Quantifying the health impacts of ACE-1 biomass and biogas stoves in Cambodia

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Prepared by Berkeley Air Monitoring Group
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Front Cover Photo: Study participant in rural Cambodia wearing a custom made vest to hold the PM2.5 monitor, essential to understanding her personal exposure to this pollutant. (Source: Patrick Kooijman, Field Team Manager)

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Protection of human subjects
The study, including protocols for gravimetric and real-time KAP (kitchen air pollution) sampling, personal exposure measurements, baseline and post-monitoring questionnaires, and stove-use monitoring, was approved by the Cambodian National Ethics Committee for Health Research (Protocol Number 221 NECHR).

Disclaimer
Jason Steele, of SNV-Cambodia , contributed to this report, providing insight on Cambodia's history and dependence on solid fuels, providing context for the study and its impacts. Mr. Steele and SNV in no way influenced the process by which the data was collected, analyzed, or reported. The content of this report is solely the responsibility of the Berkeley Air Monitoring Group and does not necessarily represent the views of the parties supporting this study.

Abbreviations

Abbreviation	Meaning
aDALY	Averted disability adjusted life year
BA or Berkeley Air	Berkeley Air Monitoring Group
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
cm	Centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
CV or COV	Coefficient of Variation
°C	Degrees Celsius
DALY	Disability adjusted life year
GDP	Gross Domestic Product
HH	Household
HAP	Household air pollution
HAPIT	Household Air Pollution Intervention Tool
g	Gram
KAP	Kitchen air pollution
kg	Kilogram
LDC	Least Developed Country
L/min or LPM	Liters per minute
LPG	Liquefied petroleum gas
m	Meter
m^3	Cubic meters
MJP	Maddox Jolie-Pitt Foundation
mg	Milligram
mm	Millimeter
PE	Personal exposure
$PM_{2.5}$	Particulate matter less than 2.5 microns in diameter
SD	Standard deviation
SNV	SNV Netherlands Development Organisation
SUMS	Stove use monitoring system
UCB-PATs or UCB	UCB particle and temperature sensor
µg	Microgram
USD	United States Dollar
WHO	World Health Organisation
WHO CHOICE	The World Health Organization's Choosing Interventions that are Cost-Effective effort

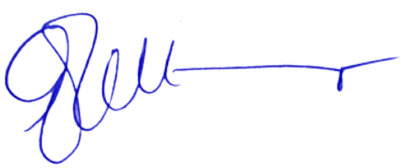
Foreword from SNV Netherlands Development Organisation

Across the globe, SNV Netherlands Development Organisation is implementing clean cooking interventions that improve the livelihoods of the poor through socioeconomic and health benefits. SNV is currently implementing 20 clean cooking intervention programmes (biogas, improved cookstoves and fuels) across Latin America, Asia, and Africa. Over the past 10 years, SNV's clean cooking interventions have benefited over 3 million people all over the world.

A common challenge that clean cookstove sector practitioners' face to scale-up access to clean cooking solutions is the limited investment by the public and private sector to support such interventions. The level of investment in the sector is not proportionate to the size of the problem that needs to be addressed. For those of us working in the clean cooking sector, there is one daunting figure that we all know very well, that over 4 million people die every year from household air pollution related to cooking with solid biomass fuels, more than HIV/AIDs, tuberculosis, and malaria combined. It is even more daunting that this number is likely to grow despite all the great effort that the Global Alliance for Clean Cookstoves and its member organisations are making to reverse this trend.

As development practitioners, we need to develop new innovative financing mechanisms to address the limited amounts of traditional finance in order to scale-up interventions and achieve greater impact. One innovative way to improve the financial viability and level of investment in clean cooking intervention programmes is to verify and monetize the health benefits for women and children under a results-based financing modality. Currently progress is being made by a number of public and private actors towards developing a methodology to standardize the process of determining health benefits from clean cooking interventions through estimating premature averted death and disability through averted disability-adjusted life years (aDALYs) and bringing these aDALYs to market. We are also pleased to see the Gold Standard Foundation consolidate these efforts and push forward to develop a credible process for bringing this important benefit to market and increase the needed investments into this sector.

We are happy to contribute to this process by having commissioned Berkeley Air Monitoring Group and the local field team to conduct this important study. We believe this report provides a practical example of validating kitchen air pollution and personal exposure from both baseline and intervention scenarios, and is therefore a key reference for sector practitioners.



Andy Wehkamp
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1 Executive Summary

SNV Netherlands Development Organisation commissioned Berkeley Air Monitoring Group and a local field team to conduct household air pollution monitoring in Cambodian households to determine the difference in kitchen concentrations and personal exposure with cooking with traditional stoves compared to cleaner cooking solutions. Exposure to household air pollution (HAP) is the largest environmental risk factor in developing countries, resulting in approximately 4 million deaths and 110 million disability-adjusted life years (DALYs) worldwide, which are a measure of premature death and disability. The World Health Organization (WHO) estimates that 13.3 million people are exposed to HAP in Cambodia, leading to 11,876 HAP related deaths per year, 1,674 of which are children (Household Air Pollution, 2013). Estimates of avoided premature death and disability were made in this study by measuring the impact of an advanced biomass stove and biogas cooking systems on personal exposure (PE) to $PM_{2.5}$ in Cambodian households. These exposure measurements were then input into the Household Air Pollution Intervention Tool (HAPIT) model, developed at the University of California, Berkeley (UCB). The HAPIT model outputs estimates of the deaths and DALYs averted from clean cooking programs, yielding the potentially tradeable commodity of averted Disability-Adjusted Life Years (aDALYs).

The advanced stove assessed was the ACE-1, which is a fan-driven gasifier stove, produced by African Clean Energy Ltd., that has recently been introduced to the Cambodian market. The ACE-1 sub-study was conducted in 24 peri-urban and 24 rural, wood-burning households and involved measurements of personal exposure (PE), kitchen air pollution (KAP), and stove use before and after the introduction of the ACE-1 stove (before-after study design). The biogas sub-study was conducted in 24 rural biogas households and 24 rural control households (cross-sectional study design) and also involved measurements of personal exposure, kitchen air pollution, and stove use.

The ACE-1 sub-study resulted in a significant reduction of mean KAP by 39% in ACE-1 user households 'before' and 'after' stove introduction, from 183 $\mu g/m^3$ to 111 $\mu g/m^3$ ($p<0.05$). The 'before' and 'after' mean PE of the ACE-1 users were 66 $\mu g/m^3$ and 47 $\mu g/m^3$, respectively, which equates to a statistically significant reduction of 19 $\mu g/m^3$ or 28% (p <0. 05). This low starting baseline makes further reductions difficult, however, since it lies on the steep part of the $PM_{2.5}$ exposure response curves, these measured reductions in exposure can yield substantial health gains. ACE-1 "use fractions" in the Phnom Penh and Samlout sample populations were calculated from stove usage monitoring data and resulted in approximately 87.5% and 75% of the study population being categorized as regular users, respectively. These were applied to the HAPIT model to scale the exposure results and were based on the threshold of "regular use" set at 0.5 ACE-1 stove uses per day or greater, on average. Traditional stove displacement by the ACE-1 stove was greater in the urban study group (49%) than the rural (8%). The ACE-1 HAPIT results showed a central estimate of the annual cost per aDALY of 1,280 USD and 680 USD given ACE-1 lifetimes of 3 and 5 years, respectively. The WHO CHOICE effort advises that interventions costing less than the GDP/capita are "very cost-effective". Given that the 2015 Cambodian GDP/capita is ~1840 USD, both of these estimates put the ACE-1 program in this category, although the uncertainty bounds around the HAPIT estimates extend the program toward the "cost-effective" or "not cost-effective" classification.

The biogas sub-study showed control and biogas mean $PM_{2.5}$ KAP values of 172 $\mu g/m^3$ and 35 $\mu g/m^3$, respectively, a significant difference of 137 $\mu g/m^3$, or 80%, between the two groups ($p < 0.05$). Control households were still relying on traditional biomass stoves. The control and biogas mean PE values were 73 $\mu g/m^3$ and 28 $\mu g/m^3$, respectively, demonstrating a significant 61% difference ($p < 0.05$). The biogas users demonstrated a traditional stove displacement of 83% based on cooking duration when compared the control group. Homes with biogas used biogas stoves for 87% of cooking events, which equated to 81% of their time spent cooking. Of the biogas owners, 100% used their biogas stove at least 0.5 times per day, which was used as the "use fraction" in the HAPIT model. Biodigesters having a 5- or 10- year lifetime result in a central estimate of the annual cost per aDALY of 3,160 USD and 1,810 USD, respectively. The 5-year digester would place this in the "cost-effective" category and the 10-year would be considered "very cost-effective". Although, the HAPIT uncertainty bounds extend it towards the "not cost-effective" classification. Biodigesters have been known to last for up to 20 years, a lifetime which the HAPIT model cannot accommodate, meaning the cost-effectiveness calculation may be underestimating the value of biogas.

The combination of low $PM_{2.5}$ levels in ambient air and well-ventilated kitchens in Cambodia means relatively low baseline PE concentrations, making further reductions more difficult. This starting point for PE, however, lies on the steep part of the $PM_{2.5}$ exposure response curve, meaning that reductions such as those observed in both sub-studies, equal larger health savings than when occurring on the higher, flatter parts of the curve. Therefore, clean cooking technology interventions in households that already cook in well ventilated areas can still have significant positive health outcomes.

2 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. Adverse health effects have been well documented in studies of cookstoves and the associated kitchen and household air pollution (KAP and HAP, respectively). HAP is a generic term for air pollution inside and around the entire household, while KAP is specific to air pollution in the kitchen area only. Exposure to HAP is now identified as the most important environmental risk factor for ill-health in developing countries, resulting in approximately 4 million deaths and 110 million disability-adjusted life years (DALYs) worldwide. DALYs measure the overall disease burden by combining the burden of mortality and morbidity. DALYs sum the years of life lost due to premature death in the population and the years of life lost due to 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 which increase the completeness of solid fuel combustion. For example, a nine-year study in China showed that replacing biomass with biogas for cooking, as well as improving kitchen ventilation, were associated with a reduced risk of chronic obstructive pulmonary disorder (COPD) (Zhou, 2014). However, such studies are long, expensive and not practical for replication. Additionally, they fail to measure the cost-effectiveness of alternative clean cooking solutions to achieve similar outcomes. Currently, a methodology is being developed to standardize the quantification of health benefits from clean cooking interventions that reduce exposure to KAP. Under this new method, estimates of avoided premature death and disability are made by inputting personal exposure measurements before and after an intervention into the Household Air Pollution Intervention Tool (HAPIT) model, developed at the University of California, Berkeley (UCB). HAPIT output deaths and DALYs averted from an intervention, yielding a potentially tradeable commodity of averted Disability-Adjusted Life Years (aDALYs).

The Clean Development Mechanism (CDM) traditionally funded many clean cookstove projects based on the reduction of CO_2 released from solid fuel combustion through improved efficiency stoves. With the recent fall in the price of certified emissions reductions (CERs) under the CDM, there is growing interest in developing a way to monetize the potential health benefits associated with clean cooking interventions. Quantifying aDALYS through exposure measurements and modeling may be one answer by monetizing the health savings associated with these programs. Investing in protecting lives, such as investing to reduce greenhouse gas emissions, may help fuel cookstove innovation and dissemination.

The Royal Kingdom of Cambodia, located in Southeast Asia, is a low income country and also holds a least developed country (LDC) status with the United Nations (List of Least Developed Countries, n.d.). Its population is approximately 15.3 million people, 79% of which live in rural areas, primarily employed in the agricultural sector (Population total, 2014; Rural population, 2014). The poverty rate of Cambodia was 17.7% in 2012, with almost 3 million poor people and over 8.1 million who are near-poor (Cambodia, 2014). Approximately 90% of the poor and near poor live in rural areas (Cambodia, 2014).

In Cambodia, 72% of total final energy consumption comes from biomass fuels and 80% of all biomass energy is consumed in the residential sector, with biomass mostly consumed for domestic cooking (World Energy Outlook 2011, 2011). As Cambodia's economy is modernizing, so is their energy use, as demonstrated by increased access to electricity and the use of liquefied petroleum gas (LPG) as a cooking fuel in Phnom Penh. However, the gains in access to modern cooking fuels, like LPG, is offset by population growth and those born into lower income families who tend to cook with solid fuels. For example, 96.2% of the population was reliant on solid fuels in 2000, which had decreased to 89.7% by 2010. However, with population growth, the number of people actually cooking with solid fuels is growing. In 2000, 96.2% of the population equated to 11 million people, and in 2010, 89.7% equated to 12 million people (NDO, 2001; NDO, 2011). So, although access to improved fuels has reduced the total percentage of the population cooking with solid fuels in Cambodia, the absolute number has actually slightly increased over time. This continued reliance on solid fuels for cooking has led to significant health issues, deforestation, and natural resource degradation.

It is currently estimated by the World Health Organization (WHO) that 13.3 million people are exposed to HAP in Cambodia, leading to 11,876 HAP related deaths per year, 1,674 of which are children (Household Air Pollution, 2013). The Global Burden of Disease 2010 report estimated that household air pollution from cooking with solid fuels is the second leading risk factor (amongst over 60 risk factors examined) as a cause of ill-health in Cambodia (GBD PROFILE: CAMBODIA, 2010).

The primary goal for this study was to measure the impact of two advanced cooking technologies, the ACE-1 stove and biogas, on $PM_{2.5}$ kitchen air pollution (KAP) and personal exposure (PE) in Cambodian homes by monitoring users under baseline and post-intervention scenarios and modeling health outcomes to produce an estimate aDALYs under a scaled up stove program.

3 Methods

3.1 Study overview

The results reported herein are from the two following sub-studies:

- A paired before and after study of 24 peri-urban and 24 rural, wood-burning households. Measurements of personal exposure, kitchen air pollution (KAP), and stove use were taken before and after the introduction of the ACE-1 stove.
- A cross sectional study of 24 rural biogas households and 24 rural control households, which were traditional stove users chosen from neighbors of biogas participants. Measurements of personal exposure, kitchen air pollution (KAP), and stove use were taken simultaneously in the two groups.

Figure 1. Enumerators receiving training on the cleaning and maintenance of instruments.

The number of ACE-1 households in each of the two sub-groups (24 peri-urban and 24 rural) was calculated using standard sample size calculations and was powered to detect a 35% or greater reduction in personal exposure concentrations, assuming a coefficient of variation (CV) of 0.55. These values are slightly more conservative than those found in a previous exposure study involving Berkeley Air on the ACE-1 stove in rural Lao PDR, which showed a percent reduction of 37% and a CV of 0.47. This sample size of 24 was also chosen to allow for a 20% loss of data due to household dropouts and/or instrument failures. We also considered analyzing all 48 ACE-1 households as one group, thus allowing for the possibility of a much larger CV of 0.80 while maintaining the power to detect a 35% reduction in exposure concentrations.

The number of biogas households (24) was chosen in part for the simplicity of harmonizing with the ACE-1 sample size as well as to fit within the logistical, resource, and budget constraints, particularly given the lack of personal exposure data related to biogas in the literature on which to base percent reduction and CV expectations. We also considered the likelihood that the percent reductions in exposure may be much higher given the cleanliness of biogas and that the CV may be much greater than the values seen in the literature for advanced biomass stoves such as the ACE-1.

Representatives from Berkeley Air Monitoring Group (Berkeley Air) conducted an intensive five-day training for a field team of eight and a field supervisor. Berkeley Air representatives also stayed through the first two weeks of sampling to ensure a smooth startup and provide supervision and expert troubleshooting.

The fieldwork occurred over a seven-week span, commencing on July 15, 2015 and terminating on August 29, 2015. Table 1 outlines the study schedule. More detail on the ACE-1 and biogas sub-studies is given in section 3.2 and 3.3, respectively.

Table 1. Study timeline for ACE-1 and biogas sub-studies.

Week	District/Province	Study Group
1	Phnom Penh	ACE-1 Before
2	Samlout	ACE-1 Before
3	Takeo	Biogas/Control
4	Kampong Spen	Biogas/Control
5	Adjustment week/ no monitoring	
6	Phnom Penh	ACE-1 After
7	Samlout	ACE-1 After

3.2 ACE-1 ‘before’ and ‘after’ study overview

The ACE-1 sub-study was segmented into three components:

1. Baseline KAP and exposure monitoring
2. Introduction of ACE-1
3. Follow-up KAP and exposure monitoring

During household selection, the following exclusion criteria were maintained: the participant (1) was over 18 years of age, (2) was not pregnant, (3) did not smoke cigarettes, and (4) cooked primarily with wood. 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. A total of 48 households were selected to participate in the ACE-1 sub-study, half in Samlout and half in Phnom Penh. Samlout is a rural district in Northwestern Cambodia, on the border of Cambodia and Thailand. The main source of income in Samlout is agriculture, with some additional income from construction and commercial sales of goods. Both wood and charcoal are used commonly for cooking. The Phnom Penh study site was a peri-urban location on the outskirts of Phnom Penh, the largest city in Cambodia. In this area, charcoal and wood use were common, as well as some LPG. These two locations were chosen based on their need for access to clean cooking solutions, as well as local support available in Phnom Penh by SNV and in Samlout by the Maddox-Jolie Pitt (MJP) foundation.

Baseline, or ‘before’, measurements were taken prior to the distribution of the ACE-1 stove, while participants cooked with primarily traditional stoves. Post-intervention, or ‘after’, field sampling occurred three weeks after the ACE-1 stoves were disseminated. During both the ‘before’ and ‘after’ monitoring, three consecutive daily visits allowed continuous 48-hour measurements of $PM_{2.5}$ kitchen air pollution (KAP) collected using light scattering UCB particle monitors, as well as two 24-hour gravimetric measurement of personal $PM_{2.5}$ exposure, and stove usage of up to three of the most commonly used stoves. Surveys which determined participant time-activity, as well as health and time perceptions, were administered during daily household visits. Half of the selected households in each location also included gravimetric measurements of KAP to use as a field adjustment to the light scattering measurement. Stove usage monitors (SUMS) were left in half the homes after the ‘before’ monitoring period to collect longer term stove usage data. Due to the before-and-after nature of the ACE-1 sub-study, stoves were disseminated with SUMS so all homes have a full four weeks of SUMS data.

Over the entire study period, outdoor ambient $PM_{2.5}$ was measured to determine the influence of ambient air pollution on KAP and personal exposure. Two monitors were mounted in different areas within the study site to capture variability in ambient conditions (Figure 2).

Figure 2. One of two AirMetrics MiniVol $PM_{2.5}$ samplers used to determine the influence of ambient air pollution on KAP and personal exposure.

3.3 Biogas cross-sectional study overview

The cross-sectional biogas sub-study included 24 rural biogas and 24 control households that were studied over two weeks in two locations. Biogas and control selection excluded participants that were under 18, smokers, or pregnant. Otherwise, biogas participants had to have and use a biodigester. Control participants were selected from the surrounding neighbors of the biogas users in order to match socioeconomic status as closely as possible. The study locations were selected based on a high density of biogas users. Monitoring of the biogas and control homes lasted over three consecutive days, collecting 48 hours of data. The same measurements were made in the biogas sub-study as the ACE-1 study, however, due to the cross-sectional study design, SUMS data was collected only during the 48-hour monitoring period.

3.4 Stove type

Table 2. Specifications and photos of stove types.

Stove Model and Specifications	Stove Image
ACE-1 • Dimensions: 33 x 33 x 35 cm • Weight: 4.6 kg. • Fuel: Solid biomass (includes, but is not limited to, wood, agricultural waste, and pellets).	
New Lao Stove • Materials: Metal covered baked clay • Height: 25.4 cm • Diameter: 18 – 28 cm • Weight: 12 kg	
Traditional Lao Stove Traditional stove design • Materials: Metal covered baked clay • Dimensions vary based on capacity	 
LPG Stove A gas stove that burns primarily propane. • Materials: Stainless Steel • Dimensions: 51 x 31 x 8cm • Weight: 5kg • Model: GC2-43	

Stove Model and Specifications	Stove Image
Rice Cooker An electrical appliance that imposes the necessary conditions for rice cooking. • Material: A stainless metal pot enclosed in a plastic housing • Weight: ~5kg Dimensions vary based on capacity	
Biogas Single and Double Burner A burner specifically designed for biogas • Materials: Stainless Steel body, cast iron burner • Dimensions: 30cm x 30cm x 10cm (approx.) and 60cm x 30cm x 10cm (approx.) • Weight: 2.5 – 4kg and 5 – 8kg	

3.5 Stove use monitoring

Stove Use Monitoring System (SUMS) were used to assess usage of various cooking appliances throughout this study. The device used as a Stove Use Monitor was the commercially available iButton, manufactured by Maxim Integrated. The iButton is small (the size of a watch battery), relatively robust, and easy to use. It contains a data-logger, real time clock, and solid-state temperature sensor. In this study, we utilized iButton model DS1922T with a maximum temperature of 120^{o}C. iButtons were synced to local time and set to log an instantaneous temperature every ten minutes. This sampling interval was chosen to maximize the number of days that could be logged to internal memory and to capture variability in temperature at a fine enough resolution to distinguish use from non-use periods. SUMs data were collected from up to three primary cooking devices during the 48-hour sampling period in all study homes. A subset of ACE-1 homes had additional SUMs, which were kept on all traditional stove types in homes for the duration of the study to show longer term usage of the stoves. All ACE-1 stoves were disseminated with SUMs, yielding 4 weeks of ACE-1 usage data for all households.

SUMs placement was guided by best practices described by Ruiz-Mercado (2012) and Mukhophadyay (2012). On ACE-1 stoves and bucket-type traditional stoves, SUMs were affixed directly to the stove. On the traditional type stoves only, if affixing to SUMs directly to the side of the stove was impossible, due to the exterior quality of the stove, the SUMs was attached to the handle of the stove, and angled to lie flush against the stove body.

The cooking events and duration per day per home of the four main cooking technologies was determined for each household. These technologies were the traditional stove, rice cooker, LPG, and introduced intervention technology (ACE-1 or biogas stove). A “use fraction” for each study group was determined by assessing the percentage of users that used the introduced technology at least 0.5 times per day, on average, over the 4 week adjustment and monitoring period. This “use fraction” is included in the HAPIT model to estimate health impacts of a scaled up stove program in a typical use scenario.

The analysis was performed using an R-based algorithm. The algorithm classifies periods of use as deviations from ambient temperature. After a subtraction of ambient temperature from each SUMS temperature trace, duration of use was counted as any point that fell above the “use threshold”, which was set at 2.5 times the standard deviation of the noise in the ambient temperature. Individual events were counted by finding where the temperature trace had one point below, and an adjacent point above, the “use threshold”, when the first derivative of the temperature curve was positive, implying the stove was heating up and being used, rather than cooling down. The temperature trace was smoothed using an hour long moving average to negate counting multiple events during natural temperature fluctuations from cooling and stoking of a stove during single cooking event, which are common in stove usage temperature curves (see Figure 3).

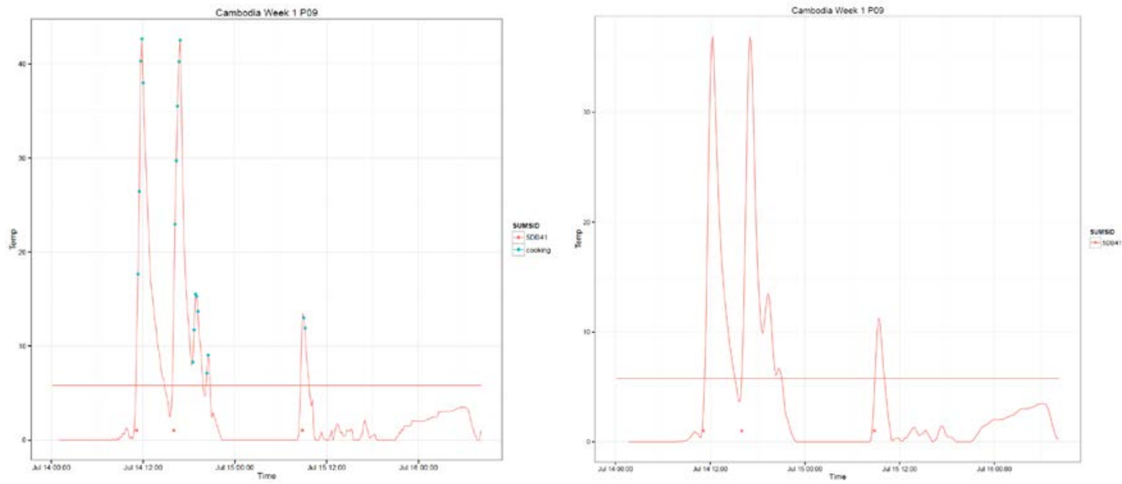

Figure 3. SUMS trace for a sample household during week 1 in Phnom Penh. The threshold for counting a SUMS peak as an event is indicated by the red horizontal line. Cooking duration is indicated by the blue dots on the SUMS trace. The unsmoothed trace would count the sums trace as containing four events over the two day sampling period (left). After smoothing out the variability in temperature fluctuations, the cooking events are actually three over the two day sampling period (right).

A "use fraction" was determined based on a lower threshold of ACE-1 "use" set at a minimum of 0.5 uses per day, or using the ACE-1 stove approximately every other day, on average. This number is used to identify the fraction of "regular users" among the study participants who likely drove the exposure reductions which will lead to health benefits associated with use of the ACE-1 stove. This fraction of the study population is used to scale the results of this study up to the total ACE-1 customer population. Individual participant's "use fraction" was determined by dividing the total number of usage events completed on the ACE-1, measured via SUMS, during the combined adjustment and monitoring periods by the total time that the measurements were made, which was approximately 30 days. A use fraction of 85% and 75% was determined in Phnom Penh and Samlout, respectively. The use fraction in biogas homes was 100%. These use fractions were used in the HAPIT model to determine health outcomes for scaled up stove programs.

Figure 4. An enumerator testing the flow rate of an AirCheck XR500 pump, used for gravimetric sampling.

3.6 $PM_{2.5}$ measurements

$PM_{2.5}$ was measured using both the gold standard gravimetric method and real-time light scattering method using the UCB particle and temperature sensor (UCB-PATS). All study participants' personal exposure was measured gravimetrically and their kitchens were fitted with UCB-PATS. A subset (25%) of kitchens also had gravimetric measurements co-located with pump and filter to determine adjustment coefficients needed to account for variability in physical particle properties, which impact light-scattering measurements.

Gravimetric pump and filter

Gravimetric personal exposure and KAP samples were collected for two consecutive 24-hour periods. Deposition of $PM_{2.5}$ was determined gravimetrically by weighing 2 µm pore size Teflon filters with PMP support rings (Pall Corporation) before and after sample collection in a constant humidity and temperature room on an electronic microbalance with 0.1 µg resolution (Mettler Toledo International, Inc., USA). Each filter sample was collected for approximately 24 hours by pulling air through them at a sampling at a rate of 1.5 liters per minute (LPM) using SKC AirCheck XR5000 pumps and BGI Triplex cyclones, which only allow particles 2.5 µm or smaller through to be collected on the filter media (Figure 4). All personal exposure samples were collected by this pump and filter method. In one quarter of homes, gravimetric KAP data was also collected.

Personal exposure monitoring

Participants were outfitted with a vest, designed to encase the pump at the lower back, with tubing connecting the pump to the cyclone holding the filter, affixed near the shoulder, to best emulate the breathing zone of the cook (Figure 5). Participants were instructed to wear the vest all day for the 48 hour monitoring period, except for bathing and sleeping, when they were instructed to hang the vest somewhere near them. A spot was designated and marked for hanging the vest at night while sleeping. A nail was placed nearby the bed if a convenient spot was not apparent. The vests were designed and manufactured in Cambodia with local feedback from Cambodian women with regard to the form factor.

Kitchen air pollution monitoring

Minute-by-minute kitchen $PM_{2.5}$ concentrations were recorded using a real-time, light scattering sensor called the UCB particle and temperature sensor (UCB-PATS). The UCB-PATS were placed in the participants' kitchen at approximately 1.0 meter from the stove and 1.5 meters above the floor, a standardized location meant to represent the approximate breathing zone of a woman standing near the stove. Environmental and contextual information that might impact indoor air quality was also collected during the studies, including kitchen volume, ventilation, and reports of other sources of indoor air pollution emitted during the monitoring period.

The UCB-PATS were calibrated by Berkeley Air at the Berkeley Richmond Field Station, using wood smoke prior to their use. During the study, the chamber containing the photoelectric detector was cleaned with isopropyl alcohol after every week.

Figure 5. A participant wearing the standard personal monitoring vest.

A subset of UCB-PATS samples was co-located with the pump and filter systems. A UCB-specific adjustment was determined based on the ratio of filter-based average $PM_{2.5}$ versus UCB-based $PM_{2.5}$ during the exact same monitoring period. This UCB-specific relationship corrects for any light scattering effects based on particle-specific optical properties. For UCBs which valid co-location coefficients do not exist, a global average is applied. Adjustment coefficients varied from 0.45 to 1.1, with an average of 0.82.

Ambient air pollution monitoring

Ambient $PM_{2.5}$ air pollution levels were determined by 24-hour gravimetric $PM_{2.5}$ samples in the vicinity of participating households using two AirMetrics MiniVol $PM_{2.5}$ samplers, which were used with 47mm diameter Teflon filters with 2µm 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. Two instruments simultaneously collected four back-to-back 24-hours samples each week of the study. They were installed in locations where they would be safe and would not be disturbed, such as on the roof of a home, in a tree, or on a pole. Each instrument was placed far apart from the other, while still within the parameters of the study area, in order to capture varying ambient conditions (Figure 2).

3.7 Fuel use approximation

Figure 6. Wood moisture reading being taken for fuel use approximation calculations.

On the first day of monitoring, in all households in both the biogas and ACE-1 study groups, the participants were asked to make a pile of fuel which represented the household fuel consumption on a typical day. All fuel types were included. The fuel piles were then weighed with calibrated Salter Brecknell ElectroSamson digital hanging scales which have a 45 kilogram (kg) capacity with a resolution of +/- 0.01 kg. To account for wood moisture in the final analysis, wood moisture readings of the fuel pile were taken using a dual pin moisture meter (Extech MO210) at three points on three randomly selected sticks in the fuel inventory. This method of recalled fuel consumption allows for changes in fuel use by the family to be approximated by comparing the 'before' and 'after' monitoring period fuel piles. For biogas, the biogas and control groups can be compared on a population level, however, is less indicative of real fuel savings since the study is unpaired.

The cross-sectional results from the biogas study are based on comparisons of population averages, which may not be as accurate. However, the sample size provides adequate power for the analysis to show statistically significant differences in the wood-used piles made by the biogas and control groups.

3.8 Quality assurance and survey methods

Survey methods

User perceptions surveys were administered with the goal of providing information related to perceived well-being impact. These surveys also contained time activity data in which participants related daily activities which may influence technical measurements. Surveys were designed in Do-Forms, a digital questionnaire application for mobile devices. Questions were both open and closed type, and also included enumerator observations. The Do-Forms 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.

Figure 7. An enumerator uses Do-Forms to complete a user perception survey.

During the first monitoring day in each location, surveys included questions regarding household descriptions, general stove usage practices, cooking behavior, kitchen and stove location, and health issues. On the second and third day in each study area, 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. During the 'after' monitoring of the ACE-1 sub-study, participants were asked a series of health and well-being questions describing their perceptions on health and time impacts since receiving the ACE-1. Biogas users were asked similar questions, in which they were asked to recall a time before having a biogas stove to compare to the present day environment.

Quality assurance

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 with built-in validation checks.
- 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.
- To ensure consistency each surveyor kept the same fuel scales and moisture meters throughout the study duration.
- Accuracy of data entry was checked on a randomly selected 10% sample of the data entry forms.

3.9 Data handling

Standardized sampling forms were used throughout field work to minimize errors during the process of linking data media ($PM_{2.5}$ filters, etc.) with corresponding household identifications, sample periods, and notes. Sampling forms were entered into an electronic database and quality assurance checks were done remotely by Berkeley Air's data quality specialist. Errors in the database were reconciled remotely by the field supervisor.

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

The default pump runtime for gravimetric samples was taken from the pump integrated timer, which was compared to the difference between recorded pump start and stop times. When discrepancies between these two methods greater than 10 minutes arose, these samples were manually examined to find any data entry errors. In a small number of samples, the pump's integrated timer was determined to be incorrect; in these cases, the difference in recorded start and stop time was used as the pump runtime. When no clear data entry error could be determined, the pump integrated timer was used as the default. Filter samples with runtimes greater than 28 hours or less than 20 hours were discarded in order to avoid samples unrepresentative of a full 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 -2.5 µg for the 'before' filters and -2.1 µg for the 'after filters, based on an average of 5 field blanks collected from each study period, was applied to all filters to account for changes in mass unrelated to particle deposition during sampling.

Mass concentration was then determined from the sample time, the mass deposition, and the average of the flow rate take before and after the sample (equation 1)

$$[PM_{2.5}] = \frac{M}{t * f} \quad \text{Eqn. 1}$$

M = mass deposition
t = sample time
f = flow rate

An ambient correction was applied to the personal exposure data to account for the difference in ambient $PM_{2.5}$ during the 'before' and 'after' monitoring, which was especially apparent in Phnom Penh. The adjustment reduced each exposure measurement by the weekly average ambient concentration per location. The overall study average for each site was then added to the location-specific exposure values. Under this method, the random variability in ambient concentrations will not bias the exposure results.

Co-located field adjustment

UCBs were collocated with pump and filter in ¼ of the KAP samples. Pump and filter data, the gold standard for measuring $PM_{2.5}$, was used to adjust the UCB data, which is less accurate. UCB, which is reliant on light scattering, is influenced by particle size, shape, and color, and so will change dependent on the stove, fuel, and other sources. By taking a direct measure of the smoke via pump and filter, a linear adjustment factor which accounts for the change in particle type can be applied to correct the data. In this case, UCB specific adjustments were applied based on the average of all colocations completed with a UCB during the study period. Particle types were thought to be driven mostly by the traditional stove-type smoke, as these were used in almost all study households over the entire study. Some UCBs co-location data was compromised, specifically in biogas households, due to low particle mass deposition and UCB measurement. For UCBs with no co-location data, a global average was applied. Adjustment coefficients varied from 0.45 to 1.1, with an average of 0.82.

Ambient correction

Minute-by-minute $PM_{2.5}$ data was adjusted based on a spatiotemporal correction of gravimetric ambient $PM_{2.5}$ data. The average ambient concentration was used to set the baseline UCB value, determined from a weekly average of the closest of the two ambient samplers. The detection limit of the UCB is 50 µg/m^3. Ambient concentrations were between 5.4 and 26 µg/m^3, meaning the low level baseline was not able to be measured accurately. When this is the case, the UCB data is set to its detection limit value of 50 µg/m^3, falsely inflating the 24-hour average value. The adjustment to manually set the baseline UCB concentrations to match the average weekly ambient $PM_{2.5}$ improved the accuracy of the UCB measurement, changing the average adjustment coefficient (the ratio of filter/UCB) from 0.61 before the adjustment to 0.82 after the adjustment.

Sums counting algorithm

Raw SUMS temperature data was processed using R, an open-source statistical computing software program. Data were organized based on sample location and household ID. All dates and times were converted to Indochina Time Zone. Ambient temperature was obtained by taking the lowest 15% quantile of all temperature data collected during sampling. A threshold temperature for determining cooking events and duration was set at 2.5 times of the standard deviation of ambient temperature, based on a visual assessment of appropriate event and duration counting. Temperature was corrected by subtracting the location-specific ambient temperature from all respective SUMS data. The corrected temperature was then smoothed, using a moving average over 50 minutes to avoid counting multiple events during a single event with fluctuating temperature stemming from cooling and stoking. Smoothed temperature was used to determine the number of cooking events and duration for each stove in participants' homes. Cooking events were counted when the smoothed temperature exceeds the threshold. Duration was counted when the smoothed temperature was above the temperature threshold and when the first derivative of the curve was positive, indicating the stove was heating up.

3.10 Sample exclusion

The final 48-hour ACE-1 PE sample size was 36 (Phnom Penh: N = 16 and Samlout: N = 20). Losses were due to participants that moved (N=1); homes which had different 'before' and 'after' primary cooks (N=1); technical pump and filter failures in one of the two 24 hour exposure samples in either the 'before' or 'after' monitoring period, eliminating the entire household (N = 6); or improper vest compliance, such as never wearing the vest or hanging the vest in the kitchen while not wearing it (N=4). An additional sub-set of households had KAP monitoring device malfunctions (N = 9), yielding a full KAP dataset of 27 households (Phnom Penh: N = 10 and Samlout: N = 17).

The final 48-hour biogas PE and KAP sample size was 23 in the control group and 24 in the biogas group. The only loss was due to a pump failure in one of the control household.

The analysis of 'Influences on exposure' (Section 5.3) included only households that were not excluded from the PE and KAP analysis. The 'Health perception' (Section 4.1) analysis was inclusive of every household in the study.

3.11 Imputed health effects and HAPIT

Pre- and post-intervention exposure data were input into the most recent version of 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.[1] Briefly, HAPIT utilizes (1) the integrated exposure-response curves (IERs) described by (Burnett et al., 2014) and (2) country specific burden of disease information from the Institute of Health Metrics and Evaluation[2] to estimate the health impact of an 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.

HAPIT uses user-input mean and standard deviation of pre- and post-intervention exposures to recreate an exposure distribution. 1000 pairs of pre- and post-intervention exposures are drawn from the recreated distributions; 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 is left due to air pollution exposures even after the intervention, i.e., what additional benefits could have been achieved if there had been 100 percent penetration of a truly clean cooking option, such as gas or electric cooking, in the same households.

HAPIT additionally can estimate program cost-effectiveness using a simple financial accounting approach that does not take into account household participation, discounting, adjustments such as tax breaks, and monetization of such benefits as reduced time spent acquiring fuel. It basically assumes a large subsidy by some donor or government agency, which is not necessarily what would occur in a program funded by private investors in Cambodia.

Cost-effectiveness is determined by comparing the expected annual cost of the intervention per DALY in United States dollars (USD) to the gross domestic product per capita (GDP PC, USD). The World Health Organization's Choosing Interventions that are Cost-Effective (WHO CHOICE)[3] effort advises that interventions costing less than the GDP/capita are very cost-effective; those costing one to three times the GDP/capita are cost-effective but require additional examination to compare feasibility across options. Those costing more than three times the GDP/capita are not cost-effective, i.e. may be pursued by the private health care system, but are not priorities for

[1] See https://hapit.shinyapps.io/HAPIT/
[2] http://www.healthdata.org/gbd
[3] More information on WHO CHOICE is available at http://www.who.int/choice/en/

public health. This is essentially a triage approach. All scenarios assume a stove dissemination program of 25,000 stoves, all installed instantaneously on the first day (January 1) of the first year of the program.

4 Results

4.1 Perceived Health and Well-Being

ACE-1

Perceived health impacts of traditional stove

During the baseline survey, all Phnom Penh households were asked if they thought that their primary cooking stove had an impact on their health. They were encouraged to consider positive, as well as negative, impacts. 78% (n=49) of households stated that they thought their primary cooking stove had an impact on health and 100% of those participants believed the health effects were negative (Table 3). When the respondents who reported negative impacts were asked to describe these further, just over one third (32%, n=19) indicated that they believed their stove affected their breathing. Other frequent self-reported symptoms included coughing (24%, n=14) and stinging and/or watering eyes (14%, n=8).

Table 3. Perceived health impacts of traditional stove in both study areas.

Believe traditional cookstove effects health (n=38)	**78%**
Reported Health Impacts	
Effects my breathing (n=19)	30%
Makes me cough (n=16)	25%
Eyes sting and water (n=8)	13%
Causes headaches (n=6)	09%
Other (n=15)	23%

When exploring the perceived impact of traditional cookstoves, the participants demonstrated a high level of awareness of the negative health effects of cooking with wood-burning traditional stoves. This awareness may be the result of educational strategies used by the dissemination program, which discussed the importance of using improved stoves to reduce smoke exposure.

Changes in heath since receiving the ACE-1 stove

When asked about whether their health had changed since receiving the ACE-1 stove, half (n=24) of all households thought that there had been changes. 100% of those households reported that the changes in health were positive. When the respondents who reported a change were asked to describe these further 46% (n=18) felt that their breathing had improved. Other commonly reported improvements in health included less coughing (15%, n=14) and less stinging and/or watering of the eyes and reduction in incidence of sore throats, both 10% (n=4).

Table 4. Perceived health impacts of the ACE-1 in both study areas.

Believe ACE-1 effected health in some way (n=24)	**50%**
Reported Health Impacts	
Breathing is improved (n=18)	46%
Less coughing (n=6)	15%
Eyes sting and/ or water less (n=4)	10%
Less sore throats (n=4)	10%
Less smoke (n=3)	8%
Fewer headaches (n=2)	5%
Other (n=2)	5%

Perceptions of cookstove safety

The ACE-1 stove was generally seen as safer than the baseline stove options. 77% (n=37) of households believed that the ACE-1 stove was safer than their previous primary stove and 21% (n=10) reported that they felt it was at the same safety level as their previous stove. Only one participant felt that the ACE-1 was less safe than their previous stove, the reason being that they believed it was more likely to tip and/or fall. The main reasons given for the improved perception of safety included that the stove produces less smoke and that the flames are more enclosed.

Table 5. Perceived safety of ACE-1 in both study areas.

Believe ACE-1 is more safe (n=37)	**77%**
Believe ACE-1 has the same level of safety (n=10)	**21%**
Believe ACE-1 is less safe (n=1)	**2%**

Reasons ACE-1 is more safe (n=37)	
Less smoke (n=27)	47%
Flames are more enclosed (n=17)	29%
Fuel does not fall from fire (n=6)	10%
Safer than LPG as no chance of explosion (n=3)	5%
Outside of stove does not get too hot (n=2)	3%

Burns to cooks

The incidence of burns was compared between the cooks using their traditional stoves in the month prior to the survey and the month after having received the ACE-1. With the traditional stove, 39% (n=19) of all households had suffered a burn. All were minor, but left 4 small scars. There was no one traditional baseline stove type that apparently caused more burns than another: The New Lao stove had the same number of reported burns as the Traditional Lao stove, both at 45% of total burns (n=9), with one other traditional cooking method causing a burn (10%, n=1).

In comparison, only 15% (n=7) of participants reported incidences of burns in the month after receiving the ACE-1 stove. Of these, 57% were burned when using the ACE-1 (n=4) with only one case resulting in a small scar. The adoption of the ACE-1 stove appears to have led to a reduction in the overall incidence of burns, however, the few remaining cases highlights the need for training and awareness to avoid such incidences when adapting to a new technology.

Reported changes in time given to cooking-related tasks

Time required to cook an average meal is made up of time spent actively tending the stove and pots, as well as the duration the stove is able to function unattended. If a stove reduces overall cooking time but requires constant attention, the overall gains in the cook's productivity may be limited. This phenomenon is measured by asking participants about their perceptions of changes in the time spent cooking next to the stove since the installation of the ACE-1. 67% (n=31) of households reported spending less time next to the stove per average meal cooked, 26% (n=12) reported spending the same amount of time next to the stove, and 7% (n=3) reported spending more time next to the stove.

Cleaning kitchen utensils, the stove, and the kitchen area can be a considerable burden for cooks, particularly when using an inefficient polluting biomass stove, which can create dirtier environments and tools, due to the deposition of incompletely combusted particulate matter. Half of participants 46% (n=22) reported to spend less time cleaning their stove and the other half reported spending more time cleaning their stove. The remaining participants 8% (n=4) reported spending the same amount of time cleaning their stoves. Further, 60% (n=29) of cooks reported spending less time cleaning the cooking area, and 49% (n=23) reported spending less time cleaning their pots.

Perceived changes in the amount of time taken to collect and/or purchase fuel were also explored with cooks. 43% of households (n=17) reported that less time was spent on procuring fuel, 50% (n=20) reported that they spent the same amount of time, and 3 participants said that they spent more time when compared to their traditional stove.

Biogas

Perceived health impacts of biogas stove

When asked about whether their health had changed since receiving the biogas stove, 42% (n=10) of households thought that there had been changes. 100% (n=11) of those households reported that the changes in health were positive. When the respondents who reported a change were asked to describe these further there were two reported heath impacts, 82% (n=9) felt that their breathing had improved and 18% (n=2) felt that their eyes watered less.

Table 6. Perceived health impacts of the biogas stove.

Believe biogas effects health in some way (n=10)	**42%**
Believe biogas does not affect health (n=14)	**58%**
Reported Health Impacts (n=11)	
Breathing is improved (n=9)	82%
Eyes watered less (n=2)	18%

Perceptions of cookstove safety

The biogas stove was generally seen as safer than the baseline stove options. 83% (n=20) of households believed that the biogas stove was safer than their previous primary stove and the remaining 17% (n=4) reported that they felt it was at the same safety level as their previous stove.

Table 7. Perceived safety of biogas in both study areas.

Believe biogas is more safe (n=20)	**83%**
Believe biogas has the same level of safety (n=4)	**17%**

Reasons biogas is more safe (n=37)	
Flames are more enclosed (n=12)	43%
Less smoke (n=11)	39%
Fuel does not fall from fire (n=2)	7%
Safer than LPG as no chance of explosion (n=2)	7%
Other (n=1)	4%

Burns to cooks

63% (n=15) of participants reported not having been burned during cooking in the past month. The remaining participants (38%, n=9) reported to having been burned in the past month, 100% of those burns occurred on the biogas stove.

Reported changes in time given to cooking-related tasks

96% (n=23) households reported spending less time next to the stove per average meal cooked, 4% (n=1) reported spending the same amount of time next to the stove, no biogas users reported spending more time next to the stove.

58% (n=14) of participants reported to spend less time cleaning their stove and 42 (n=10) reported spending more time cleaning their stove. Further, 54% (n=10) of cooks reported spending less time cleaning the cooking area, and 83% (n=20) reported spending less time cleaning their pots.

Perceived changes in the amount of time taken to collect and/or purchase fuel were also explored with cooks. 88% of households (n=21) reported that less time was spent on procuring fuel and 13% (n=3) reported that they spent the same amount of time. No participants reported to spending more time when compared to their traditional stove.

4.2 Difference in fuel consumption

ACE-1

Wood was the primary fuel used on stoves in both study groups and charcoal was also used in some households. Figure 8, shows the average mass of the approximated daily wood-used piles measured in Phnom Penh and Samlout. Analysis shows a large and statistically significant ($p=<0.003$) reduction in wood fuel consumption (kg/HH/day) after receiving the ACE-1 stove (52% savings Phnom Penh and 53% Samlout) (see Table 8 below).

Table 8. Fuel use before (baseline) and after ACE-1 introduction

	Wood Fuel	
Baseline	**Phnom Pehn kg/HH-day**	**Samlout kg/HH-day**
Mean	2.6	3.4
SD	1.5	1.6
COV	0.55	0.47
ACE-1		
Mean	1.3	1.6
SD	0.8	1.3
COV	0.63	0.81
Percent difference	-52%	-53%
p-value	0.003	0.003

*Paired sample T-test. N = 25 in Phnom Penh and 24 in Samlout.

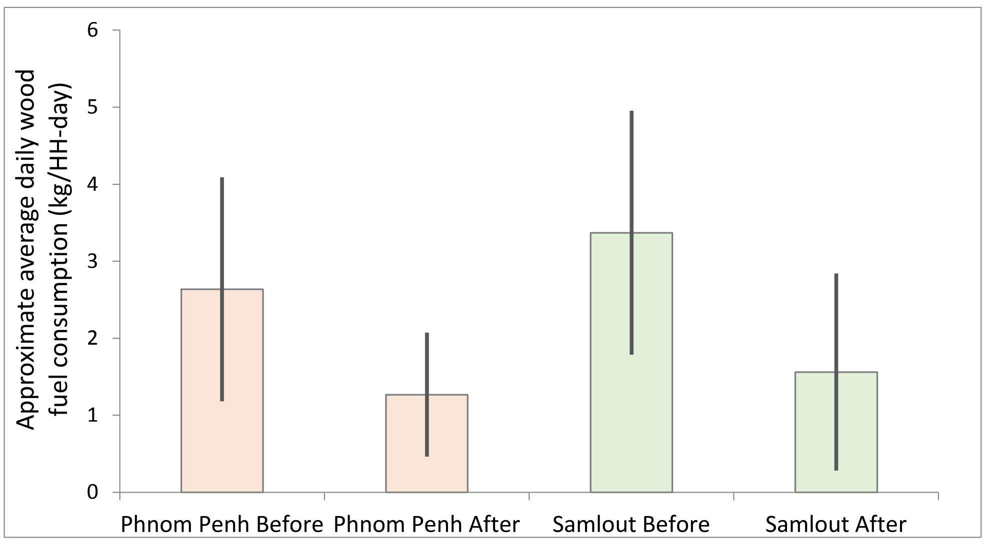

Figure 8. Wood fuel use in terms of kilograms per household per day.

Biogas

Wood was the primary fuel used on the control group stoves, with one household using some charcoal. Biogas was the primary fuel used in the biogas group (Table 9).

Table 9. Fuel use comparing control and biogas households

Wood Fuel	
Control (n=24)	**kg/HH-day**
Mean	2.8
SD	1.2
COV	0.4
Biogas (n=24)	
Mean	1.3
SD	2.0
COV	1.6
Percent difference	-55%
p-value	0.01

*Independent samples T-test. N = 25 in both study groups.

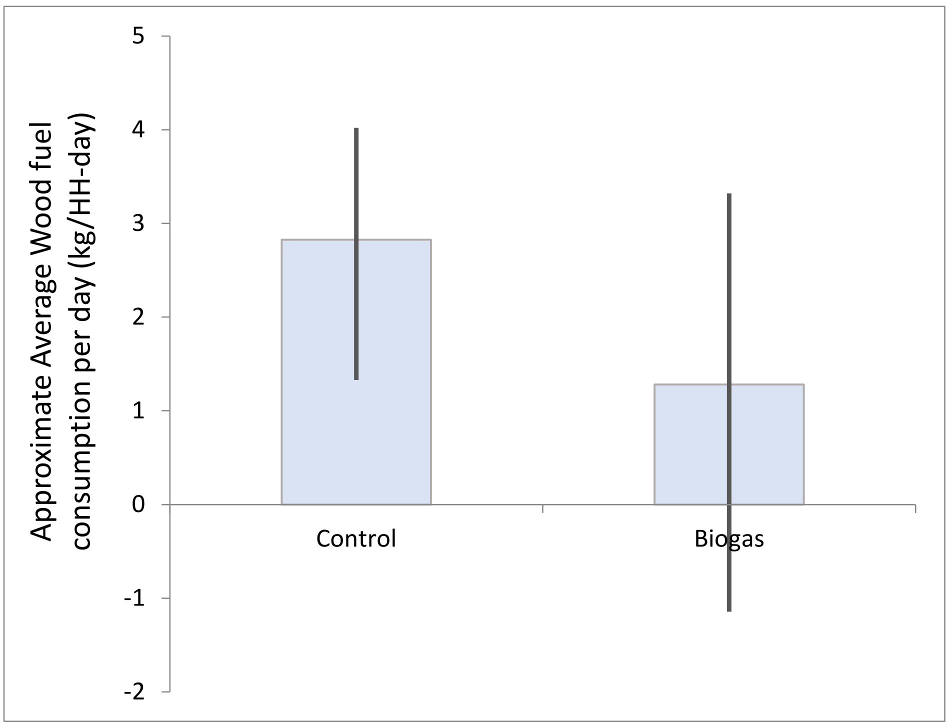

Figure 9. Wood fuel use in terms of kilograms per household per day for control and biogas households.

4.3 Stove use

ACE-1 Study

Stove usage monitoring (SUMS) data revealed stove stacking to be common in Phnom Penh and Samlout homes, both before and after ACE-1 stove dissemination. Approximately half the homes studied in Phnom Penh had two or more traditional stoves, which were fitted with SUMS. LPG stoves and rice cookers were also commonly used to achieve daily cooking tasks. Upon introduction of the ACE-1 stove, many users incorporated ACE-1 use into their daily cooking routine, displacing some, but not all, cooking tasks generally carried out on the traditional stove. From Figure 10, LPG usage has stayed fairly consistent between before and after monitoring periods. Rice cooker usage appears to have gone up slightly in the after monitoring, however, our sample size for those using rice cookers was small (N=1 ‘before’, and N=3 ‘after’) and may not be related to ACE-1 use. From Figure 10, it is clear that the traditional stove is being used less by Phnom Penh participants after receiving the ACE-1. They are using the traditional stove about 1.5 hours, or 1.2 times, less per day, which corresponds to similar rates of ACE-1 use, around 1.6 hours, or 1.4 events, per day. This relatively equal displacement of the traditional stove by the ACE-1 stove shows that, although not all cooking tasks could be done on the single ACE-1 stove held by each participant, some tasks which used to be completed on the traditional stove were being cooked on the ACE-1.

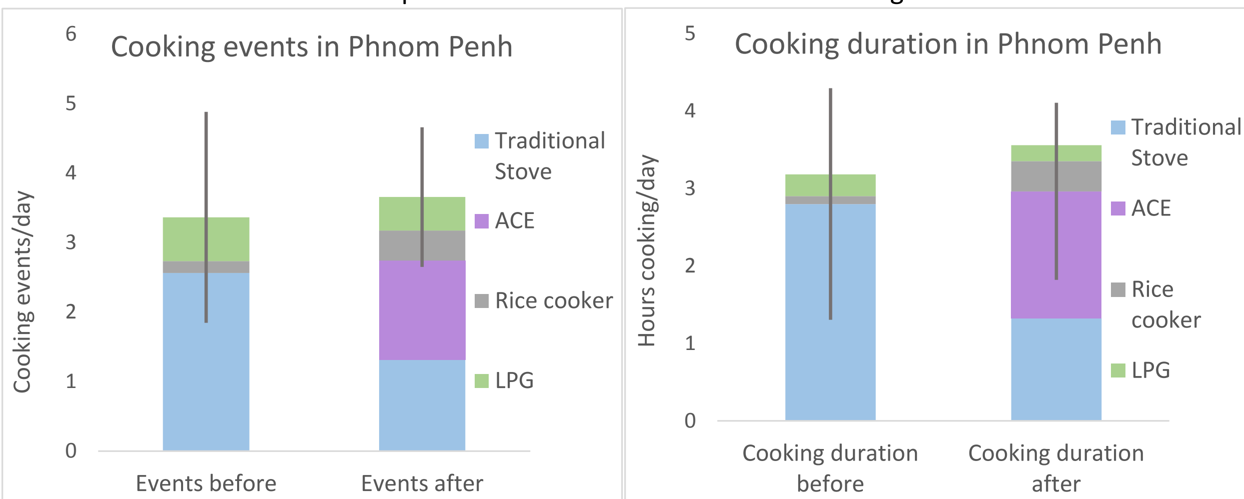

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Figure 10. Stove usage and stacking, in terms of cooking events per day (left) and hours cooked per day (right), before and after ACE-1 stove introduction in Phnom Penh. Error bars are ±1 SD. Cooking events and duration of the respective cooking technologies are based on the entire participant pool (N=16), regardless of their ownership of the cooking technology.

Table 10 shows the absolute event number and duration of cooking events based on participants who owned the corresponding cooking technologies. You can see from this table that those who kept using their traditional stoves during the ‘after’ monitoring (N=10), still relied heavily on the traditional stove, using it for about 2 hours per day. That the remaining six participants continued to use an unmonitored traditional stove also always remains a possibility. The use fraction in Phnom Penh that was used in the HAPIT model was 87.5%, based on the threshold of “use” set at 0.5 uses per day, on average.

Table 10. Stove usage statistics in Phnom Penh before and after ACE-1 stove introduction for users who own the given cooking technology.

	Stove Use in Pnom Penh						
	Before			After			
	Traditional	LPG	Rice cooker	ACE	Traditional	LPG	Rice cooker
Average event number per day*	2.6	1.1	2.7	1.4	2.1	1.0	2.3
SD	1.5	1.1	-	0.67	1.0	1.0	0.90
N	16	9	1	16	10	8	3
Average cooking duration (hours)*	2.8	0.50	1.6	1.6	2.1	0.41	2.1
SD	1.5	0.64	-	0.93	1.1	0.49	1.7
N	16	9	1	16	10	8	3
Total Use Fraction‡	87.5%						

*Based on participants who owned one or more of the corresponding cooking technologies.
‡ Based on a lower threshold of, on average, 0.5 usage events per day over the four week adjustment period and ‘after’ study monitoring

In Samlout, closer to 85% of homes had more than one traditional stove, and relied less on more advanced technologies, such as rice cookers and LPG stove. The displacement of traditional stoves by the ACE-1 stove observed in Samlout was less than that in Phnom Penh. Traditional stove usage went down by about 0.3 events, and 0.3 hours, per day. This small reduction in traditional stove use was accompanied by average ACE-1 use of about 1 event, lasting about an hour, per day. The introduction of the ACE-1 appears to have, overall, resulted in more cooking by Samlout participants.

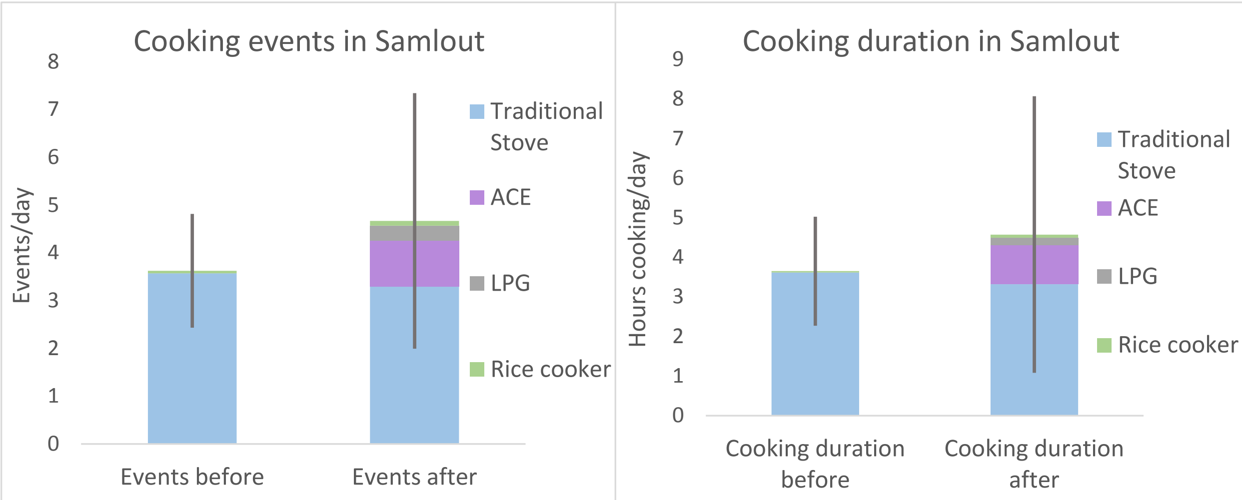


Figure 11. Stove usage and stacking, in terms of cooking events per day (left) and hours cooked per day (right), before and after ACE-1 stove introduction in Samlout. Error bars are ±1 SD. Cooking events and duration of the respective cooking technologies are based on the entire participant pool (N=20), regardless of their ownership of the cooking technology.

Table 11, which shows the absolute event number and duration of cooking events based on participants who owned the corresponding cooking technologies, shows more Samlout users than Phnom Penh users continued to use their traditional stove, a total of 17 out of 20. These 17 participants continued to use their traditional stove at high rates, on average, 3.9 hour-long events per day. In Samlout the usage rate was lower, at 75%

Table 11. Stove usage statistics in Samlout before and after ACE-1 stove dissemination for users who own the given cooking technology.

	Stove Use in Samlout						
	Before			After			
	Traditional	LPG	Rice cooker	ACE	Traditional	LPG	Rice cooker
Average event number per day*	3.6	0.0	1.0	1.0	3.9	3.1	2.0
SD	1.2	-	-	0.59	2.7	1.6	-
N	20	1	1	20	17	2	1
Average cooking duration (hours)*	3.6	0.0	0.6	1.0	3.9	1.8	1.7
SD	1.4	-	-	0.9	3.5	0.2	-
N	20	1	1	20	17	2	1
Total Use Fraction‡	75%						

*Based on participants who owned one or more of the corresponding cooking technologies.
‡ Based on a lower threshold of, on average, 0.5 usage events per day over the four week adjustment period and 'after' study monitoring

Biogas Study

Figure 12 shows the stove usage trend in biogas homes and the neighboring control household. Homes with a biodigester used the traditional stove significantly less ($p<0.05$), both in terms of events (1.8 less events per day) and time (2.6 hours less per day). Homes with biogas used biogas stoves for 87% of cooking events, which equated to 81% of their time spent cooking. Biogas users tended to have more cooking events in a day (4.8) versus control users (2.5), likely due to the ease of lighting and extinguishing a biogas stove versus a traditional stove. The overall cooking time per day was similar, though, with biogas users cooking, on average, 2.8 hours per day and control homes cooking 3.2 hours per day. Rice cookers and LPG were used very infrequently in either the biogas or control homes.

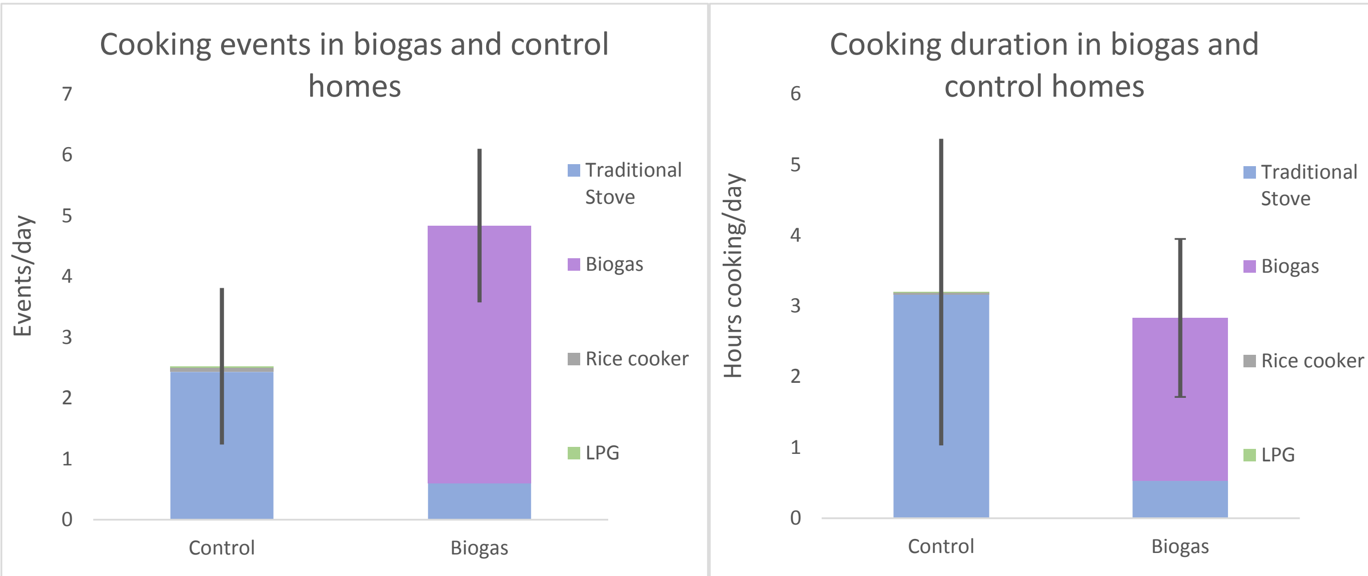


Figure 12. Stove usage and stacking, in terms of cooking events per day (left) and hours cooked per day(right), for the control and biogas study groups. Error bars are ±1 SD.

Table 12 shows the events and duration of use by participants that owned at least one of the respective cooking technologies. Only half of the biogas users continued to use traditional stoves, and only used them about 30% as frequently as the biogas stove, and only for about half as long. Of the biogas owners, 100% used their biogas stove at least 0.5 times per day.

Table 12. Stove usage statistics in control and biogas homes.

	Control			Biogas		
	Traditional	LPG	Rice cooker	Traditional	LPG	Biogas
Average event number per day*	2.4	0.53	0.51	1.2	0.0	4.2
SD	1.3	0.54	-	0.9	-	1.3
N	23	3	1	12	1	24
Average cooking duration (hours)*	3.2	0.24	0.17	1.1	0.0	2.3
SD	2.2	0.27	-	1.1	-	1.0
N	23	3	1	12	1	24
Total Use Fraction‡	100%					

*Based on participants who owned one or more of the corresponding cooking technologies.
‡ Based on a lower threshold of, on average, 0.5 usage events per day over the four week adjustment period and 'after' study monitoring

4.4 Kitchen air pollution

ACE-1 Study

The effect on $PM_{2.5}$ kitchen air pollution (KAP) by the ACE-1 stove after its dissemination was statistically similar in the Phnom Penh and Samlout study regions ($p = 0.84$), so the two locations were analyzed as a single group. KAP measurements are based on 48-hour sampling periods just before the ACE-1 stove dissemination and then again 4 weeks after dissemination.

Table 13 shows that before the introduction of the ACE-1, KAP was 183 ± 160 μg/m^3, compared to the average 'after' monitoring $PM_{2.5}$ levels of 111 ± 102 μg/m^3. The statistically significant reduction of KAP between 'before' and 'after' ACE-1 dissemination, based on the difference of means, was 39% or 72 μg/m^3 ($p = 0.015$).

Table 13. KAP statistics of paired ACE-1 participant homes before and after ACE-1 stove introduction.

	Before KAP	After KAP
Mean (μg/m^3)	183	111
Lower 95% Confidence Interval (CI) (μg/m^3)	123	73
Upper 95% Confidence Interval (CI) (μg/m^3)	243	149
Min (μg/m^3)	29	14
Max (μg/m^3)	641	428
Median (μg/m^3)	147	82
SD (μg/m^3)	160	102
COV	87%	91%
N	27	27

Change in KAP	
Difference of means	
Absolute (μg/m^3)	Percent change
72	39%
Difference of medians	
Absolute (μg/m^3)	Percent change
66	45%
p-value*	
0.015	

*Based on paired students t-test.

Figure 13 shows the paired $PM_{2.5}$ KAP distribution for all 27 homes that have complete 48 –hour gravimetric exposure data and accurate KAP measurements. The distribution is positively skewed in both the 'before' and 'after' cases. There is substantial overlap between the two distributions, implying there are 'before' kitchens that have lower $PM_{2.5}$ concentrations than 'after' kitchens, along with the more-expected inverse relationship. The variability seems slightly greater in the 'before' kitchens than the after, with both of the groups demonstrating two high KAP outliers.

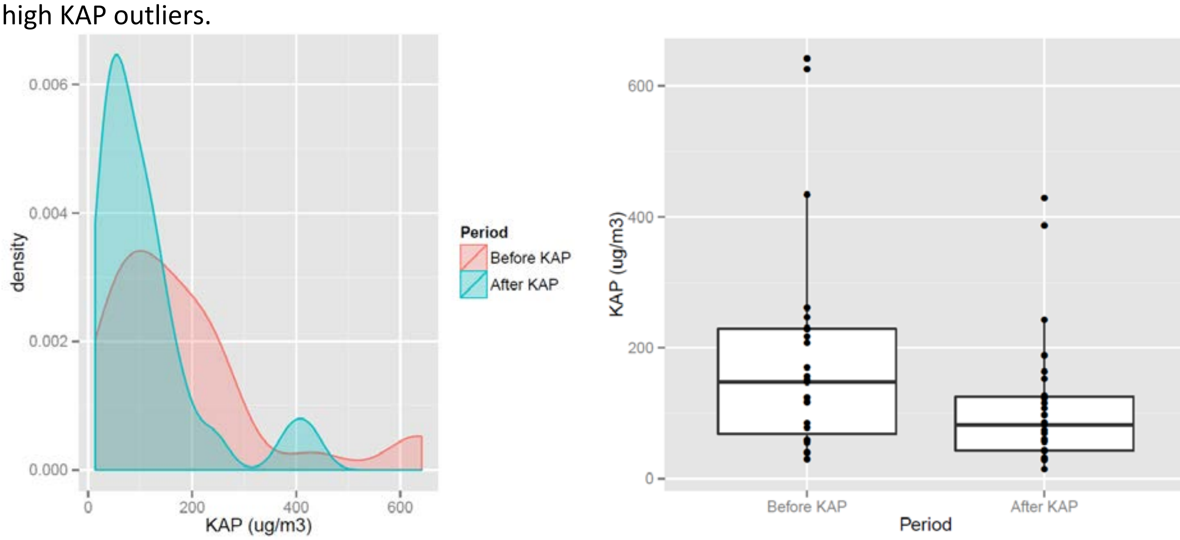


Figure 13. (a) Distribution of paired 48-hr kitchen $PM_{2.5}$ concentrations (KAP) samples before and after the introduction of the ACE-1 stove. The x-axis shows the KAP concentration and the y-axis shows the measurement frequency. (b) A boxplot of the distribution for 'before' and 'after' monitoring show the KAP on the y-axis, with the median value indicated by the middle line, and the 1st and 3rd quartiles shown by the upper and lower 'hinges'. The whiskers show points ±1.5 times the inter quartile range (IQR) from the hinges. Outliers >1.5*IQR can be seen beyond the whiskers. Individual points are plotted along with the boxplots.

Figure 14 shows the KAP values of the individual homes for which a complete 48 hour exposure/KAP dataset exists. The purple bars denote the 48 hour KAP levels before the ACE-1 stove was disseminated and the blue bars denote a 48 hour period four weeks after the ACE stove was introduced. Although many of the households showed reduced KAP during the 'after' period, a number of homes demonstrate similar, or increasing, KAP concentrations. Reasons for increased KAP may include more cooking done during the 'after' monitoring than the 'before' monitoring, coupled with continual use of the traditional stove; increased additional sources of $PM_{2.5}$ existing in the vicinity, such as trash or crop burning; and changes in the fuel types used, such as a switch from charcoal to wood between the 'before' and 'after' monitoring period, with wood typically producing $PM_{2.5}$ at higher rates than charcoal.

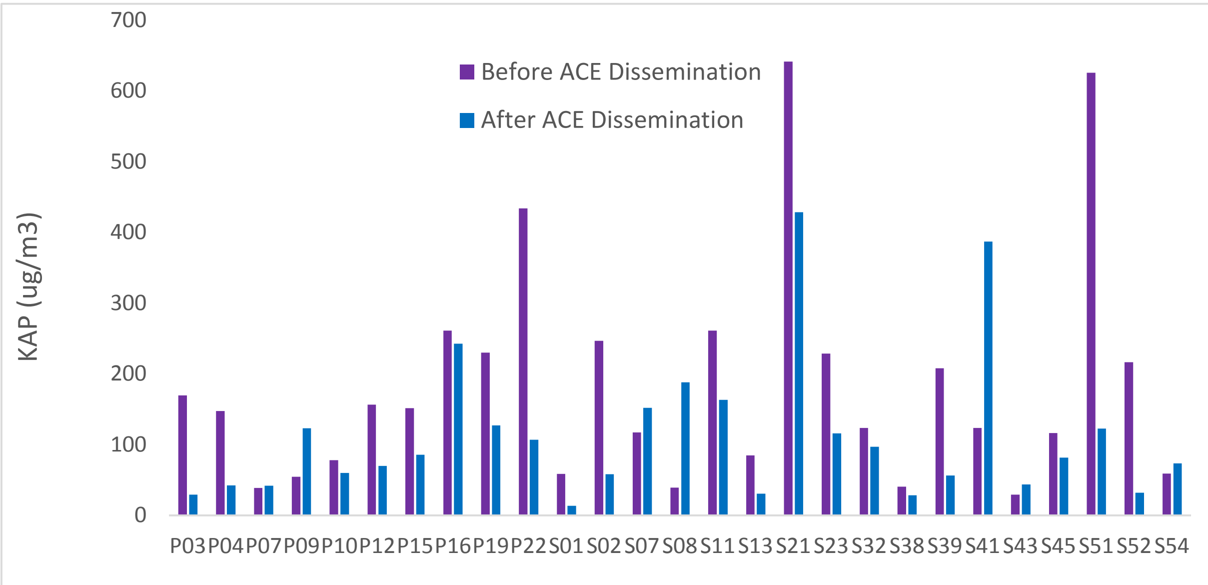


Figure 14. $PM_{2.5}$ kitchen air pollution (KAP) concentrations, shown on the y-axis, before (purple) and after (blue) ACE-1 stove dissemination for all of the 27 homes involved in the study with full 48-hour gravimetric exposure data and valid KAP measurements. Houheholds IDs are on the x-axis, those starting with 'P' represent Phnom Penh homes and those with 'S' are samlout homes.

Biogas study

The cross-sectional biogas study resulted in 21 control households and 18 biogas households with full 48-hour gravimetric exposure samples and valid KAP measurements. The control and biogas households demonstrated average $PM_{2.5}$ KAP concentrations of 172 ± 216 µg/m^3 and 35 ± 37 µg/m^3, respectively. The biogas kitchens showed a statistically significant reduction in $PM_{2.5}$ of 137 µg/m^3, or 80%, compared to the control households, which were still relying on traditional biomass stoves ($p = 0.012$).

Table 14. Statistics of un-paired biogas and control homes of $PM_{2.5}$ KAP measurements.

	Control KAP	Biogas KAP
Mean (µg/m^3)	172	35
Lower 95% Confidence Interval (CI) (µg/m^3)	80	18
Upper 95% Confidence Interval (CI) (µg/m^3)	265	52
Min (µg/m^3)	18	8
Max (µg/m^3)	867	165
Median (µg/m^3)	80	25
SD (µg/m^3)	216	37
COV	126%	105%
N	21	18

Change in KAP	
Difference of means	
Absolute (µg/m^3)	Percent change
137	80%
Difference of medians	
Absolute (µg/m^3)	Percent change
54	68%
p-value*	
0.012	

*Based on unpaired students t-test, with unequal variance.

Figure 15 shows the distribution of 48-hour $PM_{2.5}$ KAP in biogas and control households. The distributions are positively skewed for both of the study groups, with three high outliers in the control group and one in the biogas group. The KAP in the biogas group shows much lower variability than the control group, with a high frequency of KAP measurements falling close to the median value of 25 µg/m^3. The small overlap in biogas and control homes means that there were some control kitchens which exhibited KAP levels equal to, or less than, biogas kitchens over the 48-hour measurement period.

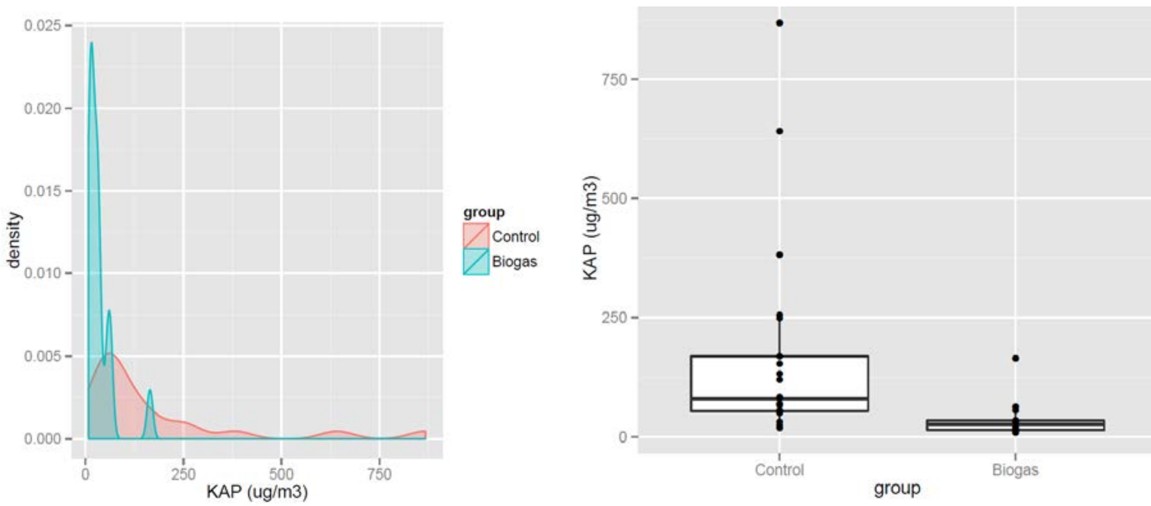


Figure 15. (a) Distribution of unpaired 48-hr kitchen $PM_{2.5}$ concentrations (KAP) samples of biogas users and control households using traditional stoves. The x-axis shows the KAP concentration and the y-axis shows the measurement frequency. (b) A boxplot of the distribution for biogas and control monitoring show the KAP on the y-axis, with the median value indicated by the middle line, and the 1st and 3rd quartiles shown by the upper and lower 'hinges'. The whiskers show points ±1.5 times the inter quartile range (IQR) from the hinges. Outliers >1.5*IQR can be seen beyond the whiskers. Individual points are plotted along with the boxplots.

4.5 Personal exposure of the cooks

ACE-1 Study

The effect on $PM_{2.5}$ personal exposure (PE) by the ACE-1 stove after its dissemination was statistically similar in the Phnom Penh and Samlout study regions (p = 0.38), so the two areas were analyzed as a single group. Table 15 shows that the PE in the 'before' monitoring period was, on average, 66 ± 43 µg/m^3, whereas during the 'after' monitoring PE was 47 ± 37 µg/m^3. The 'after' monitoring showed a statistically significant reduction of PE by 19 µg/m3, or 28% (p = 0.036), which is an improvement on the already relatively low exposure seen during the 'before' monitoring.

Table 15. Statistics of $PM_{2.5}$ personal exposure (PE) of paired ACE-1 homes 'before' and 'after' ACE-1 stove dissemination.

	Before PE	After PE
Mean (µg/m^3)	66	47
Lower 95% Confidence Interval (CI) (µg/m^3)	52	35
Upper 95% Confidence Interval (CI) (µg/m^3)	80	59
Min (µg/m^3)	16	13
Max (µg/m^3)	177	216
Median (µg/m^3)	55	42
SD (µg/m^3)	43	37
COV	66%	77%
N	36	36

Change in PE	
Difference of means	
Absolute (µg/m^3)	Percent change
19	28%
Difference of medians	
Absolute (µg/m^3)	Percent change
13	23%
p-value*	
0.036	

*Based on paired students t-test.

The distribution of PE before and after ACE-1 stove dissemination in the full 48-hour paired sample set is shown in Figure 16. The large overlap between the two distributions in Figure 16a indicates there are still many participants with similar exposure values in the 'after' monitoring as the 'before' monitoring, however, the longer positively skewed tail in the 'before' monitoring shows that there are still many ACE-1 users whose PE was reduced in the 'after' monitoring. The boxplots in Figure 16b show a reduction in the median PE from the 'before' to the 'after' monitoring, but also indicates that, among all of the exposure measurements both 'before' and 'after', the highest PE was measured in the 'after' period.

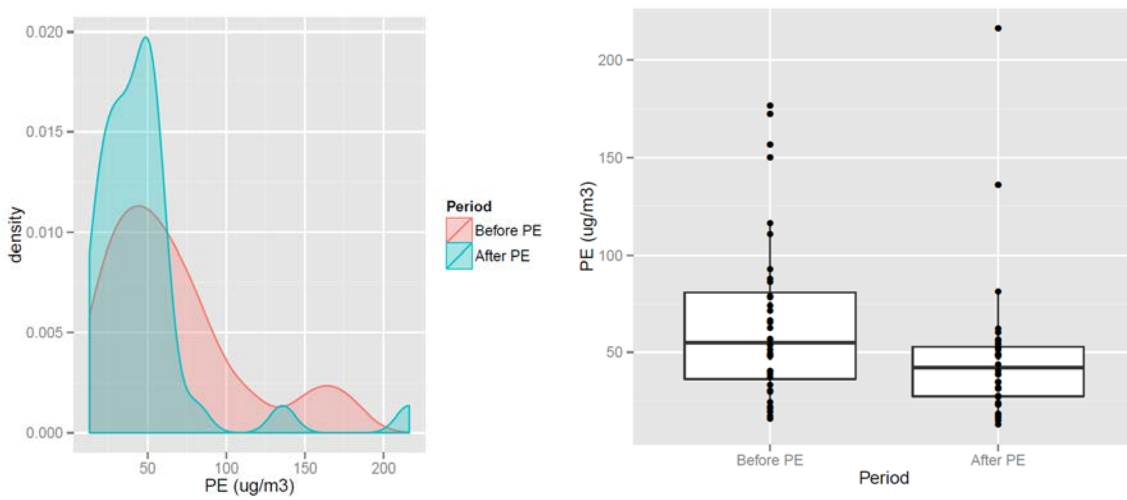


Figure 16. (a) Distribution of paired 48-hr $PM_{2.5}$ personal exposure (PE) samples before and after the introduction of the ACE-1 stove. The x-axis shows the PE concentration and the y-axis shows the measurement frequency. (b) A boxplot of the distribution for 'before' and 'after' monitoring show the PE on the y-axis, with the median value indicated by the middle line, and the 1st and 3rd quartiles shown by the upper and lower 'hinges'. The whiskers show points ±1.5 times the inter quartile range (IQR) from the hinges. Outliers >1.5*IQR can be seen beyond the whiskers. Individual points are plotted along with the boxplots.

The full set of valid, 48-hour average 'before' (purple) and 'after' (blue) PE values measured in Phnom Penh and Samlout are shown in Figure 17. While most PE values were lower in the 'after' monitoring than the 'before' monitoring, there were several samples with similar, or higher, PE. Reasons for higher PE may be: exposure to a greater number of smoke sources, such as cigarettes or neighbors cooking; more cooking or increased frequency of tending the remaining traditional stove; or changes to a fuel type which emits more $PM_{2.5}$. Sample S46 is one extreme example of the inverse of what's expected with the introduction of a cleaner cooking technology. Investigation into this sample didn't reveal anything out of the ordinary to explain this unexpected behavior.

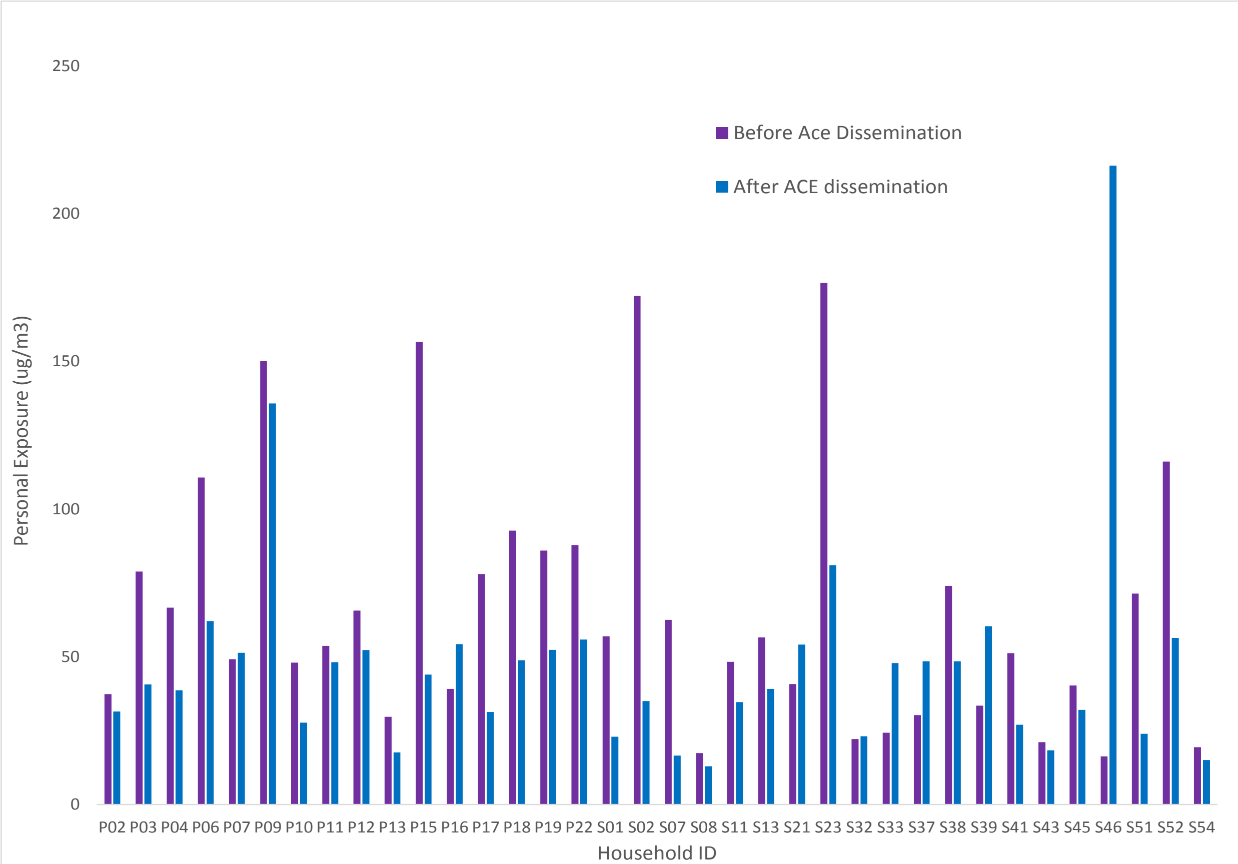


Figure 17. $PM_{2.5}$ personal exposure (PE) concentrations, shown on the y-axis, before (purple) and after (blue) ACE-1 stove dissemination for all of the 36 homes involved in the study with full 48-hour gravimetric exposure data measurements. Houheholds IDs are on the x-axis, those starting with 'P' represent Phnom Penh homes and those with 'S' are samlout homes.

Biogas study

Table 16 shows the measures of spread for the PE in the biogas and control study groups. On average, PE was 73 ± 85 μg/m^3 in the control group, whereas for the biogas users it was 28 ± 10 μg/m^3. The biogas users PE was statistically lower than the control group by 45 μg/m3, or 61% (p = 0.023).

Table 16. Statistics of $PM_{2.5}$ personal exposure (PE) of unpaired biogas user homes and control homes using the traditional biomass stove.

	Control PE	Biogas PE
Mean	73	28
Lower 95% Confidence Interval (CI)	38	24
Upper 95% Confidence Interval (CI)	108	32
Min	15	13
Max	362	51
Median	50	26
SD	85	10
COV	116%	36%
N	23	24

Change in PE	
Difference of means	
Absolute	Percent change
45	61%
Difference of medians	
Absolute	Percent change
24	47%
p-value*	
0.023	

*Based on unpaired students t-test, with unequal variance.

The distributions of the biogas and control groups in Figure 18a show two discreet peaks which don't overlap, implying a discernable difference between the groups. There is still some overlap at the lower PE concentrations, where the control group has PE similar or lower than biogas users. Figure 18b shows that the control group has some large outlier PE measures, whereas the biogas PE values are all within a relatively normal distribution range, with very little positive skew.

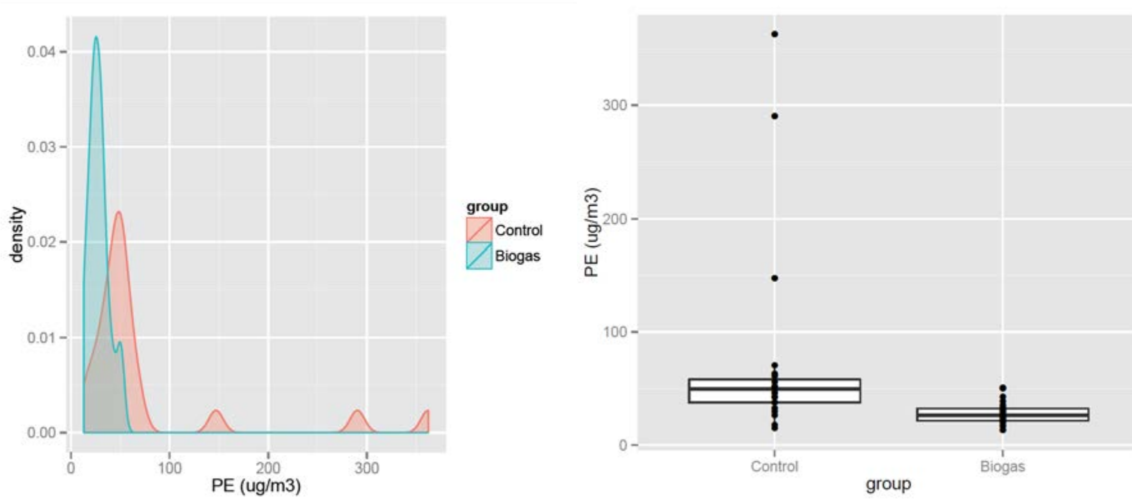


Figure 18. (a) Distribution of unpaired 48-hr $PM_{2.5}$ personal exposure (PE) samples of biogas users and control households using traditional stoves. The x-axis shows the PE concentration and the y-axis shows the measurement frequency. (b) A boxplot of the distribution for biogas and control monitoring show the PE on the y-axis, with the median value indicated by the middle line, and the 1st and 3rd quartiles shown by the upper and lower 'hinges'. The whiskers show points ±1.5 times the inter quartile range (IQR) from the hinges. Outliers >1.5*IQR can be seen beyond the whiskers. Individual points are plotted along with the boxplots.

4.6 Relationship between kitchen air pollution and personal exposure

The relationship between personal exposure and kitchen air pollution may help in future assessments of aDALYs by using KAP as a proxy for PE under some previously proven model. The simplest possible relationship between these two measurements would be a linear regression model. When plotting this relationship, personal exposure versus kitchen air pollution for all groups and phases, no clear relationship emerges (Figure 19). The R^2 value, which assesses how well a regression line fits the data (with 1 being the best possible fit), for the different groups and phases of the study are between 0.0007 and 0.2. The inability to fit a line relating the KAP and PE data sets implies a much more sophisticated model would be required to approximate PE from KAP.

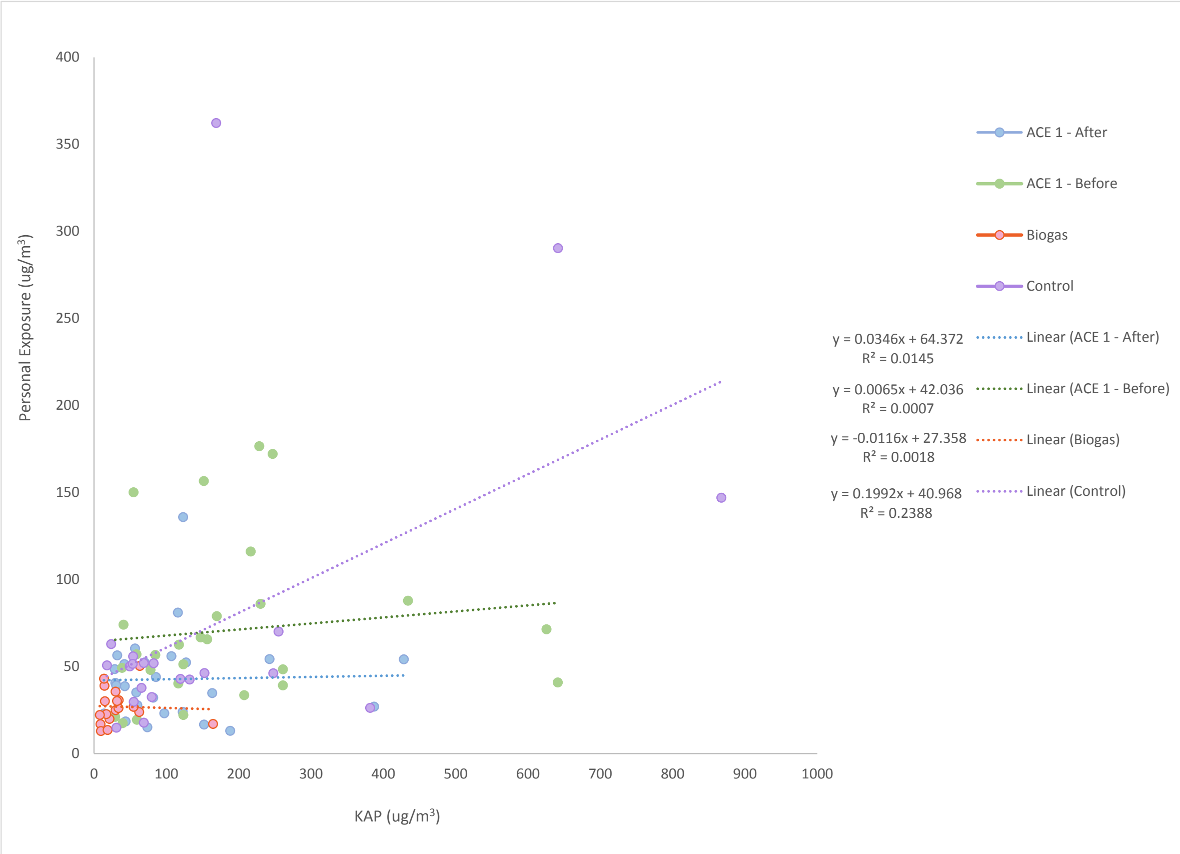


Figure 19. Linear regression of personal exposure versus kitchen air pollution for all groups and phases of this study.

4.7 Ambient air pollution

As shown in Table 17 and Table 18, a small difference in ambient air pollution 'before' versus 'after' was observed in both Phnom Penh and Samlout (-9 µg/m^3 for Phnom Penh and 2 µg/m^3 for Samlout). The difference in Phnom Penh was statistically significant ($P<0.05$), however, the difference in Samlout was not ($p=0.4$). Changes in ambient PM may be due to changes in weather or wind patterns, or increased point sources in the vicinity (i.e. increased production by the nearby charcoal factory, more trash burning or heating, etc.). Contextual information to assess reasons for changes in ambient PM was not collected and is outside of the scope of this project.

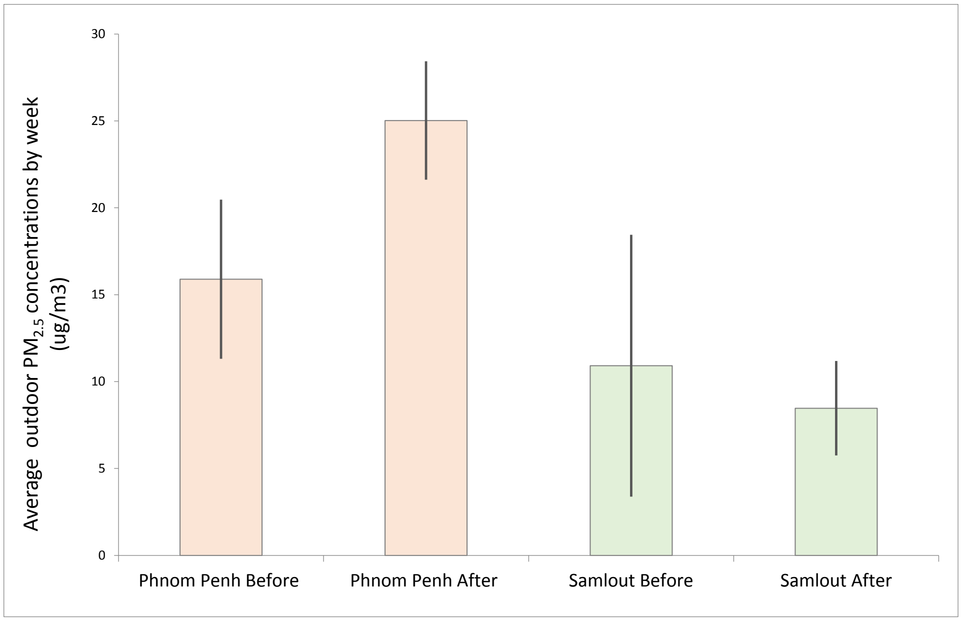


Figure 20. Average outdoor $PM_{2.5}$ concentrations (µg/m^3) by week shown on the y-axis and the 'before' and 'after' of the Samlout and Phnom Penh study areas.

Table 17. Summary statistics for out ambient $PM_{2.5}$ concentrations in the study region, by sampling period.

Ambient Outdoor $PM_{2.5}$ Concentrations	Phnom Penh Before	Phnom Penh After	Samlout Before	Samlout After
Mean (ug/m^3)	16	25	11	8.5
SD (ug/m^3)	4.6	3.4	7.5	2.7
N	6.0	7.0	8.0	8.0
Lower 95% CI (ug/m^3)	12	23	5.7	6.6
Upper 95% CI (ug/m^3)	20	28	16	10
Max (ug/m^3)	22	30	23	13
Min (ug/m^3)	12	21	3.9	6.2
Med (ug/m^3)	14	24	8.7	7.2
COV	0.29	0.14	0.69	0.32

Table 18. Student t-tests for changes in outdoor $PM_{2.5}$ concentrations between sampling periods.

Difference Between Average Before and After Concentrations	Mean Difference (µg/m^3)	p-value (unpaired)
Phnom Penh	-9	0.00
Samlout	2	0.40

4.8 Estimated health benefits

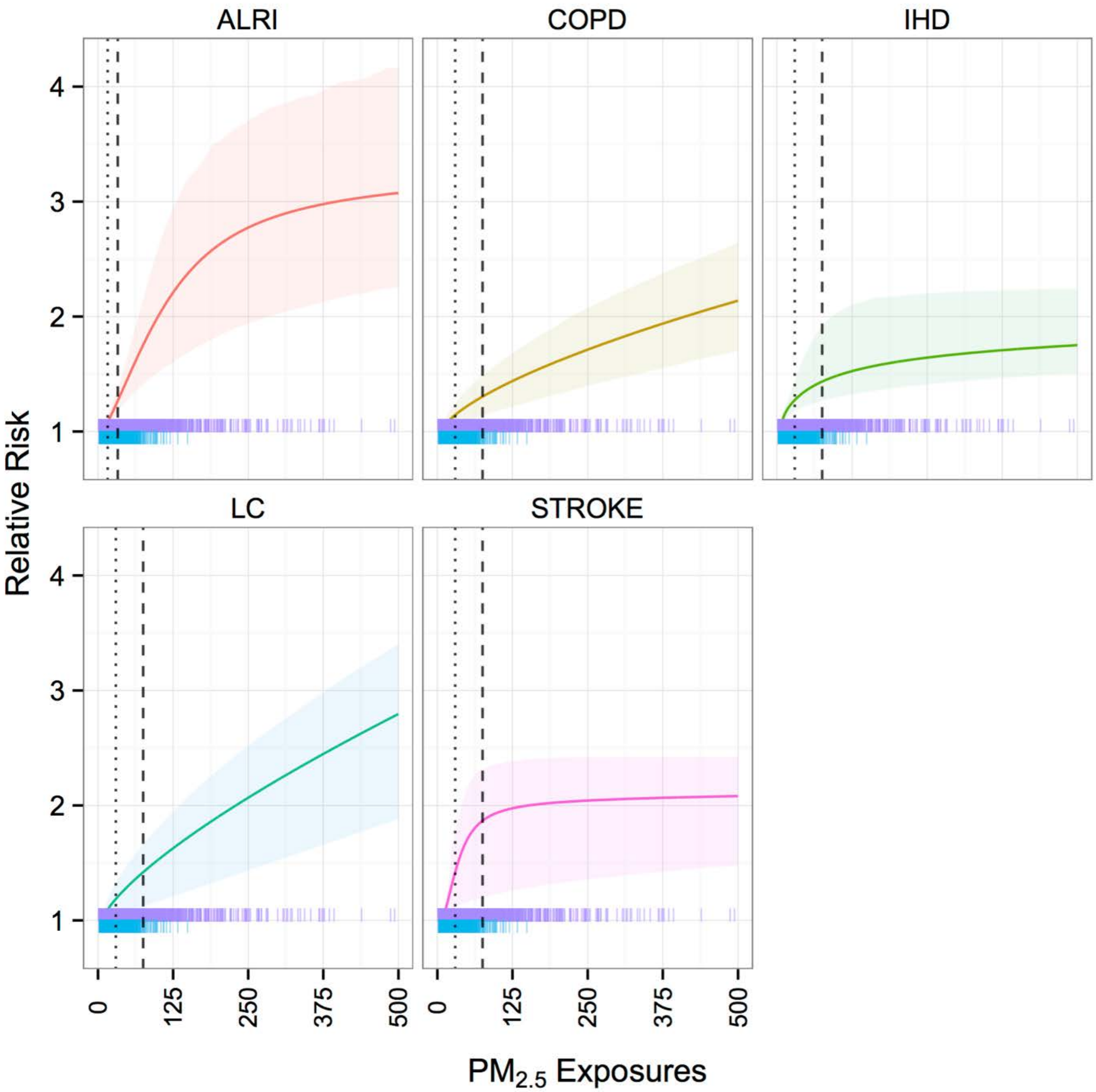
Pre- and post-intervention exposure data were estimated using the Household Air Pollution Intervention Tool (HAPIT) as described in methods. HAPIT was customized to output estimates under multiple intervention scenarios:

- ACE-1: 81% usage, separately with 3- and 5-year intervention lifetimes (35 USD per unit)
- Biogas: 100% usage, 5-year lifetime, separately at two price points (200 and 350 USD per unit)

HAPIT inputs for the scenarios listed in section 3.11 are described in Table 19.

Table 19. HAPIT inputs for ACE-1 and biogas interventions in Cambodia.

	Pre-Intervention Exposure µg/m³ (SD)		Post-Intervention Exposure ug/m³ (SD)		# Homes	Average Use %	Stove Lifetime (yrs)	Initial Cost USD	Yearly Cost USD
	Adults	**Children under 5 years**	**Adults**	**Children under 5 years**					
ACE-1	66 (43)	30 (19)	47 (37)	25 (20)	25,000	81	3, 5	35	0
Biogas	73 (84)	33 (38)	30 (18)	16 (10)		100	5	200, 350	0



ALRI
COPD
IHD
LC
STROKE
Relative Risk
4
3
2
1
0
125
250
375
500
PM$_{2.5}$ Exposures

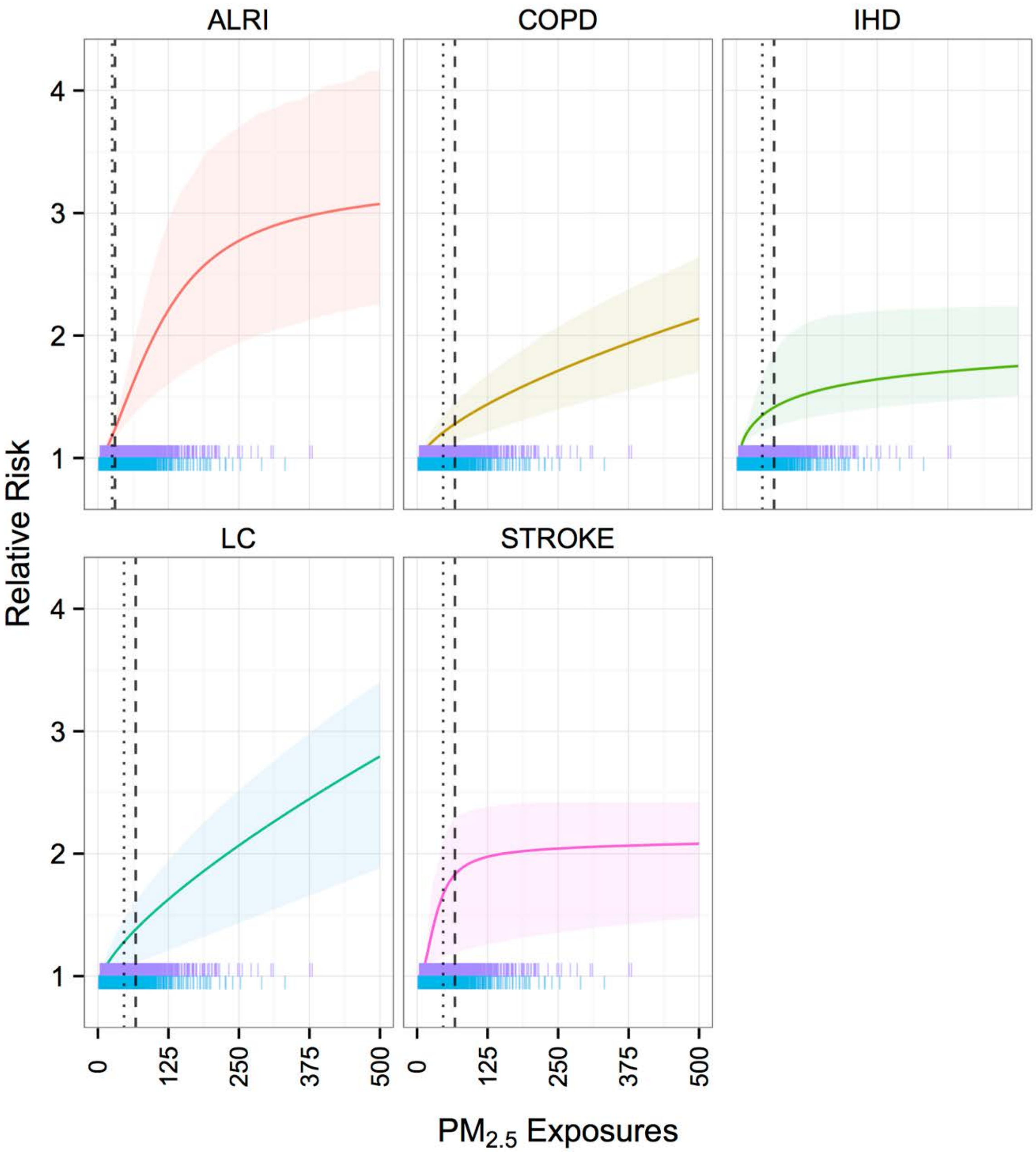


Figure 21. Integrated exposure-response curves and uncertainty bounds (lightly shaded) for each of the major disease categories associated with exposure to HAP for the biogas (top) and ACE-1 (bottom) interventions. The dashed vertical line indicates the pre-intervention exposure; the dotted vertical line indicates the post- intervention exposure. The upper and lower tick marks along the x-axis are the distributions of the simulated pre- and post-intervention exposures, respectively.

Averted DALYs and premature deaths from hypothetical stove interventions

To estimate the potential health benefits of a large-scale introduction of a stove with ACE-like performance in Cambodia, a number of assumptions must be made:

- Personal exposure of the cook before and after introduction (as measured in this study) mirror those of other adults in the household.

- The stove's performance in this study will be duplicated in the districts where the large-scale dissemination will be conducted
- The stove's usage measured during this study will be maintained for at least three respectively five years across all seasons
- To calculate averted ill-health in children, mother-child exposure ratios derived from the RESPIRE study in Guatemala are applicable to this community

If these conditions are accepted, then it is possible to estimate the health benefits of stove introductions in Cambodia of specific size using HAPIT. Estimates from HAPIT suggest that a dissemination of 25,000 ACE stoves in Cambodia – assuming 81 percent stove usage, a stacking profile as described above, and a 5-year stove lifetime – would avert approximately 1295 (range: 220 and 2,200) total DALYs[4] and between approximately 40 (range: 5 and 70) deaths, given the exposure levels and reductions measured and modeled during this analysis.[5] Under those same assumptions, but accounting instead for a 3-year-stove intervention, the estimate would be that between approximately 695 (range: 120 and 1200) total DALYs and 20 (range: 5 and 35) premature deaths could be averted.

For a dissemination of 25,000 Biogas stoves in Cambodia – assuming 100 percent stove usage, no stacking (no continued use of traditional stove), and a 5-year stove lifetime – would avert approximately 2,770 (range: between 1,060 and 4,110) total DALYs and approximately 75 (range: between 20 and 120) premature deaths, given the exposure levels and reductions measured and modeled during this analysis.[6]

Breakdowns of averted DALYs and deaths by disease type for each scenario described are also shown in Table 20, Figure 22, and Figure 23. These disease types are acute lower respiratory infections (ALRI: mostly pneumonia) in children less than five years and adult chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), lung cancer (LC) and stroke (Smith et al., 2014).

Table 20. HAPIT outputs for ACE-1 stove and biogas interventions in Cambodia.

	Years	ALRI		COPD		IHD		Lung Cancer		Stroke	
		DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)
ACE-1	3	205 (30-365)	2 (0-4)	70 (25-100)	1 (1-2)	150 (40-325)	6 (2-13)	30 (5-40)	1 (0-1)	240 (20-340)	10 (1-14)
	5	340 (45-610)	4 (1-7)	130 (50-200)	3 (1-4)	295 (80-645)	12 (5-25)	55 (10-80)	2 (0-3)	475 (35-670)	20 (1-30)
Biogas	5	1080 (610-1445)	13 (7-17)	270 (140-375)	5 (3-7)	520 (230-1035)	21 (9-42)	110 (40-145)	4 (1-5)	785 (35-1110)	33 (1-46)

[4] Disability-adjusted life year – standard global health metric for comparisons across diseases, risk factors, and populations. It combines the impacts of premature death as well as illness. See Lim et al., 2012.
[5] The range derives from the measured variation in exposures during the study.

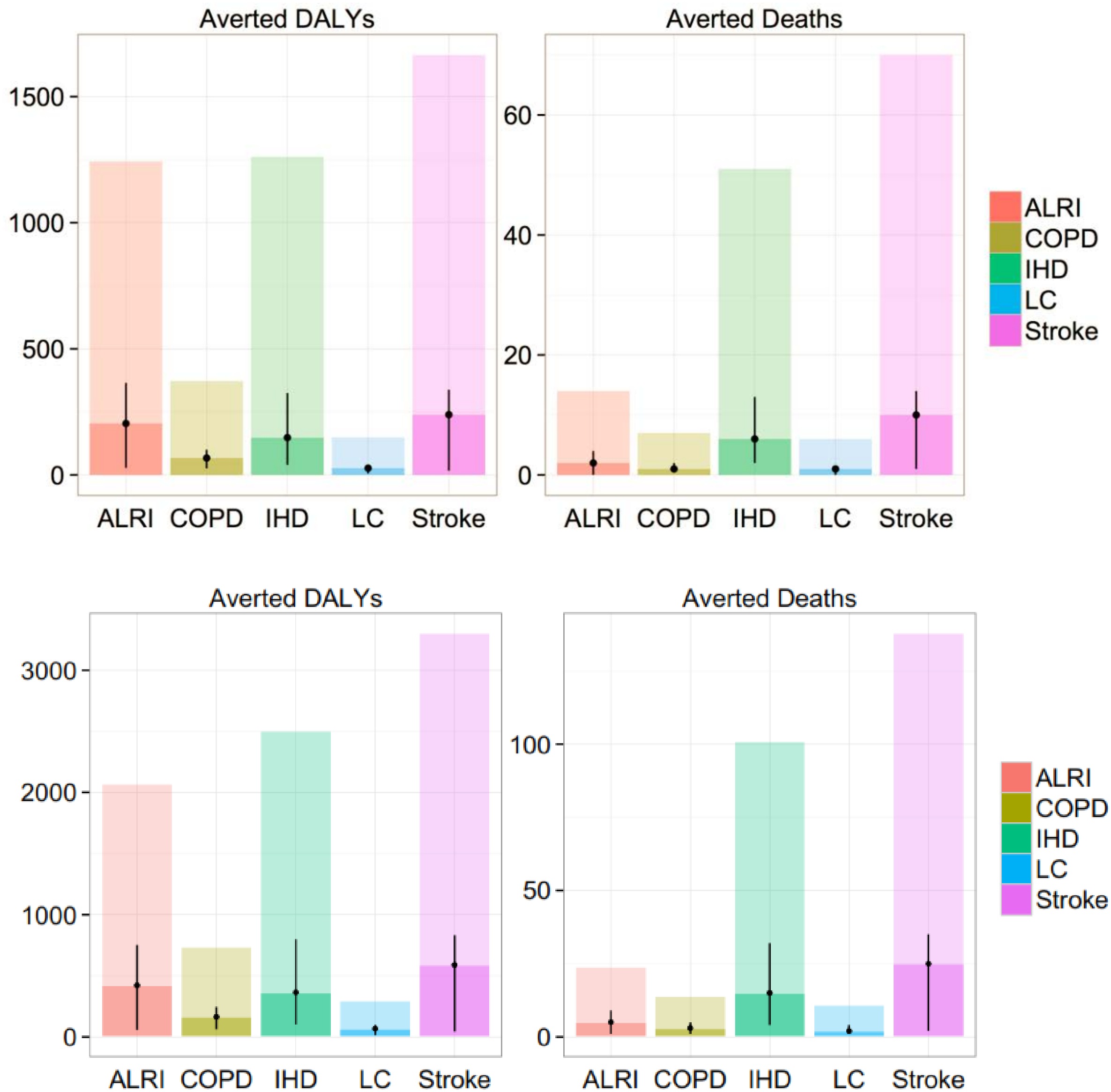


Figure 22. Averted deaths and DALYs by disease category for (top) an ACE-1 stove intervention with a 3-year lifetime (top) and (bottom) a 5-year lifetime in Cambodia. The darkest bars are the central estimate of averted ill-health; the lightest bars are the total burden avertable by the best possible intervention – one that gets down to the counterfactual exposure of 7 μg/m³. Vertical lines indicate the range of averted ill-health attributable to the intervention modeled by HAPIT.

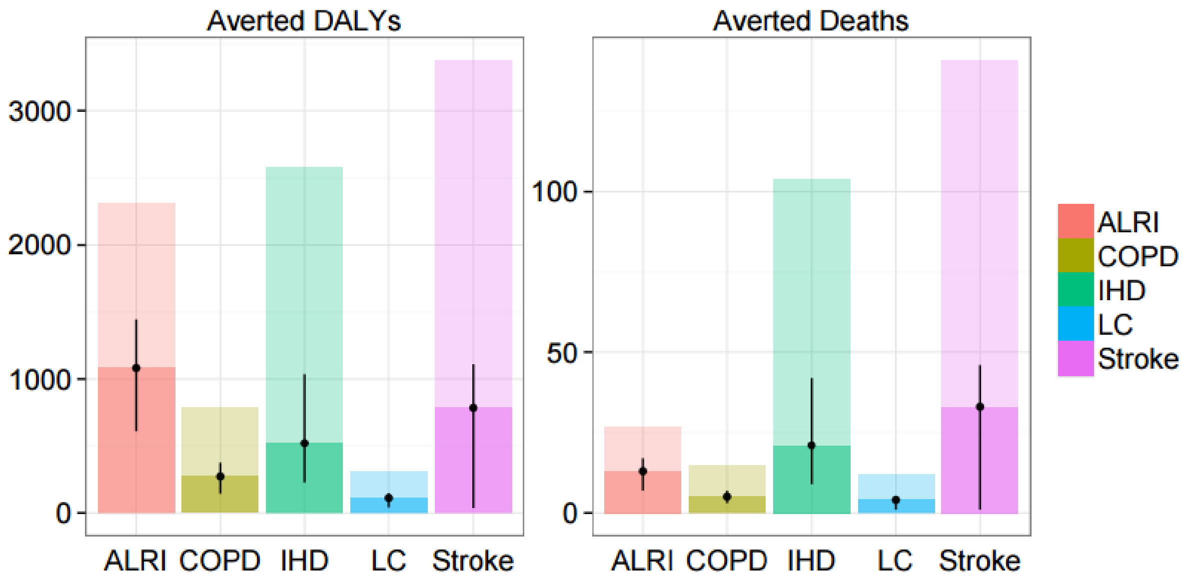


Figure 23. Averted deaths and DALYs by disease category for a Biogas stove intervention with a 5-year lifetime in Cambodia. The darkest bars are the central estimate of averted ill-health; the lightest bars are the total burden avertable by the best possible intervention – one that gets down to the counterfactual exposure of 7 μg/m^3. Vertical lines indicate the range of averted ill-health attributable to the intervention modeled by HAPIT.

In addition to the reduction in the health impacts, HAPIT also calculates the remaining ill-health that is left due to air pollution exposures even after the intervention, i.e., what additional could have been achieved if there had been 100 percent penetration of a truly clean cooking option in the villages, such as gas or electric cooking. For the ACE-1 with either a 3-year or 5-year lifetime, around 85% of the avertable burden remains. For a biogas intervention, approximately 70% of the avertable burden remains. This remaining burden is due to a number of factors, including non-complete adoption, non-complete use of the stove, and the burden remaining from the post-intervention exposure to the ideal exposure of 7.3 μg/m^3.

Simple health cost-effectiveness

For illustration only, here is an example of HAPIT's cost-effectiveness estimate with the following assumptions:

- The program cost per household of the dissemination is 35 United States dollars (USD) for the ACE-1 and 200 or 350 USD for the biodigester. For ACE-1, program costs include the costs of project management, results based financing, and monitoring and verification. For biogas, the 350 USD includes the investment subsidy for the biodigester, and program management and activities such as training and capacity building, promotion and marketing, monitoring and evaluation, and quality management. The difference in the 200 USD scenario is that it excludes the investment subsidy;
- A third biogas scenario was modeled where 350 USD was annualized over a 5-year lifetime at 70 USD per year;

- Cost-effectiveness is evaluated from a public sector perspective and does not include any payment by the households for the technology;
- All costs are borne at the start of the project for the ACE-1 and biogas interventions; except for the third biogas intervention where costs are annualized;
- The ACE-1 stoves have a lifetime of three or five years; the biodigesters have been modelled with a 5-year lifetime (the model is limited to 5 years, however, biodigesters have an estimated economic lifetime of 20 years); and
- The ACE-1 and biodigesters are used 81 percent and 100 percent, respectively, of the time by all households over its usable lifetime.

Under these conditions, the ACE-1 program costs 0.875 million USD. An ACE-1 with a 3-year lifetime results in between 120-1200 averted DALYs and 5-35 averted premature deaths. The mean cost per averted DALY would be between 750 and 7,500 USD with a central estimate of 1280 USD. The mean program cost per averted premature death would be between 25,700 and 219,000 USD with a central estimate of 43,400 USD. According to WHO-CHOICE criteria (WHO, 2003) and assuming 2010 Cambodia income levels (the base year for health analyses in this study), at this cost per averted DALY, this program would be considered very cost-effective at a GDP/capita of ~1840 USD, though the uncertainty would extend the estimate into cost-effective and not-cost effective categories.

With a 5-year lifetime, an ACE-1 would avert between 220-2,220 DALYs and between 5-70 deaths. The mean cost per averted DALY would be between 400 and 3,960, with a central estimate of 680 USD; the mean cost per averted death would be between 12,900 and 145,800 USD with a central estimate of 21,300 USD. According to WHO-CHOICE criteria (WHO, 2003) and assuming 2010 Cambodia income levels (the base year for health analyses in this study), at this cost per averted DALY, this program would be considered very cost-effective at a GDP/capita of ~1840 USD, though the uncertainty would extend the estimate into the cost-effective category. A visual depiction of both scenarios is in Figure 24.

A biogas intervention of 25,000 with a per-unit cost of 350 USD would have a total program cost of 8.75 million USD. With a 5-year lifetime, this intervention would avert between 1,060-4,110 DALYs and between 20-120 deaths. The mean cost per averted DALY would be between 2,130 and 8,280 USD, with a central estimate of 3,160 USD; the mean cost per averted death would be between 74,500 and 416,700 USD with a central estimate of 115,000 USD. According to WHO-CHOICE criteria (WHO, 2003) and assuming 2010 Cambodia income levels (the base year for health analyses in this study), at this cost per averted DALY, this program would be considered cost-effective at a GDP/capita of ~1,840 USD, though the uncertainty would extend the estimate into the not cost-effective category.

At 200 USD per biogas unit, the total cost would be 5 million USD. The mean cost per averted DALY would be between 1,220 and 4,730 USD, with a central estimate of 1,810 USD; the mean cost per averted death would be between 42,700 and 238,000 USD with a central estimate of 66,000 USD. According to WHO-CHOICE criteria (WHO, 2003) and assuming 2010 Cambodia income levels (the base year for health analyses in this study), at this cost per averted DALY, this program would be considered very cost-effective at a GDP/capita of ~1,840 USD, though the uncertainty would extend the estimate into the cost-effective category.

At 70 USD per biogas unit, the total cost would be 1.75 million USD. The mean cost per averted DALY would be between 430 and 1,660 USD, with a central estimate of 630 USD; the mean cost per averted death would be between 14,960 and 83,300 USD with a central estimate of 23,000 USD. According to

WHO-CHOICE criteria (WHO, 2003) and assuming 2010 Cambodia income levels (the base year for health analyses in this study), at this cost per averted DALY, this program would be considered very cost-effective at a GDP/capita of ~1,840 USD. A visual depiction of all three biogas scenarios is shown in Figure 25.

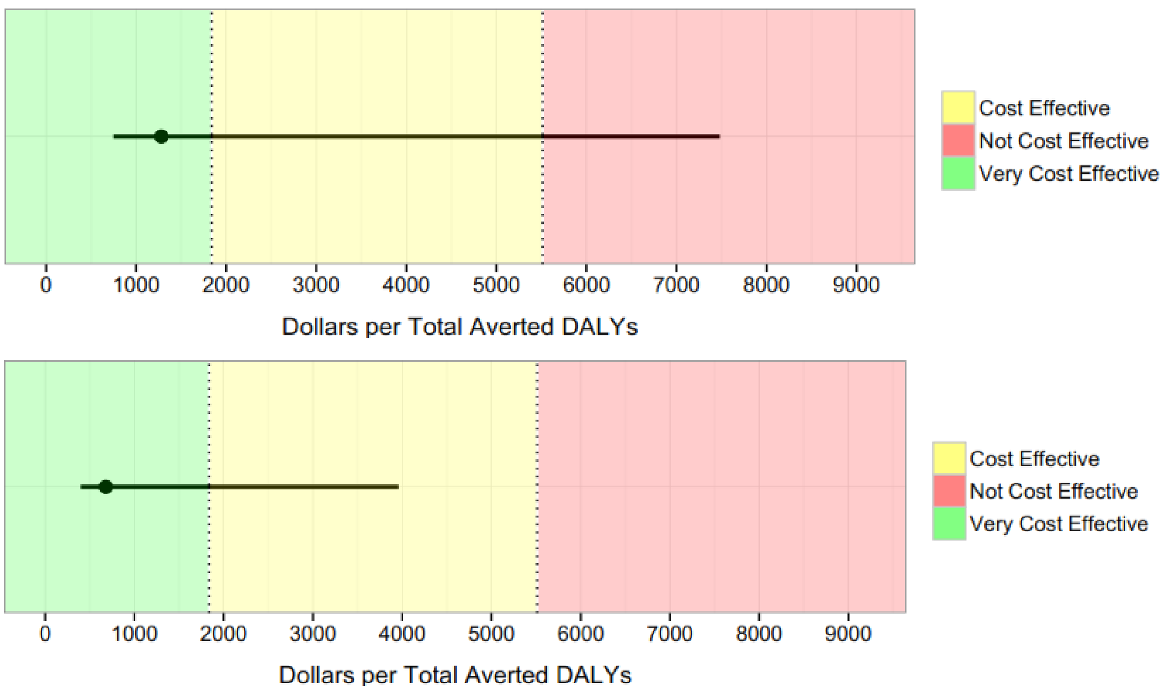


Figure 24. Dollars per total averted DALYs. The green shading indicates the WHO-CHOICE "very cost-effective category" (< GDP PC per DALY), the yellow shading indicates the "cost-effective" category (between 1 and 3 x GDP PC per DALY) and the red indicates "not cost-effective." The top panel is for the ACE-1 intervention with a 3 year lifetime; the bottom panel is for a 5-year lifetime. The 2010 GDP PC in Cambodia was approximately 1840 USD.

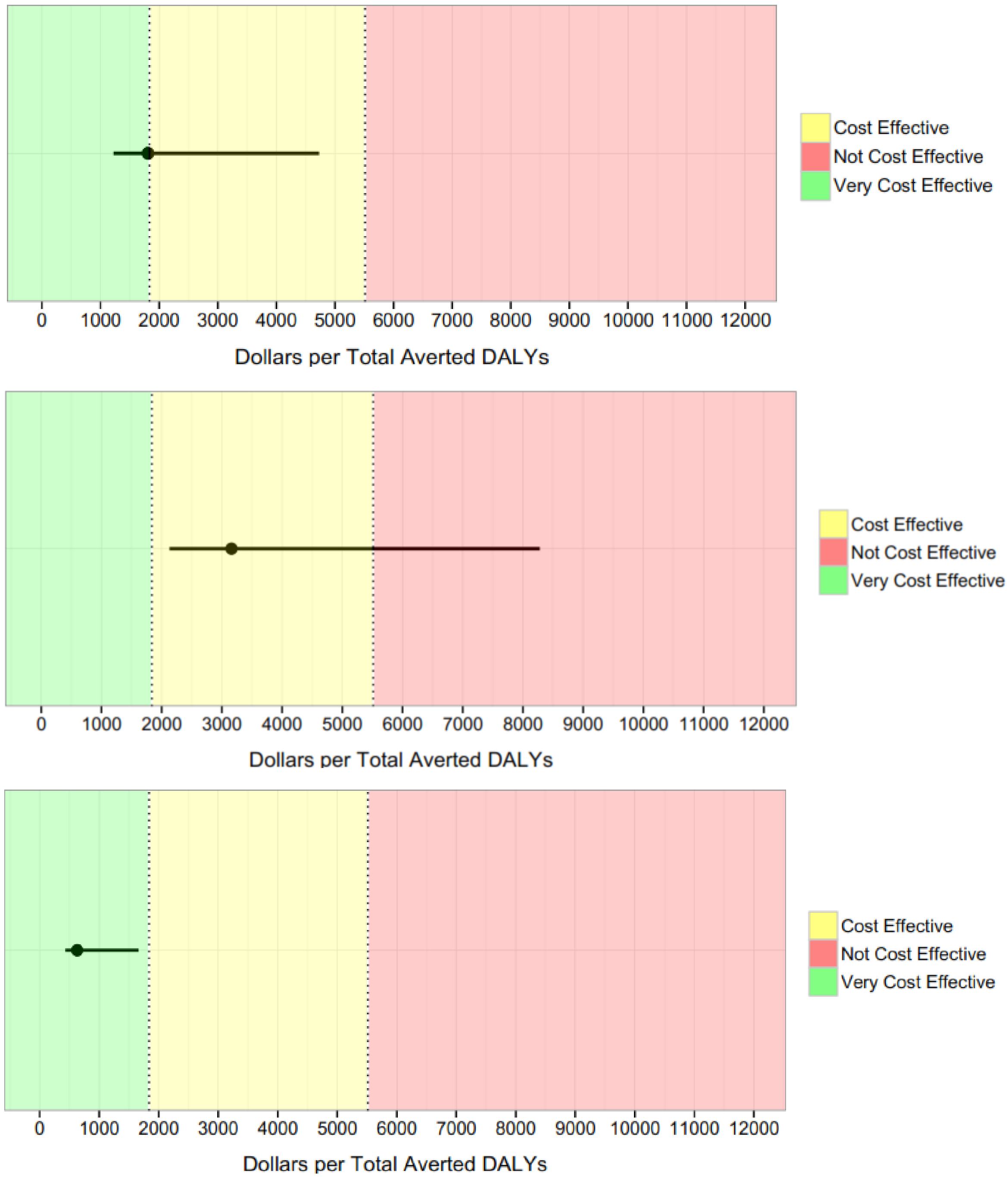


Figure 25. Dollars per total averted DALYs. The green shading indicates the WHO-CHOICE “very cost-effective category” (< GDP PC per DALY), the yellow shading indicates the “cost-effective” category (between 1 and 3 x GDP PC per DALY) and the red indicates “not cost-effective.” The top panel is for the biogas intervention with a 5 year lifetime and 350 USD per-unit cost; the middle panel is for a 200 USD per-unit cost, and the bottom panel is for an annualized intervention cost of 70 USD for the first five years of the program.. The 2010 GDP PC in Cambodia was approximately 1840 USD.

Of course, all interventions should be compared to other health investment opportunities in the country before going forward.

The cut off of cost-effectiveness would increase, however, with rising per capita incomes, which should be adjusted to the actual period of an intervention program and perhaps increase over the life of the program. In addition, any changes in estimated stove lifetimes, usage rates, or program costs would alter this calculation. For instance, incorporating costs borne by the consumer may increase cost-effectiveness as calculated by HAPIT. Additionally, as seen in the final panel of Figure 25, spreading the cost over the intervention's true lifetime – here thought to be approximately 20 years -- may better represent the program's true cost-effectiveness. Some care should be used with this approach, as few household energy interventions have the lifetime demonstrated by biogas in this setting. This sample calculation is illustrative of the kind of calculations that would inform decisions once more accurate data are available.

5 Discussion

At the Cambodian study sites, ambient $PM_{2.5}$ levels were typically low (range = 3.9 – 30 μg/m_3) and kitchens were generally well ventilated, a well suited combination for low exposure concentrations. Low ambient concentrations are required to be able to achieve health gains from an intervention. Reducing kitchen air pollution will have little effect on personal exposure and health outcomes if outdoor air pollution is still hazardously high. Good kitchen ventilation can dilute products of incomplete combustion emitted from the introduced stoves, particularly in the case of the biomass-burning ACE-1 but less so for biogas. Therefore, should the ACE-1 be highly adopted in these regions, there is the potential for very low exposure concentrations by its owners, which equates to health gains.

That said, the already low average baseline exposure concentrations measured during this study (ACE-1 = 66 μg/m^3 ± 43 μg/m^3, biogas = 73 μg/m^3 ± 84 μg/m^3), made further reductions from this baseline a bit harder to achieve. However, there is also potential to yield greater health effects since these exposure concentrations lie on the steep part of the $PM_{2.5}$ exposure-response curves.

5.1 ACE-1

In Phnom Penh, high ACE-1 usage, coupled with reduced traditional stove use, shows that the participants likely enjoyed using the ACE-1. The continued use of the traditional stove, however, implies that a single ACE-1 did not fulfill all the participants' cooking needs, and so they looked to the traditional stove to fill cooking capacity gaps. It is possible, however, that possessing two ACE-1 stoves may increase cooking capacity, leading to greater traditional stove displacement. In Samlout, participants continued to use the traditional stove during the 'after' monitoring at a similar rate as the 'before' monitoring, suggesting that Samlout users' cooking needs were mostly unmet by the ACE-1 stove.

The SUMS measurements were used to determine a 'use fraction' based on a threshold set to identify regular users of the introduced study stove. This 'use fraction' was based solely on introduced stove use, and did not depend on whether there was continued use of the traditional stove. Almost all participants continued to use the traditional stove during the study. Although statistically significant HAP and exposure reductions were observed, the continued use of the traditional stoves constrains the potential for greater improvements in both HAP and exposure. As discussed by Johnson and Chiang, just ten minutes of three stone fire (TSF) use per day can lead to exposures higher than the WHO Annual Interim Target of 35 μg/m^3 (Johnson & Chiang, 2015). Although the New and Traditional Laos stoves commonly seen in Cambodia likely emit $PM_{2.5}$ at lower rates than a TSF, displacement greater than what was observed in the ACE-1 study (approximately 8% in Samlout and 49% in Phnom Penh) would be needed to achieve that level of exposure, with the mean exposure during the ACE-1 sub-study being 47 $\mu g/m^3$, which is 12 $\mu g/m^3$ higher than the WHO interim target.

Although there was no statistical difference in exposure values between the Phnom Penh and Samlout study sites, the mean 'before' values were slightly different (Phnom Penh = 76.9 $\mu g/m^3$, Samlout = 58 $\mu g/m^3$, p = 0.19). The mean 'after' values, however, were similar (Phnom Penh = 46 $\mu g/m^3$, Samlout = 50 $\mu g/m^3$, p = 0.76). The change in exposure was nearly 2.5 times greater in the Phnom Penh region, although not statistically significant (p = 0.38). This does, however, correspond to the greater extent of traditional stove displacement observed at the Phnom Penh study site.

While understanding the limitations and assumptions involved in the HAPIT analysis, the output results allow a very general approximation of the cost-effectiveness of a program by quantifying aDALYs to determine the cost of the intervention per aDALY and comparing that to the gross domestic product per capita (GDP PC, USD). The Cambodian GDP/capita is ~1840 USD, and the HAPIT results from this study showed a central estimate of the annual cost per aDALY, if ACE-1 stoves have a 3- or 5- year lifetime, of 1,280 USD and 680 USD, respectively. The WHO CHOICE effort advises that interventions costing less than the GDP/capita are very cost-effective. Both of these central estimates would put the ACE-1 program in this category, although uncertainty bounds extend it toward the possible "cost-effective" or "not cost-effective" classification.

5.2 Biogas

The biogas users demonstrated a traditional stove displacement of 83% based on cooking duration when compared to the control group. This equated to mean exposure levels of 28 $\mu g/m^3$, which is 7 $\mu g/m^3$ below the interim target. This is an example of how high traditional stove displacement, coupled with a very low emitting stove, can significantly impact personal exposure.

Although the biogas system showed promising exposure reductions and, based on HAPIT, is likely to yield aDALYs, it is still in question whether it is cost-effective in terms of the cost of the program per aDALYs. The Cambodian GDP/capita is ~1840 USD, and the HAPIT results from this study showed a central estimate of the annual cost per aDALY, if biodigesters have a 5- or 10- year lifetime, of 3,160 USD and 1,810 USD, respectively. The WHO CHOICE effort advises that interventions costing less than the GDP/capita are very cost-effective and those costing one to three times the GDP/capita are cost-effective. The 5-year digester would place this in the "cost-effective" category and the 10-year would be considered "very cost-effective," although, uncertainty bounds extend it towards "not cost-effective" classification. The expected economic lifetime of a Cambodian biodigester is 20 years. This program started 10 years ago and those early biodigestors are still operational. Based on the lifetime of these early biodigestors, the 10 year estimate is more likely, and may even be an underestimate.

5.3 Influences on exposure

Although KAP is typically an important driver of personal exposure in homes cooking with solid fuels, as seen in Figure 19, the relationship between the KAP and PE measurements in this study is far from linear. In order to use KAP to predict PE, a more sophisticated model, which includes inputs such as participant time activity, additional sources of exposure, and cookstove tending, would be required.

Outdoor ambient $PM_{2.5}$ has a large effect on 24-hour average personal exposure values. For example, a participant may cook for four hours in one day and be directly exposed to high pollutant concentrations associated with poorly combusted solid fuels, yet may likely spend the 20 remaining hours of that day being exposed to the ambient levels. During this study, the 'before' monitoring period showed significantly lower ambient $PM_{2.5}$ than the 'after' period in Phnom Penh 16 µg/m^3 and 25 µg/m^3, respectively. This difference in outdoor $PM_{2.5}$ was unrelated to the stove-intervention and would bias the exposure results if not addressed. In order to better quantify the non-ambient, stove-related changes in exposure, an ambient correction was applied to the average personal exposure values used in the HAPIT model and, thus, this bias was avoided.

Other sources of exposure besides cookstove smoke were reported by 52% (n=25) of all ACE-1 participants in the 'before' period and 46% (n=22) in the 'after' period. 88% (n=21) of the biogas and 79% (n=19) of control homes reported having some source of exposure in addition to their cookstove. In all study groups the primary reported source of additional exposure was tobacco smoke. Other commonly reported sources of exposure included: trash burning, incense burning, mosquito coil burning, and in the Samlout 'after' group, there was a large number of reported exposures to smoke from heating by burning biomass. These additional sources, not related to cooking, contributed to the overall participant exposure. Given such practices, personal exposures can still remain above the WHO recommended levels, even if using a completely clean fuel, such as gas or electric. The continued regular use of the traditional stove will guarantee continually high exposure rates, although, as seen in this project, some improvement can be seen by a partial traditional stove displacement scenario.

The increase in ambient $PM_{2.5}$ in Phnom Penh from 'before' to 'after' periods is contradictory to the reduction observed in kitchen air pollution due to the introduction of cleaner stoves in 24 households per study area. This significant increase must be due to changes in outdoor sources, such as increased emission from the local charcoal making factory, more agricultural or trash burning, or more automobiles in the area, as well as changes to the meteorological conditions, including possible shifts in season with consequent differences in temperature, rainfall, wind direction, and speed.

5.4 Fuel and perceived health and time impacts

An important potential benefit of an advanced biomass stove is lower fuel use since it can translate to less time in fuel gathering and, where fuel is purchased, money savings. It may also have the potential to result in environmental benefits for the local habitat, as deforestation is an ongoing danger in Cambodia (Lang, 2001). Finally, even if there is no improvement in combustion, less fuel use alone may still lower total stove pollution emissions.

Based on mass measurements of perceived daily fuel use piles in the ACE-1 and biogas sub-studies, the ACE-1 stove and biogas stove seemed to require significantly less fuel for the same tasks: over 50% less per household (p=0.003) in both Samlout and Phnom Penh. This encouraging result should be considered in context, however. The fuel measurements are subject to bias, as the households are aware of the intent of the monitoring and thus may change their behavior. Finally, as is true for all the measurements done in this study, fuel use in ACE-1 homes was measured only once when the introduced stoves were relatively new. Without longer term studies, however, it is difficult to know to what extent such fuel performance would be maintained over years and across different seasons with changing biomass characteristics (type, moisture content, etc.).

Although likely to be influenced by both reporting and recall bias, there were frequently reported perceptions of improved health and reduced time spent cooking and cleaning since receiving the ACE-1. Half of all households reported changes in their health, post ACE-1 dissemination, and all of those who reported a change in health felt that change was positive. The majority of participants (77%, n=37) reported that the ACE-1 was safer than their previous primary stove and there were 63% (n=12) less reported incidents of cooking related burns.

6 Conclusions

The major findings of the ACE-1 sub-study were:

- The 'before' and 'after' mean KAP values in the ACE-1 user households were 183 μg/m^3 and 111 μg/m^3, respectively, a significant reduction of 39% ($p <0.05$).
- The 'before' and 'after' mean PE in the ACE-1 users were 66 μg/m^3 and 47 μg/m^3, respectively, a statistically significant reduction of 19 μg/m^3 or 28% ($p <0. 05$). This reduction is a substantial achievement given the low baseline exposure concentrations. Such low baseline exposure concentrations, however, lie on the steep part of the $PM_{2.5}$ exposure response curves, meaning that even small reductions in exposure can yield substantial health gains.
- The measured ACE-1 "use fractions" in the Phnom Penh and Samlout sample populations were 87.5% and 75%, respectively. These were applied to the HAPIT model to scale the exposure results and were based on the threshold of "regular use" set at 0.5 ACE-1 stove uses per day or greater, on average.
- Traditional stove displacement by the ACE-1 stove was greater in the urban study group (49%) than the rural (8%) due to the common practice of stove stacking.
- The ACE-1 HAPIT results showed a central estimate of the annual cost per aDALY of 1,280 USD and 680 USD given ACE-1 lifetimes of 3 and 5 years, respectively. The WHO CHOICE effort advises that interventions costing less than the GDP/capita are "very cost-effective". Given that the 2015 Cambodian GDP/capita is ~1840 USD, both of these estimates put the ACE-1 program in this category, although the uncertainty bounds around the HAPIT estimates extend the program toward the "cost-effective" or "not cost-effective" classification.

The major findings of the biogas sub-study were:

- The control and biogas mean $PM_{2.5}$ KAP values were 172 μg/m^3 and 35 μg/m^3, respectively, a significant difference of 137 μg/m^3 or 80% ($p < 0.05$). Control households were still relying on traditional biomass stoves. The control and biogas mean PE values were 73 μg/m^3 and 28 μg/m^3, respectively, a significant 61% difference ($p < 0.05$).
- The biogas users demonstrated a traditional stove displacement of 83% based on cooking duration when compared the control group. Homes with biogas used biogas stoves for 87% of cooking events, which equated to 81% of their time spent cooking. Of the biogas owners, 100% used their biogas stove at least 0.5 times per day. Biodigesters having a 5- or 10- year lifetime, result in a central estimate of the annual cost per aDALY of 3,160 USD and 1,810 USD, respectively. The 5-year digester would place this in the "cost-effective" category and the 10-year would be considered "very cost-effective". Although, the HAPIT uncertainty bounds extend it towards the "not cost-effective" classification. Biodigesters have been known to last for up to 20 years, a lifetime which the HAPIT model cannot accommodate, meaning the cost-effectiveness calculation may be underestimating the value of biogas

A finding related to both sub-studies was that when plotting personal exposure versus kitchen air pollution for all groups and study phases, no clear relationship emerged. More sophisticated models and inputs of other KAP- and exposure-related co-variates are required to investigate relationships between PE and KAP.

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