precluded installation of additional biogas digesters in Cameroon.

Another limitation is the small number of households in the study. We had anticipated that we would work with 48 households before and after biogas digesters were installed in Kikati. These were to be paired with 48 households without intervention. However, the high cost of installing digesters prohibited a study of this size.

6. Conclusion

Household $PM_{2.5}$ concentrations significantly decreased when households in Kikati switched from use of firewood to biogas for cooking. Use of biogas in Adamawa resulted in low $PM_{2.5}$ and CO concentrations. To the best of our knowledge, this is the only study in SSA documenting the cross sectional impact of when households use only solid biomass fuel, only biogas and use both solid biomass fuel and biogas. Small reductions in concentrations of HAP can have a large impact on livelihoods. By the end of 2016, the 57,000 biogas digesters had been installed in a number of SSA countries (ABPP, 2016). As biogas digesters adoption increases in SSA, the average HAP exposure of households will be impacted as a result of households switching from firewood to biogas as a cooking fuel, although this will often only be a partial switch. This study provides evidence for the impacts of partial conversion to biogas. Women and children will spend less time in polluted kitchens, but the study demonstrates that the potential benefits of reduced concentrations of HAP will not be fully realized if households use both firewood and biogas for cooking at the same time. Longer follow-up will be needed to detect statistically significant changes of HAP in larger household size in SSA. Furthermore, there is need to monitor personal exposure associated with cooking fuel switch in different household age groups.

Acknowledgments

The authors acknowledge the support provided by the European Union through the African Component of the ACP Research Programme for Sustainable Development as well as the African Union Commission (No. AURG/2/058/2012). Furthermore we are grateful to Afri-Flame network, Esther Pedie, Thierry Tame, Niccolo Merigi and Jelte Harnmeijer for their collaboration, contributing their knowledge, experiences and opinions.

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