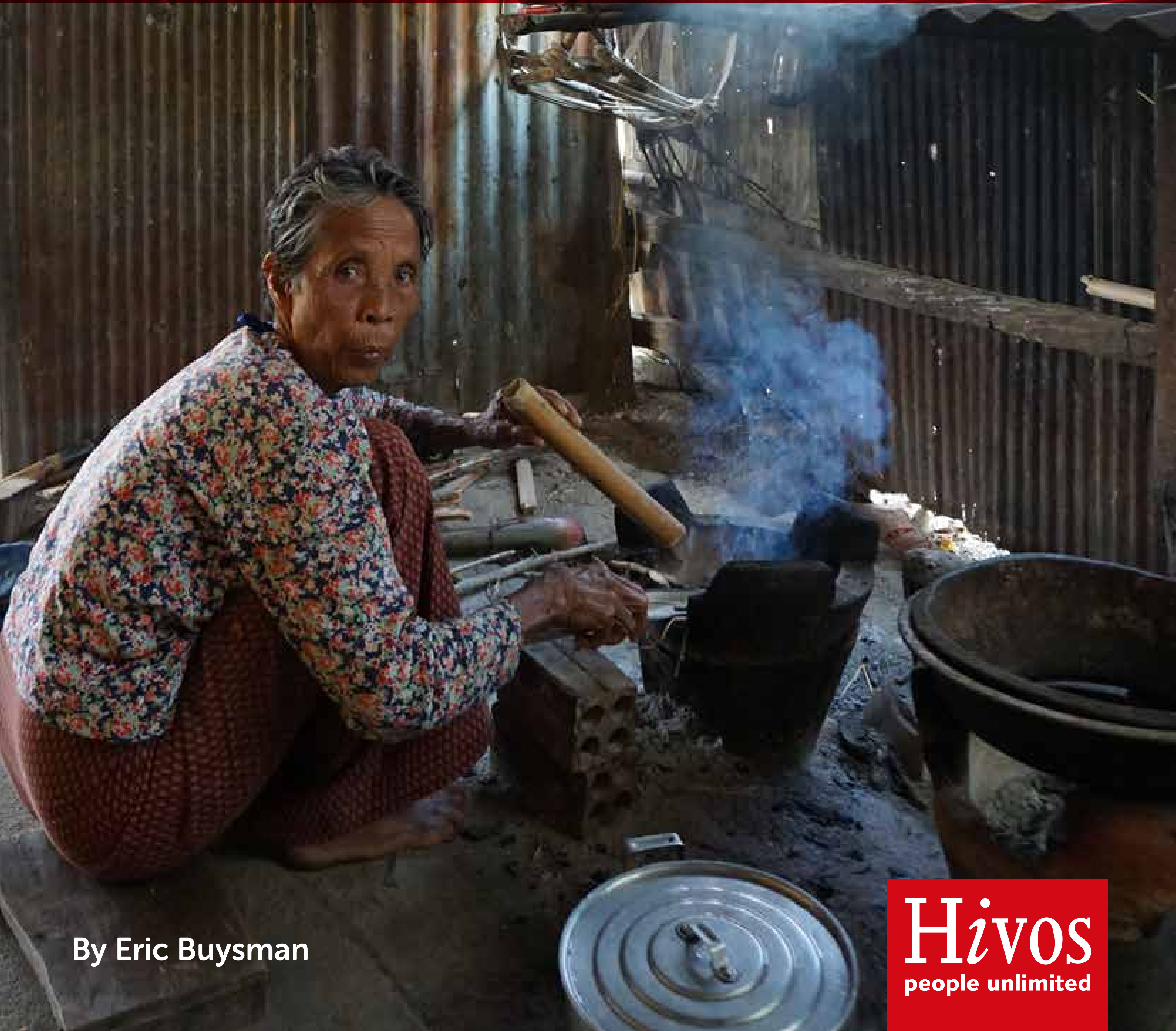
BIOGAS AND HOUSEHOLD AIR QUALITY

Study on Household Air Quality and Estimated Health Improvement of users of **Biogas Stoves** versus **Wood-fired** Stoves in *Rural Cambodia*



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Executive Summary

Household air pollution is a silent killer according to the WHO. It affects the health of 40% of the people worldwide due to the reliance on solid fuels for cooking. The WHO estimates that it results in 4.3 million premature deaths annually, of which 500,000 occur in children below 5 years of age. In Cambodia, where over 98% of the rural households rely on solid biomass, mostly wood for cooking, a similar picture emerges, around 14,729 premature deaths and 391,597 disability-adjusted life years (DALY). It is in Cambodia the second cause of DALY after dietary risks and the third cause of premature death. This health and energy conundrum has a much greater impact on human health compared to other common diseases in Cambodia, such as HIV/AIDs, malaria or even traffic casualties.

Addressing HAP requires a paradigm shift from focussing on improved cookstove (ICS) with incremental thermal efficiency gains towards advanced stoves with a much higher thermal efficiency or preferably towards clean fuels. Biogas is considered a clean fuel by the WHO and has therefore the potential to address HAP. The relationship between reduced HAP and health however has mostly focussed on improved cookstoves and few scientific studies have looked at domestic biogas as an intervention. The few studies available that did so, all reported a positive health impact, such a decreased prevalence of COPD, improved cardiovascular health and respiratory system.

The potential for domestic biogas is enormous in Cambodia with 1 million households that have sufficient livestock to feed for the smallest NBP digester. Biogas could therefore help to address HAP in Cambodia to millions of rural inhabitants. The National Biodigester Programme (NBP) of Cambodia, a partnership between SNV and the Ministry of Agriculture Forestry and Fisheries, is implementing a market-based programme and has so far reached over 100,000 Cambodians with 23,000 biodigesters installed.

This study is set-up with the aim to quantify the health impact of NBP by measuring the reduction of hazardous pollutants, CO and PM2.5 of households that use biogas and matching households in terms of family size, socio-economic conditions and cooking conditions without a biodigester. The study took place in 5 randomly selected villages in which 5 households of both groups the kitchen concentration, exposure to the pollutants by the main cook and the ambient air was measured for 48 hours.

The study showed that biogas reduces PM2.5 levels, with a reduction of around 36% reduction in exposure and 88% reduction in kitchen concentrations. CO levels are also much lower, but in most cases, including the baseline households lower than the 24-hour WHO guidelines. Short-term exposure to CO (≤ 1 hour) however remained too high for almost a quarter of the baseline households.

The study was also able to provide evidence that biogas stoves results in decreased PM2.5 and CO emissions; and that the high levels of HAP in biogas households may be attributable to the ambient air pollution. The study therefore concludes that biogas is a part of the solution to address HAP, but that the current scale and the focus on clean energy for cooking alone is not sufficient to bring the overall levels of PM2.5 near the WHO guidelines. Tackling this requires a community based approach that focusses on clean energy, addresses the ubiquitous problem with the inefficient burning of households and garden waste, the clearing of agricultural land by burning the crop waste and artisanal rice and palm sugar production.

The HAPIT tool was used to convert the improvement in household air quality (HAQ) to aDALYs and averted deaths. The cumulative benefits accrued by 2014 stand at 29.5 averted deaths and 1,442 aDALYs. With the continued implementation of NBP, this is projected to increase to a total of 51 averted deaths and 2,519 aDALYs in 2020.

NBP's implementation costs expressed as costs per averted deaths and aDALYs can be compared to a statistical value of life and the value of an aDALY. This comparison however is challenging as the value of life depends on many aspects, such as age of the people involved, the country context and is basically an ethical discussion. Based on the estimates available however, NBP, purely as a health intervention, is not cost-effective. However, given that most pollution is not related to biogas, the benefits could be much greater when more households switch to biogas or another clean fuel. In addition, the calculation ignores the range of other benefits that domestic biogas has and brings. More study on the valuation of NBP's benefits in a wider context is therefore necessary.

List of Abbreviations

µ = Greek letter Mu, the SI unit for micro representing one millionth
aDALY = Averted Disability-Adjusted Life Year
ALRI = Acute Lower Respiratory Infection
AQG = Air Quality Guidelines
BC = Black Carbon
CO = Carbon Monoxide
COPD = Chronic Obstructive Pulmonary Disease
DALY = Disability-Adjusted Life Year
EL-CO = Carbon monoxide monitor sold by Lascar
EPA = Environmental Protection Agency (of the USA government)
GACC = Global Alliance for Clean Cookstoves
GBD = Global Burden of Disease
GDP = Gross Domestic Product
GHG = Greenhouse gas
GWP = Global Warming Potential
HAP = Household Air Pollution
HAPIT = Household Air Pollution Intervention Tool
HAQ = Household Air Quality
hh = Household
HIVOS = Humanistic Development Organisation
ICS = Improved Cookstove
IHD = Ischemic Heart Disease
LPG = Liquefied Petroleum Gas
mmHg = Pressure unit: Millimetre of mercury (133.32 Pascal)
NBP = National Biodigester Programme of Cambodia
NBP = National Biodigester Programme
PM2.5 = Particulate matter sized 2.5 µm or smaller
SUMs = Stove Use Monitors
SVOLY = Statistical Value of Life Year
TSP = Total Suspended Particles
UCB-PATS = Particle and temperature monitor developed by the University of California Berkeley
WHO = World Health Organization

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1. Introduction

1.1 The global health burden of Household Air Pollution

Globally 3 billion people, or two-fifths of the world's population, continue to rely on solid fuels to meet their thermal energy needs (Neupane, et al., 2015). The reliance on these fuels, often burned in inefficient primitive stoves situated in kitchens with poor ventilation, produces hazardous concentrations of several health-damaging pollutions, including particles with a diameter up to 2.5 µm (PM2.5) and carbon monoxide (CO) (Neupane, et al., 2015). There is a considerable health burden associated with this; annually an estimated 4.3 million deaths are attributed to household air pollution (HAP) of which 1.69 million in South-East Asia alone (WHO, 2014). Most of the premature deaths are related to cardiovascular complications such as ischemic heart disease (IHD) (26%) and strokes (32%) and the remaining 40% due to adverse effects on the respiratory system; chronic obstructive pulmonary disease (COPD) (22%), acute lower respiratory infections (ALRI) (12%) and lung cancer (6%) (WHO, 2014). Women, due to their household domestic roles and children which are often in their vicinity, are to a much greater degree affected by HAP compared to other family members (Neupane, et al., 2015). It is estimated that 500,000 children's deaths are attributed to HAP from ALRI. Furthermore, prenatal exposure to HAP is linked with still-birth, impaired cognitive development and low birthweight (Martin, et al., 2013).

1.2 Cambodia's health burden attributed to HAP

Women in Cambodia typically cook on simple inefficient ceramic stoves without a chimney in open kitchens. The main fuel used is wood while richer households may also use charcoal or incidentally LPG. Over 98% of rural Cambodian households rely on solid biomass for cooking (San, Ly, & Check, 2013) and consequently women and children are exposed to high levels of pollutants that can cause a range of diseases (Pokhrel, et al., 2015) and burns and scalds from tending the fire (Martin, et al., 2013). The cumulative effect of cooking on solid biomass also leads to significant outdoor air pollution (GACC, 2015). HAP is second disease risk factor in Cambodia after dietary risks and in 2013 stood at 391,597 Disability-Adjusted Life Years (DALYs) (IHME, 2015). Furthermore, the burden of disease estimates provided by the Global Burden of Disease 2013 project and the WHO attributes 14,729 premature deaths including 856 children to HAP in Cambodia (IHME, 2015). The death toll is much higher compared to malaria (1,043), outdoor air pollution (6,685), tuberculosis (3,758), HIV/AIDS (1,403) or traffic casualties (3,657). Yet, little attention is given to this apparent health crisis compared to the other risks and diseases world-wide, including Cambodia; HAP is a silent killer.

1.3 Addressing HAP – Improved Cookstoves

There is limited evidence that switching to improved cookstoves (ICS) reduces HAP (Neupane, et al., 2015). Martin et al (2013) suggests that an HAP improvement of at least 50% is required to substantially improve health. For that reason, Neupane (2015) concludes that clean fuels higher up the energy ladder, such as LPG and biogas, are a prerequisite to meeting the WHO Air Quality Guidelines (AQG). Moving towards fuels higher on the energy ladders or biomass stoves that have significant cleaner combustion entails a paradigm shift from current approaches that tend to focus on incremental thermal efficiency improvement. An example of this is the recent focus on advanced clean cooking stoves which have a significant higher thermal efficiency and less emission of health damaging particles, such as the Advanced Clean Cooking Solutions (ACCS) project in Cambodia (SNV, 2015). Preliminary results from studies in other countries show that there is a positive health impact associated with those stoves compared to open fire stoves (GACC, 2015).

Figure 1: Typical rural kitchen. The smoke and the soot on the walls evidences HAP

1.4 Addressing HAP – Domestic Biogas[1]

Biogas is a clean and renewable fuel high up the energy ladder (WHO, 2014). However, limited scientific documentation is available on the potential of biogas to address HAP while millions of

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[1] In this report domestic refers to household. Thus a synonym of domestic biogas is household biogas. This is in line with the Cambodian draft biogas standard and the SNV/HIVOS definition.

rural inhabitants are using biogas worldwide; an estimated 46 million in China and India and another 600,000 through SNV/HIVOS initiated programs in Asia, Africa and Latin America (SNV, 2015).

One of the first scientific study on biogas and health was conducted in Kenya. That study confirmed the positive health impact of biogas; household report improved respiratory health, better (but not significant) spirometry results and improved children's health amongst 31 age-matching non-smoking women with and without biogas (Dohoo, Guernsey, Critchley, & Leeuwen, 2012). The long term impact of biogas however is not clear as households were only using biogas ranging from 3 to 24 months in the study. Longitudinal effects were studied in China with a 9-year cohort study amongst 996 participants aged 40 which looked into the impact on COPD and lung function of households that had been offered a cooking intervention: ICS, biogas or improved ventilation. The study concluded that using biogas and improved ventilation were associated with a reduced decline in forced expiratory volume and that the effect and the reduction of COPD incidence was greater with longer duration of the intervention and the greatest with the combination of biogas and improved ventilation (Zhou, et al., 2014). Another study looked at the impact on cardiovascular health of cooks that previously used solid fuels for cooking in Nepal amongst 219 biogas households and 300 that use firewood (Neupane, et al., 2015). The use of biogas was associated with a 9.8 mmHg lower systolic blood pressure and a 68% reduced odd of reducing hypertension amongst women over 50 years old. The latter was not found amongst women aged 30 to 50. In conclusion, the studies that have studied biogas, have all found a positive health impact that was attributed to a reduction in HAP.

1.5 Domestic Biogas in Cambodia

In Cambodia, the National Biodigester Programme (NBP), a partnership between the Ministry of Agriculture, Fisheries and Forestry (MAFF) and SNV, the Netherlands Development Organization, aims to establish a permanent market-oriented and self-financed biogas sector (Buysman & Mol, 2013). Around 80% of the inhabitants live in rural areas with agriculture as their primary livelihood. The dominant farming system is an integrated livestock-rice cultivation system, where rice production relies on draught power and manure from cattle or buffaloes. The sector is dominated by smallholders, families with typically a few chickens and pigs, while less poor families usually have a pair of draught animals in addition (Buysman & Mol, 2013). As such, there is tremendous potential for biogas which is estimated to be around 1 million domestic biodigesters (Kooijman, 2014). A biodigester relies on anaerobic digestion of animal manure or other biomass in a closed underground fixed dome digester resulting in biogas, a clean methane rich fuel that is mostly utilized for cooking purposes and the effluent, so-called bio-slurry is a potent organic fertilizer. As of date, around 23,000 biodigesters have been constructed benefitting over 100,000 rural inhabitants. Given the enormous potential for domestic biogas in Cambodia, biogas could help to address the health burden attributed to HAP for millions of rural inhabitants in Cambodia.

1.6 Study objectives and hypothesis

A cross-sectional study was set-up to determine the concentration of the main HAP pollutants: PM2.5 and CO, of both kitchens and exposure to these pollutants in households with a biodigesters and matching households without a biodigester. In addition, the ambient air PM2.5 and CO concentration was measured and related to the kitchen and exposure levels. Although PM2.5 is thought to be the single best indicator to measure the health impact of HAP (Pokhrel, et al., 2015), this relationship may not exist with biogas stoves and for that reason both pollutants were measured.

The specific objectives of this study are:

1. Compare the kitchen and exposure PM2.5 and CO levels of randomly selected biogas and matching baseline households. (Chapter 4)

2. Determine the share of PM2.5 and CO that can be attributed to ambient air pollution (Chapter 5.1)

3. Assess whether or not a PM2.5-CO relationship exists for exposure and kitchen concentrations (Chapter 5.2)

4. Assess the health implication of cooking on biogas by estimating the averted deaths and disability adjusted life years (DALYs) for NBP; (Chapter 6)

1.7 Reader

Chapter 2 starts with the Materials and Methods in which the research methodology and tools used are described.

Chapter 3 will focus on the characteristics of the baseline and project households and will determine whether or not the selected baseline households can be assumed to be matching and representative for the NBP target population. Chapter 3 will also focus on other sources of air pollution, sources that could be compounding variables that have to be taken into account when comparing HAP between the two study groups.

Chapter 4 will focus on the HAP results and compare them with the air quality guidelines (AQG).

Chapter 5 will assess the extent to which extent ambient air pollution contributes to HAP and will relate the CO results with PM2.5.

Chapter 6 will determine, based on the result in chapter 4, the health impact of the intervention (biogas).

Chapter 7 is the conclusion and chapter 8 contain a number of recommendations to NBP but also to other actors that focus on human health and the environment.

2. Material and Methods

The study protocol was reviewed by HIVOS and NBP before the commencement of this study. Prior to visiting the households, first the village chief was informed on the purpose of this study and only after his/her permission the households were visited. The household visit started with an explanation of the purpose of this study, the length and the data loggers that will be installed and to be worn by the main cooker. In case the household would consent and if the main cooker was available for at least 48 hours, then household would be selected for participation. Households were allowed to withdraw from the research at any time. The consent procedure was verbal; no written documentation exists of this. All village chiefs and households received as a token of appreciation a NBP designed t-shirt.

2.1 Study site and household selection

The study took place in 5 randomly selected villages spread out over 5 provinces (Table 1 and Figure 3). The villages are all located in the lowlands of South-East Cambodia. In all cases the villages were at least 10 kilometers away from the main road and factories. Outdoor pollution therefore originates mostly from local activities, such as from home-based artisanal production of rice wine by distillation, palm sugar production using wood fired stoves, burning of household and garden waste, forest and agricultural land clearing and cooking on wood-fired stoves. The biodigester population in each village is compared to the total population of households relatively small, with the exception of Trabaek Tung village (Table 1).

Table 1: Study sites, village and biodigester population

#	*Province*	*District*	*Commune*	*Village*	*Village population*	*Household population*	*Biodigester population*	*Share of hh with a biodigester*
A	**Kampot**	Dang Tong	Dang Tong	Khcheay Khang Tboung	812	187	15	8%
B	**Kampong Speu**	Kong Pisei	Srang	Trabaek Tung	655	125	26	21%
C	**Kampong Cham**	Kang Meas	Sour Kong	Boeng Trav	2000	400	13	3%
D	**Takeo**	Samraong	Boeng Tranh Khang Tboung	Hang Heng	1597	354	43	12%
E	**Svay Rieng**	Rumduol	Thmea	Pongro	403	103	12	12%

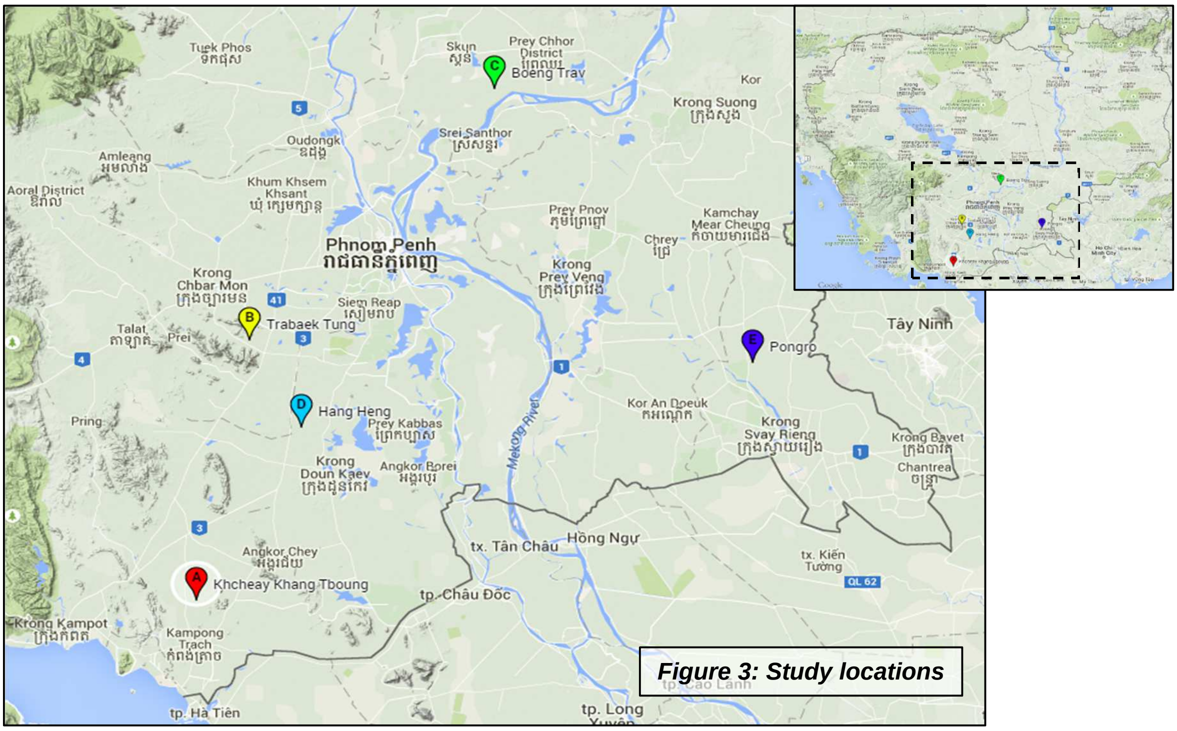

Figure 3: Study locations

2.2 Sampling and sample size

Villages were selected through a three-stage random cluster sampling. In the first stage 5 districts, out of a total population of 123 districts in which NBP is active, were selected using a probability proportional to size (PPS) random sampling method. Subsequently, in each district 1 village with at least 8 digesters was randomly selected. Finally, up to 10 households were randomly selected in the previously selected chosen villages, of which, in principle, the first 5 were surveyed and the remainder served as back-up.

Matching baseline households without biogas were selected using the sampling frame of the project households and the 'match' was based on their similarity with project households on: animal population, socio-economic status, type of stove used and family size. This study design ensures that the only difference between the baseline and the project households is the biodigester and that the baseline households belong to the group which NBP identifies as households that have the technical potential[2] to install a biodigester. The total sample population consisted for 5 baseline and 5 project households in each village making a total sample of 50 households.

With this sampling method it was attempted to annul the selection bias and thereby safe-guarding representativeness. In addition, it is aligned with Gold Standard's TPDDTEC methodology with which NBP is registered with their Voluntary Gold Standard project GS751.

2.3 Characteristics of the pollutants measured

PM2.5 stands for Particulate Matter (PM) with a size of 2.5 µm or smaller, or 2.5×10^{-6} meter, and is in general referred to as 'fine particles'. These particles are, in the case of cooking, emitted due to incomplete fuel combustion. Due to their small size, inhaled particles can lodge deep in the lungs.

PM2.5 and Global warming: Black carbon is the solid fraction of PM2.5 that strongly absorbs light and converts that energy to heat. Black carbon, also known as soot, is therefore a strong contributor to global warming, the strongest after CO_2 (Bond, et al., 2013). Roughly half of atmospheric BC comes from fossil fuel combustion and the other half from biomass and biofuel burning. While BC is short-lived in the atmosphere (1-4 weeks), it is linked to strong regional climate effects and a large share (~30%) of recently observed warming in the Arctic (UNEP, 2015). BC has a global warming potential (GWP) of 2,421 relative to CO_2 over a 20 year period (IPCC, 2013), much higher compared to, for example, methane's GWP_{20} of 86 (IPCC, 2014).

CO: Carbon monoxide is a gas molecule composed of oxygen and carbon atoms with a diameter of 112.8 pm or 10^{-12} meter. CO has an impact on global warming with a GWP_{20} of 5.9, albeit much lower than BC (IPCC, 2013). Carbon monoxide is colorless, odorless, and tasteless, but highly toxic. It combines with hemoglobin to produce carboxyhemoglobin, which usurps the space in hemoglobin that normally carries oxygen, rendering it ineffective for delivering oxygen to bodily tissues. At high levels, this could lead to carbon monoxide poisoning with the following symptoms such as headache, nausea, vomiting, dizziness, fatigue, and a feeling of weakness and, in some cases, coma and death.

Diffusion of PM2.5 and CO in the air is governed by different forces. In the case of CO by the Fick's law of diffusion where diffusion is directed by concentration gradients in the air, as anticipated by the second law of thermodynamics which states that any system moves towards maximum entropy.

PM2.5 on the other hand is governed by the gravity induced drag and the movement in the air and will therefore diffuse much slower. PM2.5 will eventually precipitate (settle) but can remain suspended in the air for weeks, while CO will slowly diffuse and disappear in the background concentration of CO in the atmosphere.

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[2] *Having enough manure to feed smallest biodigester of 4 m^3*

Relative size of PM to a human hair *CO molecule size and its triple atomic bond*

Figure 4: PM2.5 particle and CO molecule size

2.4 Monitoring equipment and installation

Monitors

PM2.5: The UCB PATS (University of California, Berkeley – Particle and Temperature Monitoring System) was used to measure PM2.5. The UCB-PATS is a low cost, passive, portable, data logging optical particle monitor that has been validated in various studies[3]. The UCB-PATS was used for the kitchen, ambient and the exposure measurement. The UCB-PATS has a lower and upper detection limit of about 25 to ~25,000 µg/m3. The monitors were calibrated the values from an SNV-Berkeley Air Household Air Pollution study that was conducted in June – August 2015. They used a SKC Universal PCXR8 Air Sampling Pump to calibrate the UCB- Monitors. The Air Sampling pump uses gravimetric methods to analyse the air that is actively collected at the breathing zone using a flexible tube (Figure 5)[4].

Due to budget and equipment constraints the UCB-PATS was used for the exposure measurement. Surveyors were instructed to hang the UCB-PATS as close as possible to the head of the main cooker, and thus the breathing zone (Figure 7 on the next page). However, due to the size and weight of the UCB-PATS, the monitor was always hung at least 30 centimeters lower than the breathing zone when used as a personal monitor. Surveyors were instructed to keep a close eye on this and re-position the UCB-PATS whenever required.

Figure 5: SKC Air Sampling Pump

CO: The Easylog Carbon Monoxide (EL-CO) data logger of Lascar[5] was used to measure CO on a 30 second interval. This logger has a range of 0 to 300 PPM with a resolution and accuracy of 0.5 and ±6% respectively. The loggers were calibrated at the factory and valid for 3 years.

SUMs: The Stove Use Monitors (SUMs) in the form of Thermochron iButtons 1921G (Maxim Integrated Products) were used to record when a stove was being used. These devices enclose a silicon temperature sensor, a memory, a signal processing circuitry and a battery in a stainless steel can that has the size and appearance of a coin cell battery. This model operates between −40 °C and 85 °C, and can record up to 2048 temperature and date-time readings with ±1 °C accuracy. The SUMS were placed at location on the stove that is does not exceed the temperature at which they fail (<85ºC), preferably at the back of the stove and out of reach of the main cook.

Figure 6: SUMS on a biogas stove

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[3] *See http://berkeleyair.com/services/ucb-particle-and-temperature-sensor-ucb-pats/*

[4] *The study is not yet published.*

[5] *http://www.microdaq.com/lascar/co_data_logger.php*

<u>Installation</u>

In total 13 CO and PM2.5 loggers were used, in each household one for the kitchen- and one for the exposure measurement. For every 5 households, 3 loggers were used to measure the concentration of the pollutants in the ambient air in the village. These were placed at least 15 meter from a possible source of pollution and at a height of 3 meter. Ideally, this number would be higher but this was not possible due to budget and equipment constraints. There were around 15 SUMS available, where possible in each household one was used to measure the ambient air temperature in the kitchen, one on the main stove and one on the secondary stove.

In the kitchen the EL-CO and the UCB-PATS where placed at 1.45-meter height, 1 meter from the edge of the main stove and at least 1.5 meter from windows, doors or other openings (as per international norms). The main cooks of the households were selected for the exposure measurement and instructed to hang the EL-CO and the UCB-PATS at all time around their neck. At night however, they were allowed to place the instruments next to their bed. The ambient sensors were placed at a location of east 15 meters away from any potential source of air pollution at a height of approximately 3 meters.

<u>Monitoring protocols</u>

Monitors were generally deployed over 48 hours in both the baseline and the project households. This period included 2-full days of cooking; entailing in most cases 6 cooking events (two times breakfast, lunch and dinner). In practice the monitors collected data for at least 52 hours to ensure that they were running at time of installation and removal, but the data were truncated to 48 hours for analysis.

UCB-PATS: Monitors recorded for at least 52 hours with a 1-minute interval and truncated to 48 hours for analysis. Each UCB-PATS was zeroed by placing it inside a particle free plastic bag for 20 minutes to 2 hours before the start of the monitoring and 20 minutes after the end of the monitoring. The UCB PATS light-scattering sensing chamber of each UCB-PATS was cleaned every week with a wipe and cleansing alcohol. Batteries were replaced when the voltage dropped below 7.5 volt.

EL-CO: Monitors recorded for at least 52 hours each time data logging at 1-minute intervals and truncated to 48 hours for analysis. The sensors did not require any cleaning except for the removal of dust or other small particles that may attach itself to the sensor hood. The batteries of the EL-CO were removed when the software supplied by the manufacturer (EasyLog) gave a low battery warning or when the sensor indicator light turned red during the monitoring.

EL-CO | *UCB-PATS* | *Exposure measurement* | *Kitchen measurement* | *Ambient air measurement*

Figure 7: CO and PM2.5 data loggers and the measurement situations (main cook, kitchen and ambient)

SUMS: The SUMS logged the instantaneous temperature at 30 second intervals. It turned out that baseline stoves are often too hot for the SUMS even when a piece of wood is placed between the SUM and the stove as insulation. As a result, 5 SUMS failed; all in the cases of baseline households with traditional stoves.

Figure 8: SUMS

2.5 Questionnaire

A household questionnaire was developed covering socio-economic conditions, stove and fuel use, health assessment and kitchen characteristics. The questionnaire also included a twice daily equipment check. In case something was wrong with the equipment, i.e. dislocation or a weak battery, the issues were solved directly onsite. This is also included ensuring that the main cooker was wearing the equipment during the whole day, from the moment awakening until the moment of going to the bed, with the exception of taking a bath.

A separate questionnaire was developed for the ambient air sensors. This questionnaire consisted mainly of the twice daily data logger checks and a couple of questions targeted at the village chief on village population, biodigesters etc.

2.6 Statistical analysis

Arithmetic mean, SD and confidence intervals were calculated of the most important data using Microsoft Excel 2015. Statistical significance was obtained using the T- test, ANOVA and the Pearson product-moment correlation coefficient (PMMC) in the case of regression analysis.

3. Results

In the following sections the descriptive statistics are presented of the sampled population. Where the characteristics deviate substantially between the baseline and project, the project's household characteristic is colored red.

3.1 Household characteristics and kitchen

The next table details the basic characteristics of the selected households and in parenthesis the SD.

Table 2: Socio-demographics of the target groups (N=50)

Variable	***Value***	***Baseline***	***Project***
Average age	Years	44 (15)	43 (14)
Gender of main cook	Male	1	2
	Female	24	23
Household size	Members	4.48 (1.7)	4.64 (1.7)
Education level	University	1	0
	High school	2	6
	Primary school	15	10
	Little education	4	5
	No formal education	3	4
Literacy	Fully literate	36%	40%
	Can read, but difficulty with writing	28%	32%
	Illiterate	36%	28%
Occupation	Farmer	96%	92%
	Construction worker	12%	4%
	Other	4%	28%

Both populations, baseline and project, are very similar on most items. Project households appear to be better educated which could explain the higher literacy levels.

The next table shows who is cooking in the households, average age that the person started to cook, the time spent on cooking, meals per day and the cooking position of both the baseline and project households.

Table 3: Basic cooking characteristics

Variable	***Value***	***Baseline***	***Project***
Main cook[6]	Husband	1	2
	Wife	19	20
	Other	5	1
Average age of starting to cook	Year	14.8	14.8
Daily cooking time (self-reported)	Minutes	123	130
Meals cooked per day	Meal/day	3	3
Cooking position	Sitting	44%	8%
	Standing	36%	76%
	Both standing and sitting	20%	4%

The baseline and project households are very similar in terms of the length of cooking and the meals per day and the age when the main cook started to cook. However, there are significant differences in the cooking position. Most baseline cooks take a sitting position while the vast majority of project cooks stand. This difference is the result of NBP promoting the installation of kitchen counters for cooking. This may have some ramifications for the interpretation of the results.

Baseline and project household's kitchens characteristic are shown in the next table:

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[6] *Husband and wife is defined in this report as middle-aged person of the second generation. Grandmother and father belong to the third generation while the first consists of the children of the second generation.*

Table 4: Kitchen characteristics of baseline and project households (N=25 of each group)

Variable	***Value***	***Baseline***	***Project***
Kitchen type	Enclosed	32%	76%
	Semi-open	36%	12%
	Closed with gaps	32%	12%
Kitchen location	Separate building	44%	16%
	Separate room attached to the house	44%	72%
	Outside under a porch or under the house	12%	4%
	Other	0%	8%
Number of walls	2	12%	4%
	3	24%	8%
	4	64%	84%
Wall type	Closed	64%	84%
	With gaps	36%	16%
Floor type	Closed	80%	100%
	With gaps	20%	0%
Volume	m^3	13.7	42
Ventilation coefficient[7]	m^{-1} (m^2 /m^3)	0.72	0.19

Few baseline household's kitchens are closed and around a third of them have 3 walls or less. Their kitchens tend to be outside the house. Kitchens of project households on the other hand, tend to be closed with four walls without gaps and in a separate room attached to the house. Often when households invest in a biodigester they also change their kitchen location or even built a new room for the kitchen. Perhaps this is because biogas stoves burn smokeless and can even be used in houses with closed walls. More study is required on the actual reasons behind this.

The ventilation coefficient is defined in this report as the sum of the open area divided by kitchen volume. This coefficient indicates the ventilation area available for each cubic meter of kitchen volume. As witnessed from the table above, the kitchens of the baseline households are much better ventilated. This is likely intentional due to the smoke emissions from their wood stoves.

The kitchens of both groups are quite different. Baseline kitchens are often outside the house and are made from different materials compared to their house and also compared to the project households whose kitchen is often attached to the house or in the house, see the table below.

Table 5: Kitchen roofing and wall materials of the baseline and project households

Variable	***Baseline households***		***Project households***	
Kitchen wall material	***Main material***	***Secondary material***	***Main material***	***Secondary material***
Thatch	12	1	3	1
Corrugated iron	5	1	3	1
Wood	3	0	3	0
Bamboo	2	5	1	5
Bricks	2	0	15	0
Other	1	0	1	0
Kitchen roofing material	***Main material***	***Secondary material***	***Main material***	***Secondary material***
Thatch	11	0	1	0
Corrugated iron	11	0	14	0
Fiber cement	1	2	5	0
Other	1	0	5	0

Baseline kitchens are most often made from thatch, corrugated iron and to a lesser degree from wood, bamboo or bricks, while most project households' kitchens are made of bricks. The roof of the baseline kitchen is either thatch or corrugated iron; the kitchens of project households are also often made from corrugated iron but not from thatch.

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[7] *Calculated as $\sum$ (ventilation area / kitchen volume)*

This indicates that the kitchens of project households are a structure that belongs to the house and is a much more permanent structure.

In conclusion, baseline and project households have very different kitchens made with different materials, where baseline kitchens are much better ventilated compared to project households' kitchens (the ventilation coefficient is 3.79 times larger).

3.2 Stoves and fuels

3.2.1 Stoves in use

Baseline households

The survey found that all baseline households use wood for cooking; the use of other fuels is negligible. The most popular baseline stove is the Traditional Lao Stove (TLS) followed by the Thai Stove. A significant share of the households, 24%, use a primitive stove with a very low thermal efficiency: the double clay homemade stove (16% of the households) and a three stone stove (8% of the households).

Table 6: Frequency of stoves used by baseline households (survey method only)

Stove	***Percentage of households owning this stove***	***Average number per households***	***Used daily***	***Used weekly or less***
Traditional Lao Stove (TLS)	36%	0.56	89%	11%
Thai Stove	20%	0.32	100%	0%
Neang Kong Ray stove (NKS)	16%	0.16	75%	25%
Clay homemade	16%	0.32	100%	0%
Three stone stove	8%	0.08	50%	50%
New Lao Stove (NLS)	8%	0.08	100%	0%
Other	24%	0.24	86%	14%
Sum		**1.48**		

Just one household owns a LPG stove. That stove is only used a few times per month and only during special events and not for daily cooking. The next figure shows pictures of the best situation encountered, the most common and the worst.

Figure 9: Left to right: Best situation encountered: Fixed stove with chimney, most common situation (TLS) and worst situation encountered (Clay homemade stove)[8]

Project households

All project households use biogas for cooking and almost 50% uses wood in addition to this. All households own a biogas stove, one household a biogas rice cooker and a range of baseline stoves of which the TLS and the three stones stove are the most popular, see the next table:

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[8] *Three stone stoves may even have a lower thermal efficiency, but these stoves are generally used less frequently and in locations with more ventilation (in general outside the house)*

Table 7: Stoves owned and frequency of usage by the project households

Stove	***Percentage of households with this stove***	***Average number of stoves/hh***	***Used for every cooking event***	***Once per day***	***A few times per week or less***
Biogas stove	100%	1.84	96%	0%	0%
Biogas rice cooker	4%	0.04	100%	0%	0%
Traditional Lao stove (TLS)	16%	0.16	0%	33%	67%
Three stone stove	16%	0.16	0%	75%	25%
Other	40%	0.44	11%	44%	44%
Sum		**2.6**			

Project households own more stoves compared to the baseline households. They continue to own and use around 0.7 baseline stoves.

Around 36% of the biogas households are using a wood-fired stove on a daily basis and 48% are using a wood-fired stove on a weekly basis. The most common use is boiling water followed by animal feed preparation, see the figure to the right.

Cultural traditions, like making certain soups or special food during religious festivities often also impede using biogas. This however is not a frequent occurrence but when it happens it may result in using the baseline stove for multiple days.

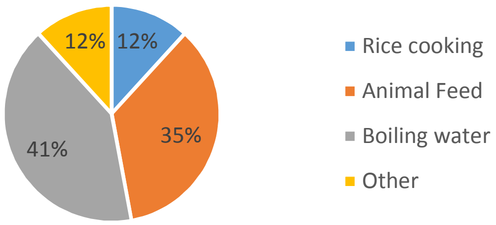

Figure 10: Purpose of using of the baseline stoves by project households

The picture below shows a relatively common kitchen of a project household.

Figure 11: A project household's kitchen with a baseline stove with chimney at the left and 2 biogas stoves at the right

3.2.2 Fuel use and fuel use reduction

The amount of fuel used for cooking, boiling water and animal feed preparation is shown in the next table.

Table 8: Wood fuel used by the baseline and project households

Use*	***Baseline household kg/day***	***Project household kg/day***	***Difference kg/day***
Cooking food and boiling water	3.34 (25)	0.34 (4)	3.00
Wood for animal feed preparation	0.23 (4)	0.46 (5)	-0.23
Sum	**3.57**	**0.80**	**2.77**

** n in parenthesis*

The primarily use of biogas is cooking and water boiling. Biogas will therefore displace around 3 kg of wood each day. Assuming that the thermal efficiency of the baseline stove is 20% and of the biogas stove 55% and the net calorific value of biogas 21.6 MJ/m^3 then this amounts to the use of 0.79 m^3 biogas per day. According to NBP, one kilogram of manure generates 40 litres of gas, thus around 20 kilogram of manure enters the digester on average each day.

Interestingly, fuel use for animal feed is higher in the project situation. This is the result of owning on average almost two times more pigs, 0.56 versus 0.20 on average of the baseline households (see chapter 3.3)

3.3 Animal ownership

An important determinant whether or not the baseline households are matching with the project households is the animal ownership, an important proxy for potential biogas production and fuel displacement potential. The next table shows that this is indeed the case, the population of the most important animal, cow, is similar between the groups as determined by a one-way Anova (F(24,25 = 0.948, *p* =0.55).

Table 9: Animals owned by the baseline and project households

Animal type		***Baseline households***		***Project households***	
		#/hh	***% owned***	***#/hh***	***% owned***
Cow	Adult	2.84		2.88	
	Youngster	1.24		1.00	
	Total	**4.08**	96%	**3.88**	92%
Buffalo	Adult	0.32		0.24	
	Youngster	0.12		0.20	
	Total	**0.44**	8%	**0.44**	12%
Pig	Adult	0.12		0.28	
	Youngster	0.08		0.56	
	Total	**0.20**	12%	**0.56**	20%

3.4 Other sources of air pollution origination from the households

There are various sources of air pollution other than cooking observed. The main ones are cigarette smoking and burning waste.

3.4.1 Cigarette smoking

Around a third of the households have one or more members that smoke cigarettes. In almost all cases it is a male member; either the husband or the grandfather. Smoking mostly occurs outside. Smokers smoke on average 13 to 18 cigarettes (baseline and project households respectively) per day, see the next table.

Table 10: Number and gender of smokers, cigarettes smoked and location of smoking (n=25 in each group)

Variable	***Value***	***Baseline***	***Project***
Total smokers	Yes	9	10
	Never smoked	16	15
	Ex-smoker	5	3
Smokers	Smokers in smoking hh	1.13	1.25
	Average in population	0.36	0.40
Share of family members that smoke	Wife	0%	0%
	Husband	20%	16%
	Grandfather	12%	16%
	Other	4%	8%
Gender	Male	89%	100%
	Female*	11%	0%
Where do you smoke?	Kitchen	0%	0%
	In the house	40%	29%
	Outside/other	60%	71%
Cigarettes per day	AVG smokers	12.78	17.4
	AVG in population/hh	4.60	6.96

** Only one elderly female smoked in the survey population*

The number of smokers is similar amongst the study groups. Project households however, smoke around 36% more cigarettes. Since the smokers most often smoke outside the house, it is not expected that smoking will affect the household air quality significantly.

3.4.2 Burning waste

There are no waste collection and disposal facilities in rural Cambodia. Households therefore, burn all their households and garden waste on a regular interval; around 1.4 times per week. Project households burn waste in 77% of the cases 1.94 times per week and in 23% of the cases 2.2 times per months. 65% of the baseline households do this 2.27 times per week and 35% does this 1.16 times per month, see the table below.

Table 11: Percentage frequency of households burning their waste

Variable	***Value***	***Baseline***	***Project***
Burning waste	Total (%)	88%	88%
	Weekly or more frequent (%)*	65% (2.27)	77% (1.94)
	Monthly or less frequent*	35% (1.16)	23% (2.20)
Population average	Times per week	1.39	1.36

** Frequencies are depicted in brackets*

In the sample population this turns out to be around 1.36 to 1.39 times per week on average. This source of pollution should not be underestimated. Households often burn their waste for a couple of hours each time and since it burns in the open with materials that are not always dry and may include plastics, the amount of smoke generated is considerable as the picture below exemplifies.

Figure 12: A relatively common example the smoke from burning household and garden waste

3.4.3 Other sources of air pollution in the villages

A number of other sources are not accounted for in the questionnaire or the measurement campaign. The main ones are:

- **Clearing of agricultural land**
  Rice stalks and other remaining agricultural residues from the previous harvest are generally removed by setting it on fire. Depending on the size of the land these fires can run for hours and generate a substantial amount of smoke and therewith high levels of PM2.5 and CO emission.

- **Clearing of forested areas**
  The only remaining forest in low land Cambodia are on the hills. These hills are also increasingly cleared by burning the bushes and other vegetation that remain behind when the trees are logged.

- **Road dust**
  The particulate size of road dust is in the order of 70 µg or larger. These coarse particles can aggravate heart or lung-related conditions such as asthma. Most roads in the village are unpaved while with the rapid economic development the amount of traffic is rapidly increasing. In the dry season this results in local dust clouds around the houses which affects health.

- **Home-based rice wine production and palm sugar production**
  Rice wine is produced through distillation of fermented rice and water and is a popular activity in rural areas. Rice wine stoves often run for the whole day and many days in the week. They are often built without a proper chimney and most of the times fuelled with rice husk. Local palm sugar production is made on large specifically designed stoves in a wok shaped pan of a diameter of approximately 80 cm. The palm sugar stoves are often fuelled with wood and most of the times do not have a chimney. Also this process takes a long time and these stoves are frequently used during the day during the palm fruit season.

  Both activities have received very little attention on how to improve the fuel efficiency and on how to reduce the associated air pollution caused by these stoves

Figure 13: Artisanal palm sugar production (left) and rice wine production (right)

3.5 Main cook's perception of air pollution

Main cooks were asked what, according to them, are the most important sources of indoor air pollution (Table 12). Not surprisingly, baseline households, which cook on smoky stoves, consider cooking a much more prominent source of indoor air pollution compared to project households.

Ambient air pollution is mostly, by both groups, attributed to burning waste, both residential and agricultural. Burning waste is an activity that can take several hours and often includes all the materials that have dropped on the land such as leaves, branches, and stalks, plastic and other waste. Project households also mention dust and cooking of other people. This may indicate a heightened awareness on the pollution that smoke from wood fired stoves causes. Traffic and dust is also mentioned more by the project households.

Table 12: Households' perception of the main sources of pollution

Variable	***Attribution***	***Baseline***	***Project***
Indoor air pollution	Cigarette smoking	32%	40%
	Burning fuel against insects	20%	28%
	Cooking	56%	28%
	Cooking by neighbors	12%	8%
Ambient Air pollution	Dust	12%	24%
	Burning of waste	68%	68%
	Traffic	8%	24%
	Cooking of other people	8%	28%

4. Household Air Pollution

In the next sections the results from the CO and PM2.5 measurements are described. '*Significant'* difference in the text means p-value of 0.05 or less and '*highly significant'* 0.01 or less.

4.1 Selected Air Quality Guidelines

The next table shows the WHO Air quality guidelines (AQG) for household fuel combustion (WHO, 2014), the Cambodian AQG guidelines (sub-decree 42), the PM2.5 AQG of neighboring countries (CAI, 2010) and the EU and the USA AQG.

Table 13: WHO, Cambodian, neighbouring countries, EU and the USA AQG

Guideline	***Pollutant***	***15 min***	***1 hour***	***8 hour***	***24 hour***	***1 year***
WHO AQG	PM2.5 target (µg/m^3)	-	-	-	20	10
	PM2.5 interim target I (µg/m^3)	-	-	-	-	35
	PM2.5 interim target II (µg/m^3)	-	-	-	-	25
	PM2.5 interim target III (µg/m^3)	-	-	-	-	15
	CO (mg/m^3)	100	35	10	7	-
European Commission[9]	PM2.5 (µg/m^3)	-	-	-	-	20
	CO (mg/m^3)	-	-	10	-	
USA EPA[10]	PM2.5 (µg/m^3)	-	-	-	-	12
	CO (mg/m^3)	-	35	9	-	-
Cambodia[11]	PM2.5 (µg/m^3)	-	-	-	-	-
	CO (mg/m^3)	-	40	30	-	-
Thailand and Vietnam	PM2.5 (µg/m^3)	-	-	-	-	50

Cambodia has not established an air quality standard for PM2.5. In Cambodia only a standard for total solid particles (TSP) sized 20 to 50 µm is available which are respectively 0.33 and 0.10 mg/m^3 for 24 hour and annual average (CAI, 2010). According to the Clean Air Initiative for Asian cities, TSP guidelines have lost their relevance because the larger particles that are part of TSP can be filtered by the nose and the mouth and are therefore not a good indicator for hazardous airborne particles (CAI, 2010). PM2.5 and PM10 guidelines are now preferred for a more targeted approach.

The results from the exposure and kitchen measurements will be compared against the WHO guidelines as these are the most updated, complete and reflect the latest scientific insights. In the case of PM2.5, it will be compared against the annual values as it is assumed that the results are representative for the annual PM2.5 levels. In the case of CO, it will be compared against the annual level, but also against short term exposure guidelines.

4.2 Ambient air PM2.5 and CO concentration

Differences in the exposure and kitchen concentration can be caused by compounding variables, such as the ambient air concentration during the measurement campaign (MC) of the baseline and project households. If however, there is no significant difference in the ambient air concentration of CO and PM2.5 between the studied groups then a reduction in exposure to these pollutants and a reduction in the kitchen concentration can be attributed to the improved cooking situation; biogas.

4.2.1 CO concentration in the ambient air

There is no significant difference in the average ambient air concentration of CO during the monitoring of the baseline and project households (p=0.41) (table 14). In most cases the average 24-hour concentration was 0.00

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[9] *http://ec.europa.eu/environment/air/quality/standards.htm*
[10] *http://www.airinfonow.org/html/data.html*
[11] *http://www.sithi.org/temp.php?url=law_detail.php&id=91*

mg/m^3 except for one measurement that was in both conditions above 0. Thus, the CO level in the ambient air is in general negligible.

There is also no significant difference in the average maximum concentration (p=0.067). However, although not significant, there is a considerable difference in the maximum values of 63%. It should be noted that the maximum concentrations are often short peaks and hardly affect the average concentration.

Table 14: Ambient CO concentration during the measurement of baseline and project households.

Ambient CO *(mg/m^3)*	***Baseline MC***	***Project MC***	***Percent difference***	***t-Test (p-value)***
24-hour average	0.017 (0.04)	0.012 (0.04)	30%	0.41
Peak concentration	16.6 (19.5)	3.6 (3.8)	63%	0.067

**standard deviations are shown in parentheses*

Although there is no statistically significant difference in the CO concentration, it should be noted that the sample was relatively small. In total only 10 measurements were available for each group instead of the 15 planned. This was the result of 2 EL-CO data loggers that were malfunctioning or were not properly calibrated at the factory and due to issues related to underperforming spare batteries.

4.2.2 PM 2.5 Concentration in the ambient air

The average ambient air concentration of PM2.5 lower when the project households were monitored but the difference was not significant. The 15 peak on the hand was statistically different, see below.

Table 15: Ambient PM2.5 concentration during the measurements

Ambient PM	***Baseline MC***	***Project MC***	***Percent difference***	***t-Test (p-value)***
24-hour average (µg/m^3)	41.32 (27)	31.93 (20)	-29%	0.16
15 min peak concentration (mg/m^3)	5507 (6570)	2008 (2560)	-64%	0.04

In conclusion, although there is a difference in the concentration of the pollutants during the MC, the situation is not statistically different and can therefore be assumed, with some reservations, as equal. Therefore, any differences observed in the levels of PM2.5 between the groups are not caused by differences in the ambient air levels but may be attributed to the different cooking technologies or other unmeasured compounding variables.

4.3 Kitchen concentration of PM2.5 and CO

4.3.1 Kitchen concentration of CO

The difference in CO kitchen concentration is highly significant (Table 16). Kitchens in households that rely on biogas have a very low concentration of CO which indicates a good combustion of biogas. The average peak value is reduced with 59% compared with baseline households and the average 24-hour concentration with 96%.

Table 16: Average CO kitchen concentrations in baseline households using wood-fired stoves and project households using primarily biogas stoves

Kitchen CO *(mg/m^3)*	***Baseline scenario***	***Project scenario***	***Percent reduction***	***t-Test (p-value)***
24-hour average	4.19 (7.49)	0.15 (0.17)	96%	0.006
Average peak	201 (127)	20.6 (34)	59%	5.33×10^{-8}

The discrepancy in the reduction between the 24-hour average and the average peak may be caused by the fact that almost half of the biogas households continue to use wood, albeit with a much lower frequency compared to the baseline households: typically baseline stoves are only used once per day and not for every meal by project households that continue to use wood, see table 7. Once the wood stove is used, the CO concentration may reach high peak concentrations for a short moment, similar to what occurs at baseline households. This may explain why the average peak concentration is reduced to a lesser degree compared to the average.

All the project households meet the WHO AQG, their CO levels are within the range to what is considered not causing harm; below the counterfactual level. Two baseline households on the other hand do not meet the AQG_{1y} but their 8-hour levels remained lower than the AQG_{8h}. The next table shows the baseline household that did not meet the WHO AQG_{1h} and AQG_{15min}.

Table 17: Baseline households with unhealthy 15 min and 1 h CO kitchen concentrations

Household	***$AQG_{15\ min}$ (≥100 mg/m^3)***		***AQG_{1h} (≥35 mg/m^3)***	
#	*Minutes/day*	*mg/m^3*	*Minutes/day*	*mg/m^3*
1	202	177.6	254	175.9
2	125	204.6	255	133.6
3**	15	117.1	94	42.7
4*	-	-	60	40.8
5*	31	160.2	60	90.7

** 1-hour concentration was only observed one time in 48 hours: * only occurred once in 48 hour

In total 5 out of 25 baseline household kitchens, or 20%, have unhealthy levels of CO for a short period during the day. The level is often much higher than to what is considered healthy. For example, household 1 has for 202 minutes per day an exposure of 177.6, or 77% higher to what the WHO considers as acceptable.

The 1-hour CO concentrations in those kitchens are also too high as per the Cambodian AQG_{1h} of 40 mg/m^3.

4.3.2 Kitchen PM2.5 concentration

The difference in PM2.5 kitchen concentration is highly significant, in spite of the much higher ventilation coefficient of the baseline kitchens. The overall 24-hour mean is reduced with 83% and the maximum mean with 67% (table 18)

Table 18: Average PM2.5 kitchen concentrations in baseline households using wood-fired stoves and project households using primarily biogas stoves*

Kitchen PM2.5 *(µg/m^3)*	***Baseline situation***	***Project scenario***	***Percent reduction***	***t-Test (p-value)***
24-hour average	229 (265)	28 (32)	88%	0.0002
15 min peak concentration	5759 (6844)	536 (547)	91%	0.0002

**standard deviations are shown in parentheses*

The annual WHO AQG for PM2.5 is 10 µg/m3. None of the kitchens can meet that guideline. The interim target I, the least stringent target of 35 µg/m^3, however is met by 20 project households' kitchens, or 80% of them and by 1 baseline kitchen. The interim target II of 25 µg/m3 is met by 16 (64%) by the project households and by 1 baseline household's kitchen. Based on this it can be concluded that cooking in biogas kitchens are much cleaner compared to kitchen's where wood is used as fuel.

The next table shows the 15 minute highest, second highest and the third highest average kitchen concentrations.

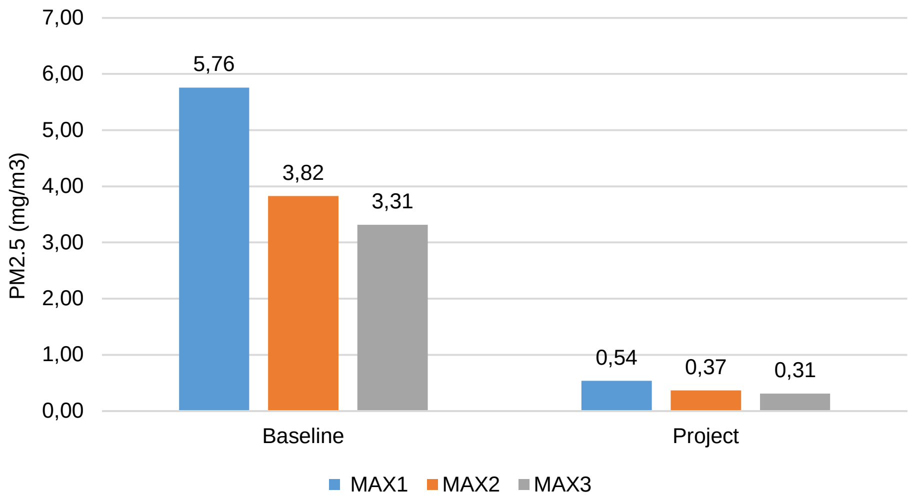

Figure 14: First, second and third highest 15 minute maximum average kitchen concentration of PM2.5 over a 48 hour period

The differences between the 15-minute highest average is over 10 times lower and highly significant (*p* = 0.0002) in the project kitchens compared to the baseline kitchens. This clearly demonstrates that biogas is a much cleaner fuel. Potential health effects of short-term high levels of PM2.5 are discussed in chapter 4.4.2. In addition, the 15-minute highest 15-minute maximum of the biogas kitchens are on average *lower* than the 48-hour average concentration in baseline households' kitchens.

Ranking

The kitchens have also been ranked by the cleanest to the dirtiest based on the 24-hour mean PM2.5. The cleanest 25 households are 24 project households and 3 baseline kitchens (rank 11, 22 and 25). In case of the baseline kitchen, this includes one households with a home-made clean stove in a kitchen made of thatch with large openings, one cement stove with a chimney and one with 2 relatively new TLSs. The project households that did not belong to the 25 cleanest, were ranked 30, 33 and 34th cleanest. Two of the kitchens looked very clean, but were mostly closed with limited ventilation and one was an open but dirty kitchen. One of these households also burned waste nearby which was measured by the data logger in the kitchen.

4.4 Exposure to PM2.5 and CO

4.4.1 Personal exposure to CO

The reduction in exposure to CO is highly significant. The 24-hour mean is reduced with 80% and the average maximum mean with 63%.

Table 19: Average exposure to CO in baseline households using wood-fired stoves and project households using primarily biogas stoves

CO exposure* *(mg/m^3)*	***Baseline scenario***	***Project scenario***	***Percent reduction***	***t-Test (p-value)***
24-hour average	0.18 (0.20)	0.03 (0.08)	80%	0.0024
Peak concentration	78.64 (59.29)	28.80 (24.82)	63%	0.0007

**standard deviations are shown in parentheses*

The exposure to CO is lower than the CO kitchen concentration (see chapter 4.3.1), both the 24-hour mean and the average peak. Typically, rural Cambodian houses are built on stilts which creates a large open and well ventilated space under the house. As that space is the coldest place in the house most people reside there during the day. Exposure values to CO but also PM2.5 (see section 4.2.2) are consequently very low during those times.

Given that most kitchens have 3 or more walls the ventilation is less and that may explain why the kitchen concentration is much higher compared to the exposure (see Table 4 on the kitchen characteristics in chapter 3.1).

None of the main cookers experienced CO concentrations above the WHO AQGs, including the 8 and 1 hour and 15-minute guideline.

4.4.2 Personal exposure to PM2.5

The reduction in exposure to PM2.5 is highly significant for the reduction to the maximum value (78%, p=.002) and significant (p=.025) for the 24-hour mean value:

Table 20: Average exposure to PM2.5 in baseline households using wood-fired stoves and project households using primarily biogas stoves

PM2.5 exposure (µg/m^3)	***Baseline scenario***	***Project scenario***	***Percent reduction***	***t-Test (p-value)***
24-hour average	93.9 (69)	59.7 (49)	36%	0.025
15 min peak concentration	3,522 (344)	1,020 (1050)	71%	0.0005

Only 8 main cooks using biogas and 4 main cooks using baseline stoves are exposed to levels that meet the WHO interim target I. Two the baseline cooks are exposed to levels as low as WHO interim target II and out of the 8 project cooks that met WHO interim target II, 7 also meet interim target II. In conclusion, most cooks of both groups are exposed to unhealthy level of PM2.5, 68% in the case of the project households and 84% in the case of the baseline households.

The personal exposure to PM2.5 is lower for baseline households compared to their kitchen, but higher for project households. This indicates that the baseline kitchen causes more PM2.5 pollution compared to other sources. In case of the project households that situation is reverse, most of the PM2.5 does not come from the kitchen but from other, outside the kitchen, sources.

Interestingly, the reduction of exposure to CO (chapter 4.4.1) is much higher compared to PM2.5. This may be caused by the different modes of diffusion:

- PM2.5 is an aerosol; aerosols are a colloidal system of solids in a gas (air). Aerosols will eventually settle due to gravity-induced-drag. Near houses or trees however aerosols can cause locally high concentrations in the air. This was often observed at the end of the day, when the air turned hazy at the moment that all households started to cook in the village.
- Diffusion of CO on the other hand less is affected by the gravity because the molecular mass of CO is quite similar to other molecules in the air. CO will therefore freely diffuse in the air, where the flux depends on the concentration gradient between two regions of gases (the Fick's Law) and the wind direction. CO will therefore diffuse more freely and much faster. This may explain why the reduction in exposure to CO is larger than the reduction in PM2.5.

The first, second and third maximum 15-minute average is also lower in the case of project households, see the figure below.

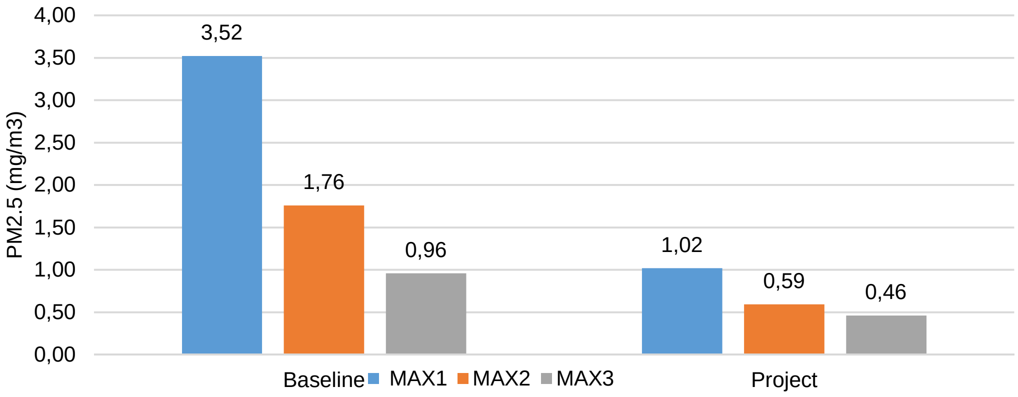

Figure 15: First, second and third 15 minute maximum average exposure to PM2.5 over a 48 hour period

The cooks of baseline households are exposed to higher PM2.5 peak concentrations compared to biogas households.

The WHO did not institute 8 hour or shorter guidelines for PM2.5. Some studies however have found indications that short-term exposure to PM2.5 levels can increase death from heart disease and respiratory diseases (Newby, et al., 2014). According to Newby et al (2014), a 10 µg/m^3 increases mortality with 1%, mortality due to respiratory diseases with 1.5% and cardiovascular diseases with 0.8%. However, Newby et al (2014) caution that there is substantial regional variation worldwide. Another study executed in Massachusetts, the United Stated, for example on short-term exposure found that for every 10 µg/m^3 increase in PM2.5 exposure there was a 2.8% increase in PM related mortality (Kloog, Ridgway, Koutrakis, Coull, & Schwarts, 2013).

In general, there is evidence that short-term exposure to high concentrations of PM2.5 is damaging to health and increases PM2.5 related mortality. However, more epidemiological research is required to estimate the exact health impact of short-term exposure to high levels of PM2.5.

5. Analysis of results

5.1 PM2.5-CO relationship

PM2.5 is thought to be the single best indicator to measure the health impact (Pokhrel, et al., 2015). Many studies have established a PM2.5-CO relationship for kitchen concentrations of wood stoves and recently a longitudinally personal-exposure PM2.5-CO relationship (MCraken, Schwartz, Diaz, Bruce, & Smith, 2013). The focus of these studies was on wood fired stoves and the relationship may not exist for clean fuels such as biogas.

The stoichiometric equation of the combustible part of biogas, methane, is the following:

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

Complete combustion only has 2 products, carbon-dioxide and water. Incomplete combustion is the main cause of PM2.5 emissions. However, when biogas is combusted incompletely, the follow stoichiometric relationship only yields carbon monoxide and water as products.

$$CH_4 + 1.5O_2 = CO + 2H_2O$$

It is therefore hypothesized that a PM2.5-CO relationship only exists with wood fired stoves and not with biogas stoves.

5.1.1 *Kitchen CO-PM2.5 relationship*

In the following figure the relationship between CO and PM2.5 of baseline kitchens is shown. The Pearson product-moment correlation coefficient (PMMC) r is 0.64, thus 64% of the PM2.5 concentrations can be explained by between subject variance in kitchen CO.

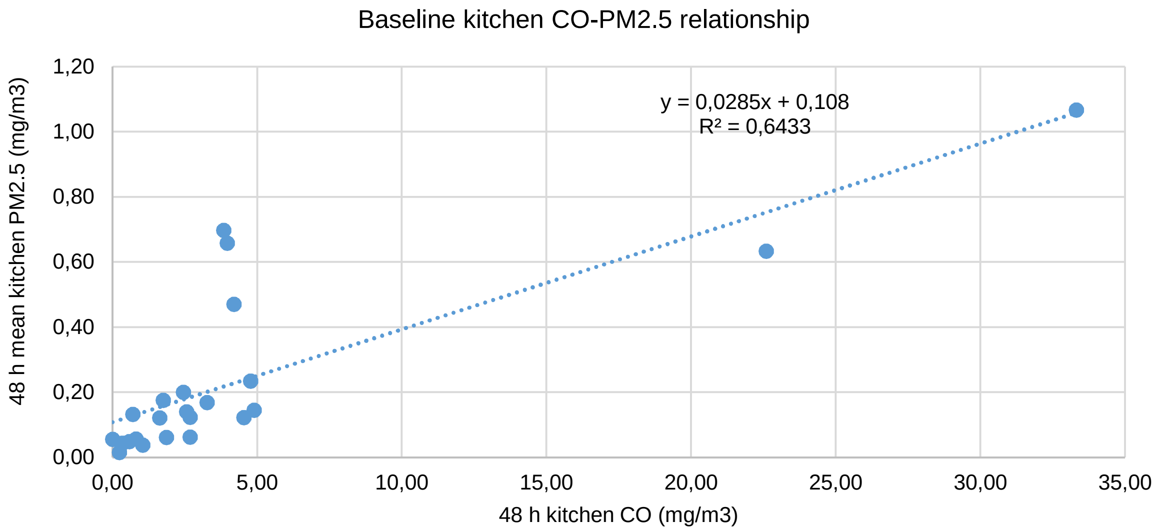

Figure 16: Scatter plot of simultaneous 48-hour baseline kitchen PM2.5 and kitchen CO

In another study a stronger r^2 of 0.76 was found for the CO-PM2.5 relationship (Northcross, Chowdhury, McCracken, Canuz, & Smith, 2010). The CO and PM2.5 is different which is not that surprising given that their study was conducted in a completely different country; Guatemala.

The PMCC of project household’s kitchen CO-PM2.5 relationship is only 0.23, see the graph below.

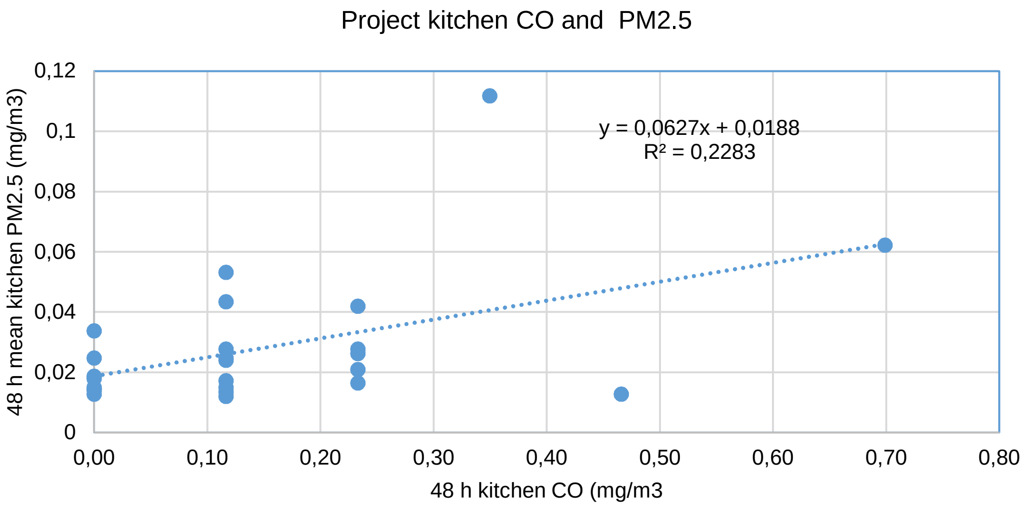

Figure 17: Scatter plot of simultaneous 48-hour Project kitchen PM2.5 and kitchen CO

Based on this it can be concluded that a CO and PM2.5 are only weakly related in biogas-using kitchens. In the case of biogas 77% of the observed variance can be explained by other compounding variables. For that reason, CO or PM2.5 cannot be used as a proxy for the other pollutant in the case of biogas.

5.1.2 Personal CO-PM2.5 exposure relationship

McCracken et al (2013) found that personal CO explained 78% of the between subject variance in personal PM2.5 in a longitudinally study in Guatemala where wood combustion was the main source of pollution. In another study at this site this was estimated to be 73% cooking on open fires (Northcross, Chowdhury, McCracken, Canuz, & Smith, 2010).

This relationship was not observed in Cambodia. In the case the baseline households the PMCC was only 0.02. In the case of project households, it was not even possible to establish a relationship as the average CO exposure level concentration was often very low and at those levels the monitors are not very accurate.

5.2 Attribution of Ambient Air Pollution to HAP

HAP is the sum of the pollution generated in-house and of the polluted ambient air that enters the house. In relatively clean kitchens where households use biogas, it is hypothesized that most pollution originates from the ambient air and not from the stoves.

5.2.1 Attribution of ambient CO to HAP

The next figures show kitchen and exposure concentrations of the two conditions (baseline and project) and the ambient pollution adjusted value where the CO level in the ambient air is subtracted from the kitchen and the exposure CO levels. The remaining HAP may be attributed to the emissions from the stove.

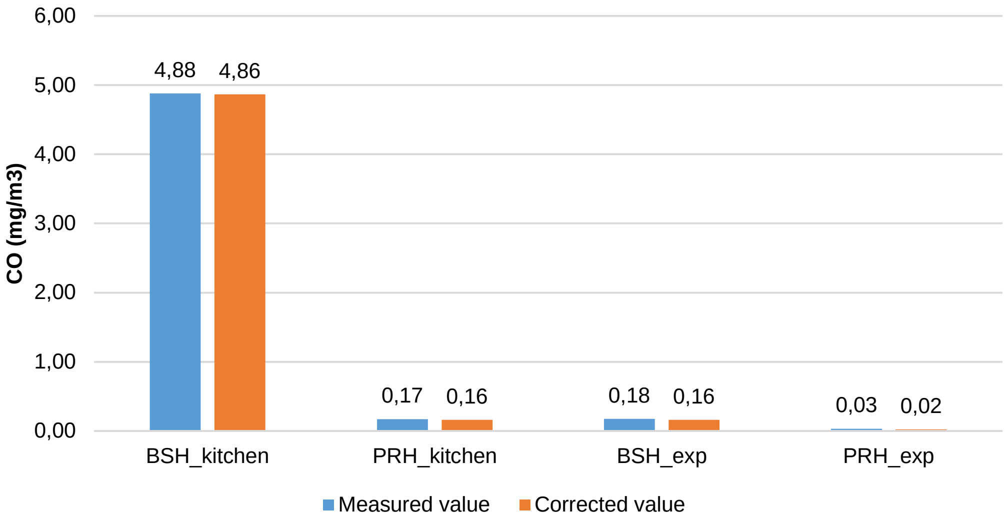

Figure 18: CO measured and adjusted values across the 2 conditions

(BSH = baseline households, PRH = Project households)

In neither of the cases there is a substantial difference between the adjusted value and the measured value. This mostly the result of the negligible CO concentration in the ambient air.

The project household's adjusted exposure value is 33% lower; however, the non-adjusted value is already much lower than the WHO AQG and below the counterfactual level. Given that the levels are so low; the reduction may well be within the margin of measurement error.

5.2.2 Attribution of ambient PM2.5 to HAP

The next figure shows the adjusted emission values by subtracting the PM2.5 ambient level from the measured kitchen and the exposure levels. The difference could be attributed to the PM2.5 emissions from the stove.

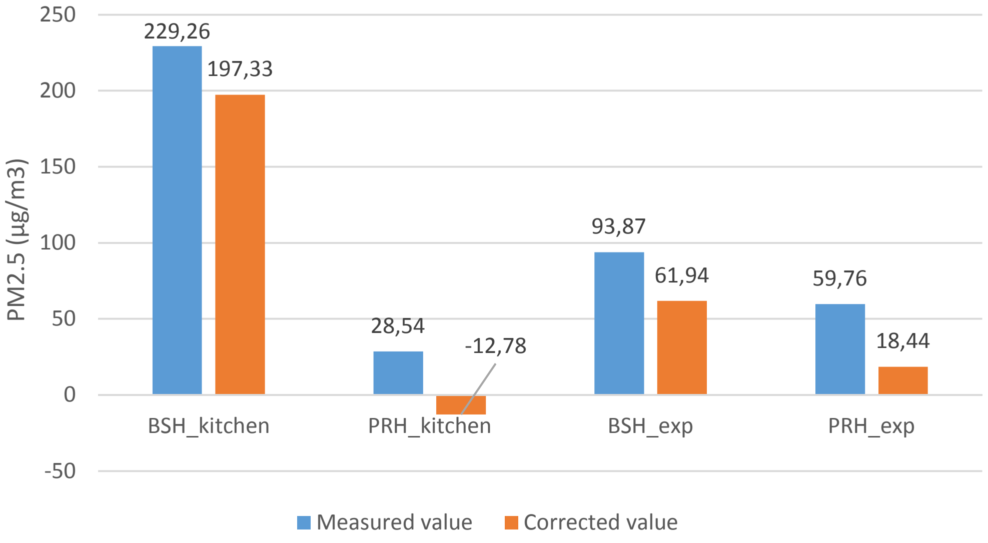

Figure 19: PM2.5 measured and adjusted values across the 2 conditions

(BSH = baseline households, PRH = Project households)

In the case of exposure, the ambient air explains around 69% of the PM2.5 exposure of the biogas users and around 34% of the baseline users. The baseline kitchen however, is much less affected by the ambient air levels, only 14% is attributed to the ambient air, but this situation is completely opposite in the case of biogas households. In the latter, the average ambient PM2.5 level is higher than the project household’s kitchens level. This indicates that the PM2.5 emissions from biogas stoves is negligible and that kitchens of biogas households are polluted by sources outside the kitchen. The negative PM2.5 adjusted level is likely the result of a measurement inaccuracy stemming from the fact that there were only 3 ambient air sensors available for every 5 households.

However, although plausible, it is not possible to conclude that biogas stoves do not produce PM2.5. This can only be established by measuring the emissions from the biogas stove directly with a stove emission measurement system which analyses the particles and gases released during the combustion of biogas in the exhaust air. The emissions however are likely low, for example, according to WHO the PM2.5 emissions of LPG stoves are around 0.015 g/MJ compared to a 100 times higher value of 1.2 g/MJ for wood stoves (WHO, 2014). Biogas, being a clean gas similar to LPG is likely to have a similar PM2.5 emission factor.

The average non-adjusted PM2.5 concentrations in the kitchens are higher than the WHO AQG interim target I and are considered unhealthy. However, this study suggests that most of the pollution in project households are due to activities outside the households. Therefore, only when these sources are addressed the PM2.5 concentrations can drop to levels lower than the WHO AQG guideline of 10 µmg/m^3. Achieving this will be challenging as it requires a community approach where households not only switch to clean fuels but where also other sources of pollution are addressed such a burning household and garden waste (see chapter 3.4.3 on the other sources of air pollution) and tackles issues related to stove stacking as a considerable share of biogas households continue to use a baseline stove (often outside their kitchen).

6. Health impact

6.1 Disability-Adjusted Life Year (DALY)

DALY, Disability-adjusted life year, is a metric used in health sciences to assess the health impact. One DALY can be considered as one lost year of ‘healthy life’. This measurement unit is used to quantify and compare the burden of diseases, injuries and risk factors across different populations, disease, risk factors, etc. The unit is grounded on cogent economic and ethical principles and can guide policies towards more cost-effective and equitable health care (Murray & Acharya, 1998).

The sum of these DALYs across the population, or the burden of disease, can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability. DALY is the sum of Years lived with disability (YLD) + the Years of Life Lost (YLL) due to premature death, see the next figure:

Figure 20: Understanding DALY, YLD and YLL

6.2 Burden of disease in Cambodia

The Global Burden of Disease 2010 study estimated the DALYs attributable to HAP at 429,426 in Cambodia (IHME, 2013). The 2013 update puts this at 397,597 disability-adjusted life years (DALY) (IHME, 2015). HAP is the second risk factor to disease after dietary risks, see the next figure

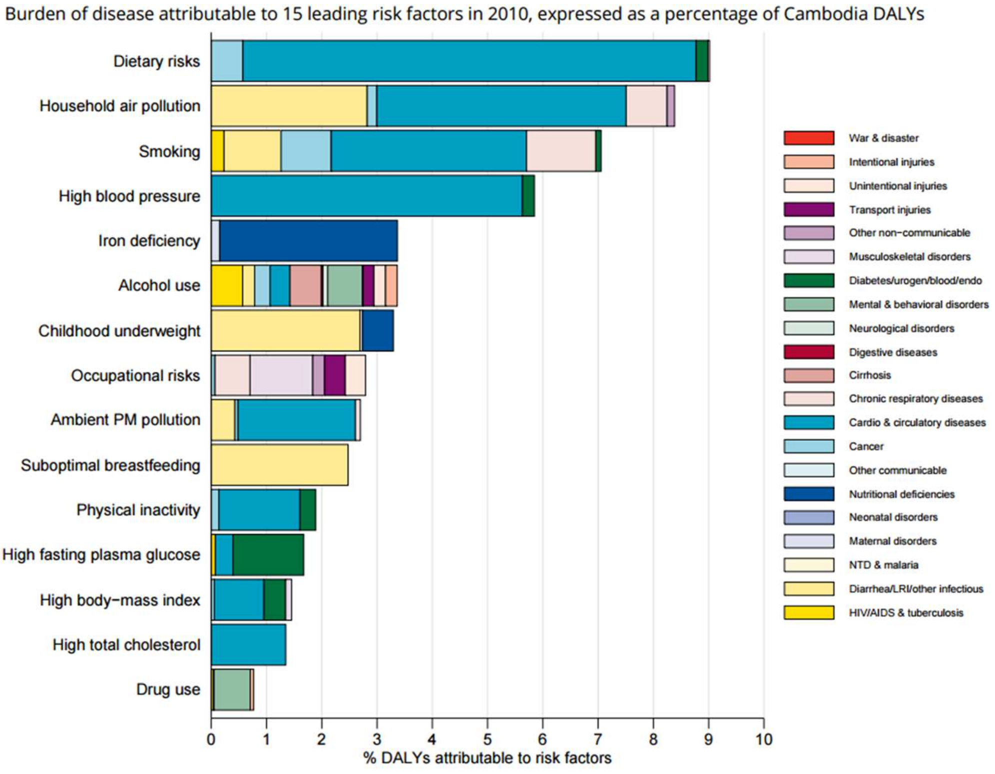

Figure 21: The top 15 risk factors. The coloured portion of each bar represents the specific disease attributable to that risk factor (IHME, 2013)

HAP is the second risk factor to DALY in Cambodia. In 2010 the total number of HAP DALYs in Cambodia is around 429,426 and of those 11,876 premature annual deaths are attributed (Table 21); 6,029 males and 5,847 females (IHME, 2013). This was updated in 2013 to 397,597 DALYs and 14,729 premature deaths (IHME, 2015). In this report however the 2010 values are used as based on that the tools for the health impact are based (see chapter 6.3). HAP is the third cause of death in Cambodia, the fourth for males after dietary risks, smoking and high blood pressure and the third cause of death for females after dietary risks and high blood pressure. The figure below lists the causes of premature death in Cambodia (IHME, 2013):

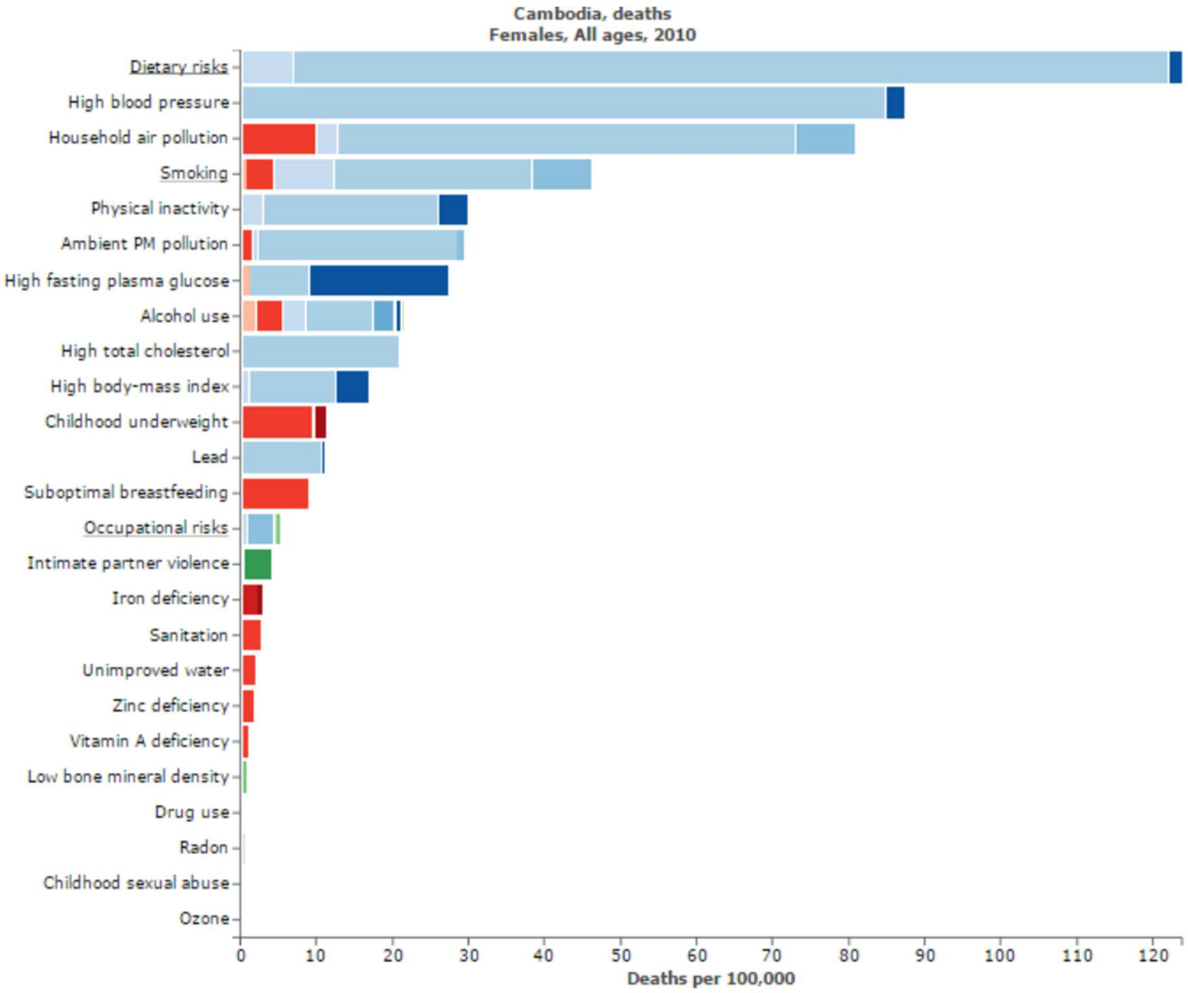

Figure 22: Risk factors attributed to premature death in Cambodia

The number of premature death by gender and for children aged 4 years or below is shown in the next table:

Table 21: Causes of premature deaths attributed to HAP in Cambodia

Cause of death	*Male*	*Female*	*Total*	*Children (<5y)*
Lower respiratory infections, meningitis and others	958	716	1,674	716
Neoplasms	140	196	336	0
Cardiovascular and circulatory diseases	4,476	4,362	8,838	0
Chronic respiratory diseases	455	573	1028	0
Sum	**6,029**	**5,847**	**11,876**	**716**

Most HAP deaths attributed to lower respiratory infections, i.e. ALRI, occurs at children lower than 5 years of age.

The WHO's latest assessment of Cambodia of 2012 estimated a lower burden of disease attributed to HAP; a mortality estimate of 8,942 and 367,604 DALYs (WHO, 2015). The WHO has adopted a simpler form of DALY used in the global burden of disease study: '*Age-weighting and time discounting are dropped, and the YLDs are calculated from prevalence estimates rather than incidence estimates'.* According to the WHO, estimates can differ substantially, which is the case for HAP.

Other noticeable differences between the data sets arise from the impact of HAP by gender. The WHO estimates that HAP affects more women than men (3,183 versus 3,691 deaths) while the Global Burden of Disease study estimates that HAP affects more men (see Table 21) except for the deaths related to chronic respiratory disease (i.e. COPD) and neoplasms.

It is out of scope of this report to assess the exact reasons behind the discrepancy between the data sets. The Global Burden of Disease (GBD) project seems more comprehensive compared to the WHO and is also used for the Household Air Pollution Intervention Tool (HAPIT) that is used in the next chapter to assess the health impact biogas. This report therefore relies on the GBD data.

6.3 Averted HAP DALYs and Deaths

Switching to a clean energy service will reduce the burden of disease attributable to HAP. This reduced burden of diseases can be expressed in averted DALYs or aDALYs and averted deaths and can be calculated with HAPIT. HAPIT is created by Ajay Pillarisetti and Kirk R. Smith of the Household Energy, Climate & Health Research Group and supported by the GACC is designed to assess the health benefits attributable to stove and/or fuel interventions that reduce HAP[12]. HAPIT expresses the benefits in aDALYs and prevented premature deaths. HAPIT is based on the 2010 GBD assessment. The 2013 update shows that the number of estimated HAP attributed DALYs decreased slightly but the mortality estimated increased substantially, see the figure below (IHME, 2013) and (IHME, 2015):

Table 22: HAP burden of disease in Cambodia

GBD Cambodia	DALYs	Premature Deaths
2010	429,426	11,876
2013	397,597	14,729

The reduction of DALY is caused by a lower ALRI DALY estimate while the increase in premature deaths is associated with a mortality increase of HAP attributed cardiovascular diseases and chronic respiratory diseases. In this section however, the 2010 GDB is used as HAPIT is based on this. The actual estimates may therefore be higher in the case of the premature deaths and a bit lower in the case of DALYs.

HAPIT also assesses the cost-effectiveness of the health intervention, where the costs for each aDALY is calculated due to the intervention. HAPIT considers an intervention cost-effective when it costs at maximum 3 times the per capita Gross Domestic Product (GDP) per aDALY. The HAPIT tool however cannot be used to assess the cost-effectiveness of biodigesters as HAPIT can only be used for an intervention that lasts up to 5 years. Fixed dome biodigesters on the other hand, have a lifespan of 20 years or more (Buysman & Mol, 2013). HAPIT will consequently deem biodigester projects as not cost-effective. In addition, biodigesters have a wealth of other (health) benefits arising from improved sanitation (and related health benefits) to increased and improved crop yields which are not accounted for. HAPIT was therefore only used to assess the health impact of the use of biogas as cooking fuel.

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[12] *HAPIT can be found here: https://hapit.shinyapps.io/HAPIT/*

6.3.1 Calculation HAPIT background

HAPIT applies a cessation lag to chronic diseases, where 30% of the benefits are accrued after 1 year of the project intervention, 80% after 5 years and the final 20% are only accrued in year 20, see the figure below.

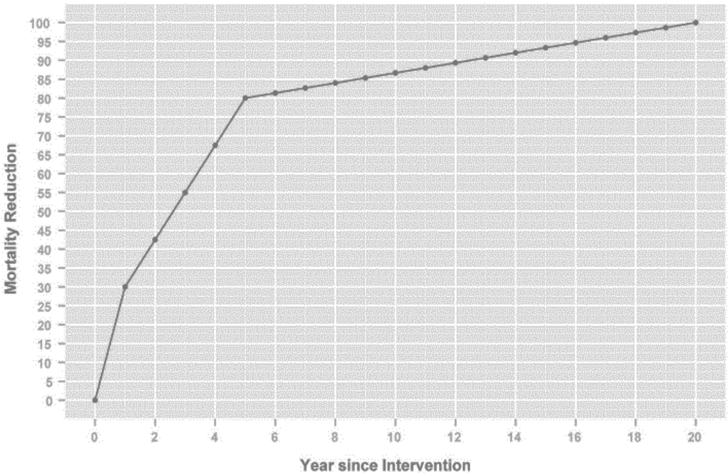

Figure 23: EPA's cessation lag function (Smith & Pillarisetti, 2015)

Non-chronic diseases such as ALRI however are linearly accrued, where in each year the number of aDALYs will increase with the same amount.

Therefore, if one wants to calculate the benefits accrued as a results of the NBP sales, a separate calculation is required for each year. For example, the total attainable benefit depends on the evaluation period and the application of EPA's 20 Year cessation lag. A graphical depiction of how benefits are calculated – which takes into account both the evaluation period and the EPA lag -- is presented below.

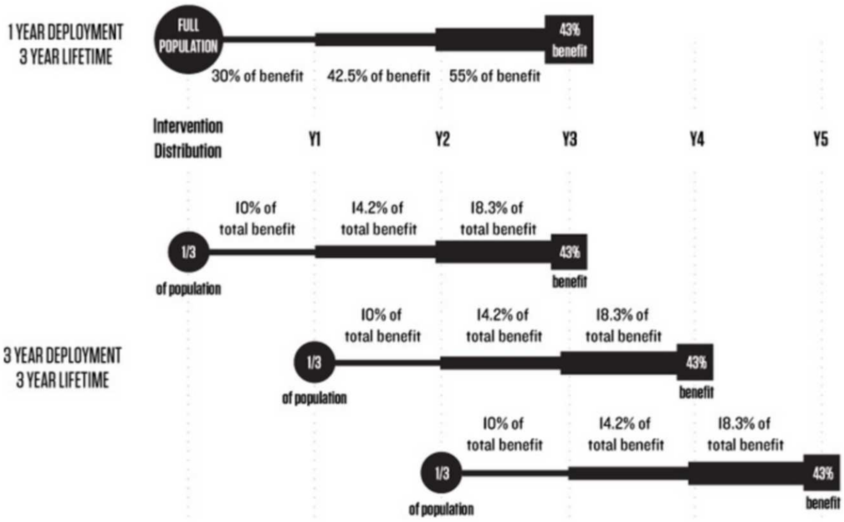

Figure 24: Benefits accrued for different deployment years (Smith & Pillarisetti, 2015)

Thus, an intervention attains 30% of its benefit after 1 year, 42.5% after 2 years and 55% after 3 years.

The benefits are calculated with the following assumptions/data:

- **Data used**
  The data used for HAPIT originates from the annual NBP Carbon Monitoring reports, authored by the same author. These reports are all third party verified and rely on primary data collection through field surveys and include quality control checks. Important data from those reports are: the usage rate (share of units in use in a particular year) and the number of digesters installed each year.
- **Start-date: Benefits accrued per year**
  The start date of the benefits accrued is calculated as the average aDALYs of an intervention period starting at year y and year y+1. For example, the intervention period at year 2010 from a population of digesters built in 2006 (year y) is 4 years (2010-2006) and the intervention period of year y+1 is 3 years (2010-(2006+1)). The average number of aDALYs attained is then the average of an intervention period of ((4+3)/2) = 3.5 years. This method ensures that the number of aDALYs corresponds with the average digester age, which is 3.5 years in 2010. This method is a simplification of the reality as it assumes that the digesters are constructed evenly distributed in each month of the year.
- **Chronic diseases**
  Chronic diseases, COPD, IHD etc. are calculated using the EPA cessation lag function. This function takes into account that HAP improvement does not immediately yield health benefits, this may take years for certain chronic diseases. The average cessation lag of a digester population is calculated by weighting the accrued share of benefits by disaggregating the digester population in when the digesters were built, the benefits attained in that particular year based on the EPA cessation lag and weighted based on the number of digesters built, see Annex I for an example calculation.
- **Non-chronic diseases**
  Benefits accrued are linear for non-chronic diseases. The number of benefits B accrued in year y+1 are based on the benefits A of year 1 from HAPIT and calculated with the following equation

$$B = \frac{year\ y + 1}{year\ y} \times A$$

- **Benefit of intervention:** The benefits calculated in HAPIT are based on PM2.5 improvements. The exposure PM2.5 results from this study are used, which are and 114.6 and 81.60 µg/m^3 for the baseline and project households respectively.
- **Counterfactual exposure:** Burden of disease estimates and health benefits estimated by HAPIT require definition of an 'ideal' counterfactual exposure, below which there is no risk to health. In the 2010 Burden of Disease, this value was set at 7.3 µg/m3 for annual average PM2.5 exposure. In HAPIT, the default value is 10 µg/m3, which is the official Air Quality Guideline of WHO.
- **Model validation**
  This method has been discussed extensively with HAPIT staff[13]. They approved this method and said that they use a similar method for initially determining the number of benefit years for which an intervention can be credited. They warned to be careful with projection of results after 5 years, as, according to their own experience, the intervention of many projects ceased after 5 years, including biodigester projects. They additionally cautioned that use of HAPIT over long durations of time ignores changes in background disease rates and development, which will impact both the calculated cost-effectiveness of the intervention and the total number of deaths and DALYs averted. In the case of NBP, the annual monitoring report show that digesters continue to be used after 5 years, but that the drop-off rate increases with around 2% per year. For example the average weighted drop-off rate in the year 2013 was 90% and in 2014 88% of the digester population built since 2006 (Buysman, 2015).

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[13] *Email communication with Ajay from HAPIT by email on 24 June, 2,4,5,7,9,13,20 and 21 July 2015*

6.3.2 NBP aDALYs accrued in 2006 to 2014

In the period 2006 to 2014 NBP has constructed 22,117 digesters. The table below specifies this by year.

Table 23: Digester sales by year

Year	*Digester sales*	*Cumulative*
2006	294	294
2007	1,150	1,444
2008	2,340	3,784
2009	2,616	6,400
2010	3,744	10,144
2011	4,826	14,970
2012	4,201	19,171
2013	1,115	20,286
2014	1,831	**22,117**

The benefits accrued where calculated with the method specified in chapter 6.3.1 and are based on the following input values:

Table 24: HAPIT input values

Item	*Baseline PM2.5 exposure*	*Project PM2.5 exposure*	*Units built (31-12-2014)*	*Usage rate*[14]
Value	94	59.17	22,117	88%

** rounded to 94; HAPIT does not accept a value with digits for the baseline*

Annex I details the calculations. Based on the EPA cessation lag, the average weighted benefit of the population is equivalent to EPA lag year 3 and 4. The results are calculated by averaging the results from an intervention with a lifespan of 4 years and one of 3 years.

- ***Health impact in the period 2006-2014***

The total number of premature deaths averted of the NBP's digesters constructed in the period 2006-2014 due to HAP improvement is shown in the figure below and amount to 29.5 in total.

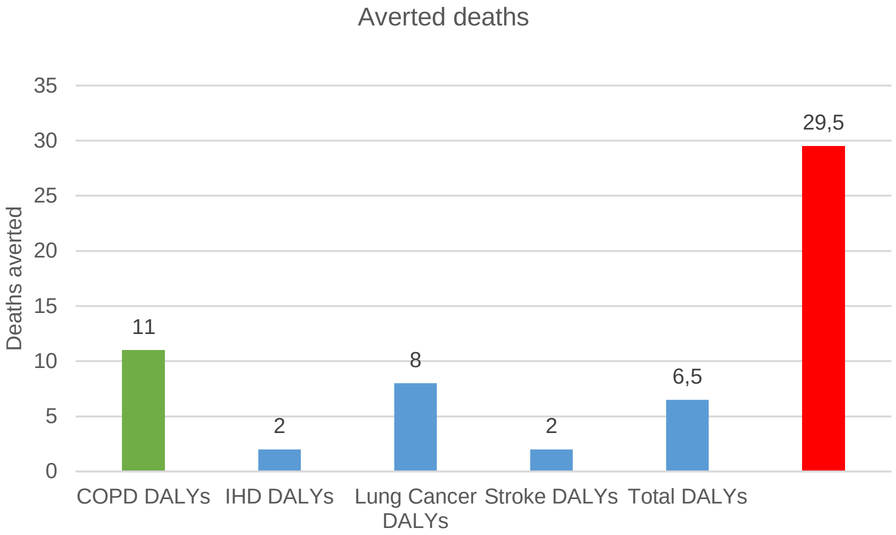

Figure 25: Deaths averted due to HAP improvement 2006-2014

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[14] *(Buysman, 2015)*

The number of averted premature deaths are the sum of the averted ALRI deaths of children aged 0 to 4 and of the chronic diseases COPD, IHD, lung cancer and strokes. The number of aDALYs are depicted in the next figure:

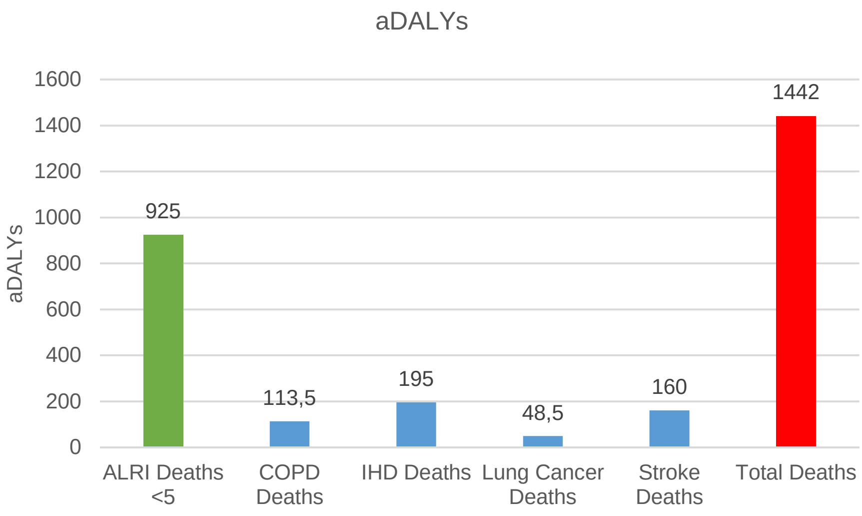

Figure 26: aDALYs accrued due to HAP improvement 2006-2014

The number of aDALYs amount to 1442 which are mostly the result of averted ALRIs. HAPIT assumes that the benefits from non-chronic diseases occur immediately which could explain the high share of aDALYs that stem from reduced number of ALRIs.

6.3.3 Additional health benefits of the 2006-2014 population in 2020

The continued use of the 2014 population of digesters will result in additional health benefits beyond 2014. The health benefits are projected until the year 2020 for this purpose. It is assumed that the usage rate will continue to drop and that at 2% per year to 76% in 2020. The average usage rate over the period 2014 to 2020 is then 82%.

In Annex II the attained weighted benefits and the corresponding EPA cessation lag year are calculated, which is lag year 9. It is not directly possible to calculate the benefits of year 9 with HAPIT; it is possible however, to calculate the results from a known value in HAPIT and recalculate this based on the relative increase in benefits attained in another year based on the EPA cessation lag function. I.e. if in year 8 the benefits accrued are 90% and in year 4 these are 50%, then the number of aDALYs and averted deaths in year 8 are (90% / 50%) larger. This method has also been discussed and approved by the HAPIT staff. The averted deaths for the continued use of the 2014 population of digesters is shown in the next figure:

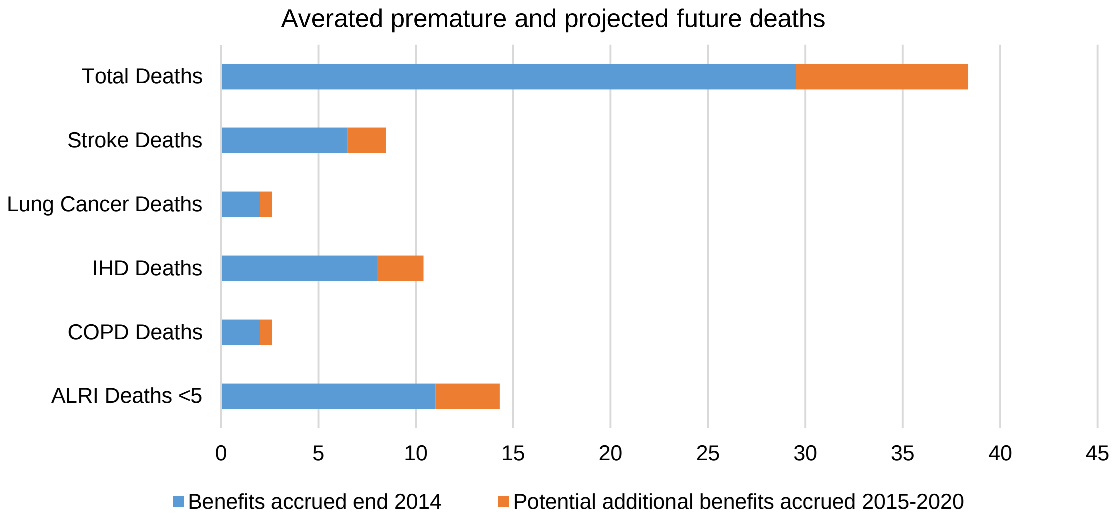

Figure 27: Averted premature and potential deaths of the 2014 biodigester population by 2020

The continued use does not yield a significant increase in averted premature deaths from chronic diseases. This is because the EPA cessation lag function assumed that most deaths are averted during the first 5 years (80%) and the remaining 20% during the years 5 to 20.

The aDALYs show a similar figure, an increase from 1442 to 1875 aDALYs, which is also mostly attributed to ALRI aDALYs.

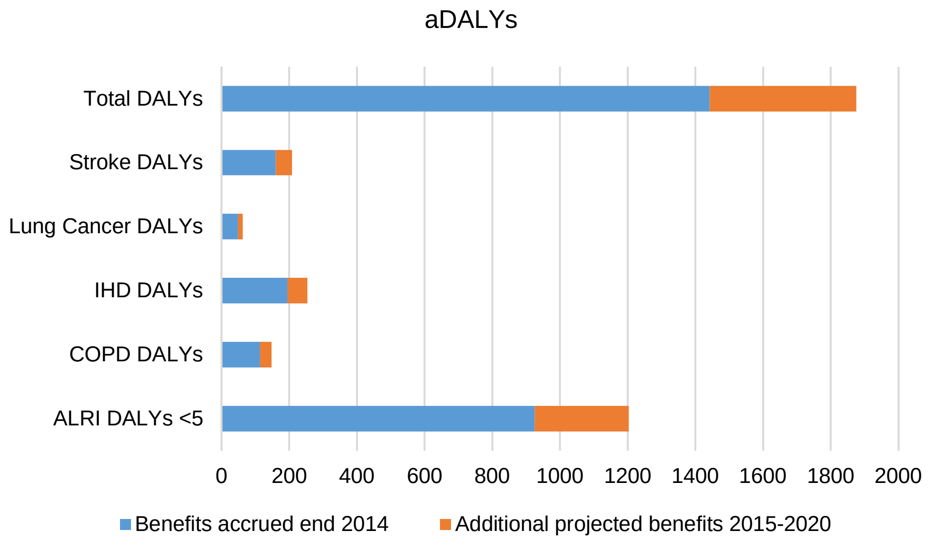

Figure 28: aDALYs accrued of the 2014 digester population in 2020

Annex 2 details the calculations.

6.3.4 NBP 2006-2020 health impact attributable to HAP improvement

The estimated health impact of NBP to 2020 are the sum of:

1. The 2006-2014 digesters that are still in use in the period 2015-2020 (calculated in chapter 6.3.3)
2. Newly built digesters in 2015-2020

According to the projections provided by NBP[15] there will be around 15,000 digesters sold in the period 2015 to 2020, see the table below:

Table 25: NBP's 2015-2020 biodigester sales projection

Variable	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*
Number of digesters	2,000	2,200	2,400	2,600	2,800	3,000
Cumulative 2015-2020	2,000	4,200	6,600	9,200	12,000	15,000

With HAPIT and with the application of a conservative usage rate (88%) the benefits are calculated (see Annex III for the calculation), see the table below:

Table 26: Averted deaths and DALYs of the 2015-2020 digesters at the end of 2020

ALRI DALYs <5	*ALRI Deaths <5*	*COPD DALYs*	*COPD Deaths*	*IHD DALYs*	*IHD Deaths*	*Lung Cancer DALYs*	*Lung Cancer Deaths*	*Stroke DALYs*	*Stroke Deaths*	*Total DALYs*	*Total Deaths*
425	5	48.5	1	82.5	3.5	21	1	66.5	2.5	643.5	13

The cumulative health improvement in 2020 of the total population of digesters; the 22,117 at the end of 2014 and the 15,000 additionally built digesters by 2020, is shown in the two figures below:

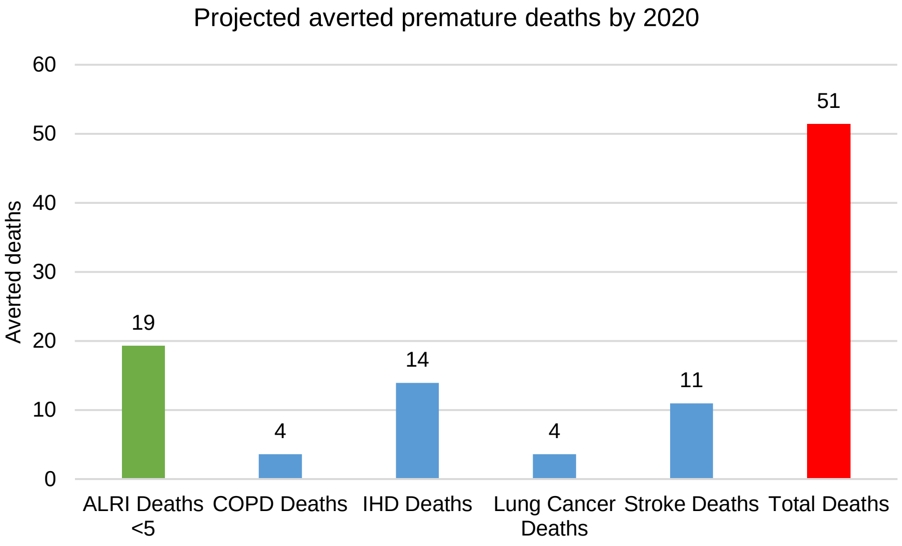

Figure 29: Projection of averted deaths accrued in 2020 (37,117 digesters)

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[15] *Provided by Saoleng Lam, NBP programme coordinator – email communication 24 June 2015*

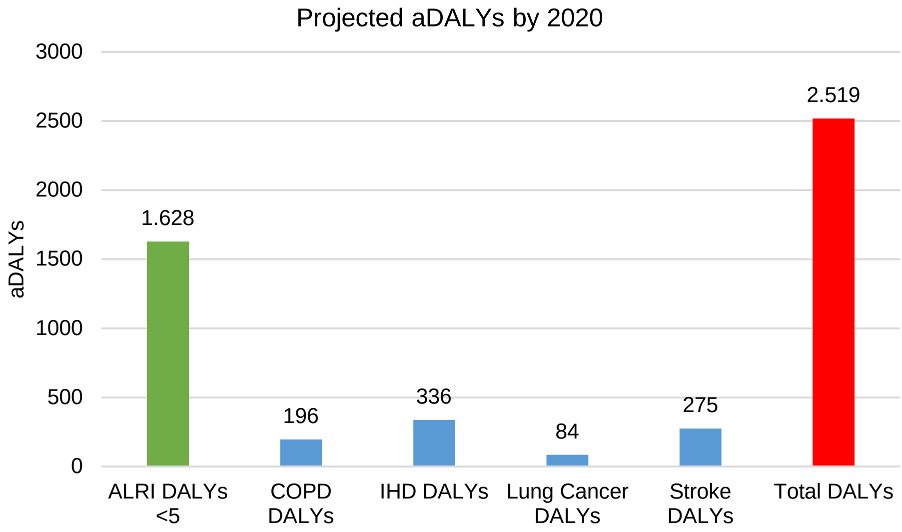

Figure 30: Projection of aDALYs accrued in 2020 (37,117 digesters)

With continuation of NBP to 2020, the following health impacts that are attributed to a reduction in 2020 are expected on top of the achieved results by the end of 2014:

Table 27: Achieved and projected benefits of NBP's biodigesters

Population	***Year benefits accrued***	***Digesters***	***Applied usage rate***	***aDALYs***	***averted deaths***
2006-2014 digesters*	end 2014	22,117	88%	1,442	29.5
*Projection to 2020***	end 2020	22,117	82%	433	9
2015-2020 digesters**	end 2020	15,000	88%	644	13
Total	**end 2020**	**32,117**	**-**	**2,519**	**51**

** achieved, ** projection*

The continuation of NBP until the year 2020 is projected to increase the accrued aDALYs by 2014 with 67% and averted deaths with 66%. This is the result of the continued use of the 2014 digesters, which accounts for 289 aDALYs and 5 averted deaths, albeit with a lower usage rate of 82%. On top of that, the newly constructed digesters in the period 2015 to 2020 is projected to results in another 643 aDALYs and 13 averted deaths.

Note: *The projection of the benefits accrued is based on the 2010 disease patterns in the Cambodian population and the 2013 estimate showed that the HAP attributed DALYs has decreased slightly but the attributed premature deaths increased with 20%, see table 22. In the future this change in disease pattern and underlying causes may change and this may result in a higher or lower estimate of the HAP risk factor in the burden of disease in Cambodia. This should be taken into account when interpreting the results in chapter 6.3.2 and 6.3.3*

6.4 Self-reported health improvements

All project households reported that their health has improved since they have a biodigesters, 100%. Health improvements could be attributed to HAP but also to, for example, improved sanitation, reduced drudgery or other aspects that are improved when having a biodigester.

Project households were asked on the health improvement that they experience related to the respiratory system, eyes and general well-being. The outcome of this is presented in the table below.

Table 28: Reported health improvements since installed a biodigesters

Reported improved health item	***N***	***% reported***
Easier to breath and less coughing	19	76%
eyesight improvement	16	64%
Sleep better and wake up with more energy	8	32%
Less headache	4	16%
Less dizziness	3	12%
Happier, more weight, look better	3	12%

Most households reported health improvements of the respiratory system as they found it easier to breathe and they were coughing less. Also around 2/3 of the households reported eye-sight improvement. Other improvements were mentioned less but it is interesting to note that around a third claims to have more energy and that they sleep better.

Self-reported health aspects related to the eyes and the respiratory system showed that baseline households tend to experience more issues, 73 issues versus to 57 with biogas. The next figure breaks this down by health ailment.

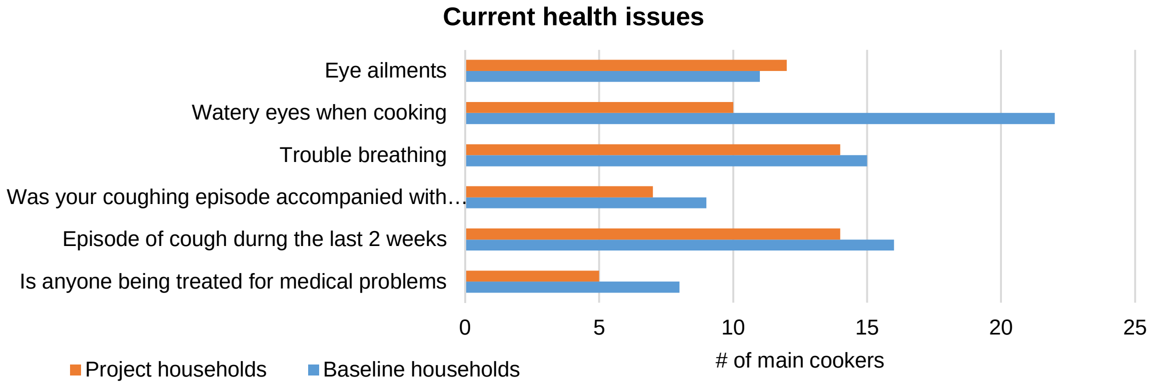

Figure 31: Self-reported health issues related to eyesight and respiratory system

At this moment 8 baseline household members are being treated for a medical problem versus 5 in the project households.

The self-reported health improvement and decrease in health issues support the findings in this report. However, given the small sample size and that surveyors were not trained by health experts it is difficult to attribute the improvement directly to improved household air quality (HAQ). Although this study demonstrates that the HAQ has improved in biogas households, it has also shown that the exposure to PM2.5 remains above the levels to what is considered healthy. In addition, general improvement of health could also be associated with improved sanitation, less drudgery and better nutrition.

6.5 Valuing health outcomes

It is not the intention of this study to provide a comprehensive assessment of the health outcomes of NBP and how this can be valued in monetary terms. The next two sections, 6.5.1 and 6.5.2 provide an overview of what the value of the health outcomes of NBP could be and how this relates to the overall costs of NBP. The assessment is not complete and ignores other benefits associated with having biogas and leverage effects that are created due to the private sector development activities of NBP.

6.5.1 The statistical value of life and aDALY

The statistical value of life

The statistical value of life is often used to estimate in dollar terms the benefits of reducing the risk of death. The value of statistical life is an estimate of the financial value society places on reducing the average number of deaths by one unit. A related concept is the statistical value of life-year (SVOLY), which estimates the value society places on reducing the risk of premature death, expressed in terms of saving a statistical life year (Net Balance, 2014).

Net Balance (2014) sourced for their report to the Gold Standard '*the real value of robust climate action*' a SVOLY value from an Australian government study: Office of Best Practice Regulation (Australian Government, 2007). The social value of one SVOLY is according to that report, in USD terms $325,000. In their report to the Gold Standard they applied that SVOLY value to the rest of the world based on the argument that the value of life should be valued identical everywhere in the world. From an ethical point of view this is valid, however, in a world with vast income and cultural differences this value may not be universal. Whether or not that is the case and under which conditions, is out of scope of this report.

The Copenhagen Consensus Center lists two other approaches: (1) 50 times the GDP per capita and (2) a fixed value of $1, 000 to $5,000 per life year (Copenhagen Consensus Center, 2015).

The next table shows the estimate SVOLY value in Cambodia by method:

Table 29: Statistical Value of Life by studied source

Source	*Method*	*SVOLY*	*Comment*
Net Balance	Australian standard	$325,000	-
Copenhagen Consensus Center	50 times GDP per capita	$50,034	GDP per capita Cambodia: $1,084.4[16]
	$1,000 to $5,000 per life year	$22,000 to $110,000	Female life expectance 66.32 years[17], average age cookers: 44 years; basis of calculation 22 life years (66-44)

The statistical value of an aDALY

There is not that much information available in the literature on the monetary value of a DALY. A WHO commissioned study on the benefits of access to water executed by the Stockholm International Water Institute cites Jeffrey Sachs, a famous American economist who puts the value at $500 in low income countries (SIWI, 2007). For the purpose of this report, that value is used.

6.5.2 Value of Life saved and DALY - NBP

According to NBP, their total budget for the period 2006-2014 was around $8 million. Based on this the average cost per avoided aDALYs and averted death was calculated based on the 2014 population of digesters (22,117), see the next table:

Table 30: Health unit cost of the 2014 biodigester population

Unit	*Unit cost at the end of 2014*	*Unit cost at continued use of the digester at the end of 2020*
aDALY	$5,548	$4,266
Averted premature death	$271,186	$208,523

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[16] *http://data.worldbank.org/indicator/NY.GDP.PCAP.CD*

[17] *http://www.indexmundi.com/cambodia/life_expectancy_at_birth.html*

NBP, as an HAP health intervention, costs around $4,266 to $5,548 per averted DALY and $208,523 to $271,186 per averted death depending on the evaluation period. The actual costs may in fact be much lower as there are many other benefits associated with NBP, from employment generation, to increased productivity of farmers due to better health, improved nutrition due to the use of bio-slurry as fertilizer, increased harvests, decreased expenditure on chemical fertilizers and fuels, value of reduced carbon emission etc. This however is outside the scope of this report.

Table 29 has shown that NBP as a health intervention has a unit cost of averted deaths of $209k USD in 2020. This value is lower than what Net Balance (2014) considers as the universal value of life: $325,000. The costs however, are much higher than the other estimates as per table 29.

The aDALY value however is around 10 times higher than the value that Jeffrey Sacks ($500) puts on an aDALY in low income countries (SIWI, 2007).

A follow up study is necessary to put these estimates in a broader perspective by including other benefits and by provided better estimates of the value of DALY and averted deaths. It is likely that a comprehensive analysis would show that a biodigester is a cost-effective method to address HAP when the wealth of the other benefits are included in the assessment.

7. Conclusion

In this study the HAQ, CO and PM2.5 levels, between 25 randomly selected biogas households and 25 matching baseline households, was compared based in a measurement campaign of 48 hours. Based on the findings and the analysis, the following conclusions are drawn:

- The selected baseline households match very well with the project households on most characteristics. This group of households can therefore be considered as equivalent to the project households with the only main difference of not having a biodigester. Other than relying on wood instead of biogas for cooking; the other main difference is that baseline kitchens are often not attached to the house and are much better ventilated. Biogas households on the other hand, have kitchens attached to the house, which are often closed.

- This study provides evidence that biogas households' kitchens are much cleaner compared to baseline households in spite of being less ventilated:
  - The CO and PM2.5 kitchen concentrations are much lower, and highly significant, in project households compared to baseline households.
  - The exposure to CO and PM2.5 is much lower and highly significant in the case of CO and significant in the case of PM2.5 in project households compared to baseline households.

- The CO level in the project households' kitchen is below the WHO AQG_{24} guideline and that is also the case for 23 out of the 25 baseline kitchens. The WHO AQG_{8h} and AQG_{15} is also met by all the project households but not met by 20% and 16% respectively of the baseline households. Those households also did not meet the Cambodian AQG_{1h}. None of the main cooks however experienced CO levels above the WHO AQG, including the 8 and 1 hour and 15-minute guideline. In rural Cambodia CO air pollution appears to be negligible outside the kitchens.

- PM2.5 levels are in all kitchens above the WHO AQG. However, 80% of the project kitchens meet the interim target I (35 $\mu g/m^3$) and none of the baseline kitchens. Interim target II, of 25 $\mu g/m^3$ is met by 64% of the project households. Most main cooks however are exposed to unhealthy levels of PM2.5, 68% of the project main cooks and 84% of the baseline cooks are exposed to levels higher than interim target I.

- The personal exposure to PM2.5 is lower for baseline households compared to their kitchen levels, but higher for project households. This indicates that the baseline kitchens are a source of HAP while in the case of the project households that situation is reverse, most of the exposure to PM2.5 does not come from the kitchen but from sources outside the kitchen.

- Although biogas stoves are much cleaner compared to wood stoves, the maximum 15-minute average PM2.5 levels remains around 10 times higher than the WHO AQG_{24}. In the case of baseline kitchens, the 15-minute is around 100 times higher. The WHO did not institute a guideline for short-term exposure, but several studies have shown found links between an increased incidence of HAP attributed diseases and short-term exposure. The peak exposure level to PM2.5 are not the result of PM2.5 emissions from the biogas stoves as the maximum 15-minute average kitchen concentrations were always much lower. The peak PM2.5 levels are attributed to baseline stoves and other sources of pollution (i.e. burning of household waste).

- The ambient air in the selected villages is low in CO but relatively high in PM2.5. The average PM2.5 concentration is with 41 to 31 $\mu g/m^3$ during the baseline and household measurement campaign respectively near the WHO interim target I of 35 $\mu g/m^3$. This relatively high concentration is the cumulative effect of households that cook on solid biomass, mostly wood, burning of households and garden waste, fire-clearing of agricultural land and artisanal production of rice wine and palm sugar.

- Around a third of the households that have a biodigester continue to use wood on a daily basis. This means that families, mostly women, continue to be exposed to smoke and hazardous pollutants. Most of the wood however is used for pig feed preparation or water boiling. None of the biogas households is using biogas for animal feed preparation.

- Families are exposed to relative high concentrations of ambient air pollution from a range of sources from cooking on solid biomass, to burning of waste and artisanal production of rice wine and palm sugar. The adoption of a clean cooking technology, such as biogas, will reduce the overall exposure to PM2.5 and CO and make the kitchen significantly cleaner; but the overall exposure to PM2.5 will remain higher than the WHO AQG. The findings of this study suggest that this can only be improved by addressing the ambient air pollution and the pollution that originates from others households that cook on wood. The ambient air pollution also contains a number of sources which have not received that much attention in the literature on HAP, such as – in the case of Cambodia -artisanal rice wine production, palm sugar production and the burning of household and garden waste.

- A CO-PM2.5 relationship does not exist for biogas in Cambodia. In the case of biogas 78% of the observed variance can be explained by other confounding variables. For that reason, CO or PM2.5 cannot be used as a proxy for the other pollutant in the case of biogas.

- The burden of disease attributed to HAP is the second cause of DALY and premature death in Cambodia. Based on the improvement in HAQ, it is estimated that by 2014 with 22,117 digesters installed, 29 deaths are averted and 1,442 aDALYs in the period 2006-2014. This number will increase to 51 and 2,519 averted deaths and aDALYS respectively by 2020 with the continued operation of NBP and with the projected installation of another 15,000 biodigesters.

- The cost of NBP as health intervention is around $4,266 to $5,548 per aDALY and $208,523 to $271,186 per averted death. This calculation is one-sided and does not take into account all the other benefits and leverage effects that are created through NBP.

- Valuation of the health benefits against a certain statistical value of life is challenging as there is no agreed definition on what this value entails and secondly it may not be universally applicable to all countries. From a pure health perspective, the costs per averted DALY and death are too high, however, since biogas addresses multiple issues and entails many other benefits, this should not lead to the conclusion that domestic biogas is not viable intervention. More study on this aspect is necessary.

Study limitations

The study was executed during the dry season. During that season farmers prepare their fields for the rice planting by burning away the residues from the previous harvest. This generates a considerable amount of air pollution. In addition, during the dry season there is often little wind and this allows the concentration of PM2.5 to remain at high levels locally. During the wet season PM2.5 levels may be lower as rain would clean up the air by removing all the PM2.5. During the dry season large communal events take place, such a wedding to which often the up to 500 people are invited and Buddhist festivals. This interrupts daily activities and as a result, households may cook less. In the case of this research, it happened on a number of occasions that household members, including the main cookers that were carrying the data loggers attended these festivities. For that reason, this research was put on hold during Khmer New Year (mid-April) including week before Khmer New Year.

The PM2.5 UCB-PATS used for the exposure measurement was not designed for that purpose. Although the monitor accurately records the PM2.5 levels it was not possible to place the sensor closer than 30 centimeters to the breathing zone of the main cooker. The exposure levels are therefore taken from the air that is around 30 centimeters lower than ideal and this may have resulted in a slight under or over estimate of the concentrations. However, since this applies to both groups, the inaccuracy may have cancelled each other out.

The UCB-PATS were not calibrated during the execution of this study but instead relies on calibration values from another HAP study in Cambodia. Whereas the conditions are similar, the study was executed in a different season and at different locations.

Final considerations

This study is one of the few studies that have compared biogas stoves with wood-fired stoves. Biogas is a clean fuel, with an assumed CO and PM2.5 emission rate comparable to LPG, tier 4 IWA performance[18] (Berkeley Air Monitoring Group, 2012). This study indirectly supports this assumption, CO and PM2.5 levels in biogas households can be linked with sources other than the biogas stove. The emissions from the biogas stove itself, are

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[18] *International Workshop Agreement on Clean and Efficient Cookstoves (IWA) distinguishes 4 efficiency, safety and emission performance tiers, where the first is the poorest and the tier 4 is the most ambitious.*

similar to the levels in the ambient air and may therefore be negligible. Therefore, it can be argued that biogas is a more preferable fuel from a health perspective compared to biomass, i.e. wood or charcoal, burned in an improved cookstove or even in advanced clean cooking stoves. Baseline households in this study have a stove that is either Tier 1 or at best Tier 2 in the case of the fixed stove with chimney. Even if these household switch to the best advance biomass stove, they will not reach a higher performance than Tier 3 (Berkeley Air Monitoring Group, 2012) and their kitchen will consequently be less clean compared to biogas.

For households that have livestock a biogas solution is the most preferable option. It is however a considerable investment, in the order of $500, but at the same time the payback period is around 3 years and the technology can last for 20 years or more.

For other households, a carefully weighting is required on which approach is most feasible. This is often very context specific but at the same time, economies in this region are developing quickly and so are lifestyles. LPG and electricity are often not promoted as alternative to biomass in this region (Mekong Region) as it assumed to be costly, not available and not accessible. However, 85% of the communes and 60% of the households are connected to the grid as of date (Derbyshire, 2015). Cooking on electricity is expensive, however, for example, a rice cooker on electricity, is very efficient and has very low running costs. Such a rice cooker is common in urban areas in South-East Asia and will quickly disburse to rural areas as well. The remaining cooking could be done with LPG. A simple LPG stove starts at $10 and small refillable bottles start at1500 riel ($0.375) and lasts for a couple of days or longer if used in combination with a rice cooker.

Improved biomass stoves also have a role to play, but ultimately, only a switch to clean fuels can bring the HAQ within the WHO AQG. According to Buysman (2013) the **energy security conundrum** in least developed countries is how to provide safe and clean energy to a low income rural population. The aspect ‘clean’ is becoming with recent WHO studies and of recent data of the Global Burden of Disease (IHME, 2013), much more prominent in issues related to stoves. The focus on incremental efficiency improvement that aim to satisfy thermal energy demands is not sufficient anymore and cannot be separated from the health context (Smith, 2015). Smith (2015) proposed therefore a new paradigm to clean cooking; the problem should not be treated as an energy problem but as a health issue given that it affects 40% of the world’s population.

Given the enormous burden of diseases attributed to HAP, a better appropriation of the paradigm to clean cooking is coining it as the **health conundrum** or the **household energy and health conundrum**. The conundrum of household energy and health is interdependent and should be treated as such. Biogas is well poised in that respect by securing the families’ energy requirements and at the same addressing the HAP attributed burden of diseases that affect almost half a million of Cambodians.

8. Recommendations

8.1 Recommendations to policy makers and researchers

1. This study concluded that switching to a clean fuel, such as biogas, results in a significant HAQ improvement, but it is not sufficient to meet the WHO targets. This can only be achieved by simultaneously addressing both indoor and ambient air pollution. Ambient air pollution needs a community approach (multiple households) and address multiple sources of which cooking is the main but not the only one.

   Addressing HAP requires a community approach (Smith, 2015); only when a significant number of villagers switch to a clean fuel or an advanced clean cooking stove HAP can effectively be addressed. Parallels in this could be drawn from the approach taken in sanitation projects. For example, the WASH (Water Sanitation and Hygiene) project of SNV takes a community approach because disease vectors such as houseflies have a tremendous range, much alike air pollution. Their aim is open defecation free communes and organize that together with the local authorities. In the case of air pollution, the situation is more complex as there are more sources that need to be addressed. Therefore, developing a community approach to air pollution requires the cooperation of a great number of actors, NGOs and authorities. This should include for example, the Ministry of Health, Ministry of Agriculture, Fisheries and Forestry (MAFF), Ministry of Environment, NGOs working on ICS, i.e. SNV and GERES, NBP together with private sector actors and local microfinance institutions.

2. The challenge remains on how to meet the WHO interim target I or to move beyond target. This study indicates that there are a number of important challenges that need to be addressed before cleaner, smoke-free, kitchens can be realized; households that continue to rely on wood, biogas households that use wood, artisanal production of rice-wine and palm sugar and ambient air pollution. Ambient air pollution from burning waste and clearing of land is in many countries greatly reduced by intervention of the government. Informal discussion with the Ministry of Environment revealed that they are focusing on this issue and hopefully this report would give them the justification to develop policy and/or enforce policy focusing on the prevention of outdoor fires.

3. There is an urgent need to establish air quality guidelines in Cambodia. The current guidelines only focus on TSP which is not a good indicator for the health impact. For the latter PM2.5 and PM10 guidelines are necessary. These guidelines would be very useful to assess the impact of an intervention, of new policy and/or to enforce certain pollution limiting activities. The HAPIT tool used in this report could also be used to estimate the effect of policy on certain air quality standards. Such a policy would be a cross-cutting theme covering many aspects related to health, climate change, forestry and energy. It is therefore recommended that NBP and HIVOS share the results of this study with relevant ministries such as MAFF, MME, MoE and the Ministry of Health. This could also give input to national plans aiming to create smoke-free kitchens such as Bangladesh's 2030 goal or the Ghanaians action plan (see figure 33). **Cooking should not kill must be core message**.

Figure 32: From Ghana's sustainable Energy for ALL (SE4ALL) country action plan

4. HAPIT is an excellent tool to assess the health impact for an intervention of up to 5 years. This period is sufficient for ICS project but not for biogas projects. In addition, the tool cannot be used to assess the cost-effectiveness of a biogas intervention as not only the biodigester can be used for much longer than the appraisal period, 5 years, but also because justifying biogas based on only the health aspects ignores all the other benefits that biogas brings. Enlarging the intervention period and by allowing the inclusion of savings on other non-health benefits in the cost analysis is crucial to assess the potential of biogas as a cost-effective intervention.

8.2 Recommendations to NBP

1. There remains scope for NBP to improve the efficiency of their biodigester systems. The stove in use is vulnerable to draft and some households have even installed makeshift windshields. In some cases these are even made of cardboard which poses a fire-hazard. Modifying the stove by enlarging the skirt or making better windshields available would improve the thermal efficiency of the system and allows the households to cook more with their biogas. This would reduce the need to use wood. It may also be worthwhile to explore introducing stoves designed for animal feed preparation.

2. It is recommended that NBP includes a health message in their communication to potential clients and current clients. The number of averted deaths and aDALYs are significant and this may also motivate current and prospective biogas users to stop using wood altogether. Alternatively, a health campaign could be organized, highlighting the huge impact that HAP has on Cambodia's burden of disease and how biogas could address this.

3. Behavioral research: Anecdotal evidence indicates that many users are 'afraid' to use biogas for all their cooking even when it is obvious that they have enough gas. As a result, often water is boiled on the most primitive stove that the households has, such as the three stone stove. Much of the reduction in HAP is offset by these practices. It is recommended to study this in more detail, why do people continue to use that stove?

Figure 33: NBP promotion: $150 dollar subsidy, 1 pot and 1 t-shirt

   Alternatively, it may also be the case that households do not use their kettle on the biogas stove as frequently the kettle is old, full with sooth and has a dedicated stove and place of use. In such a case, NBP could also consider to provide a kettle specifically for the biogas stove as a promotion article instead, or in addition to, the existing promotion of 1 pots (see Figure 33).

8.3 Follow-up Study

1. There is a significant difference in cooking position between baseline and project households, this can have ramifications for the exposure to HAP and the kitchen concentrations. A follow up study should look into this.

2. This study has shown that biogas is a cleaner fuel and that it reduces the exposure to PM2.5 and CO. Based on this, a follow up study should try to quantify the health effects in the population based on this using medically validated questionnaires, spirometry, palpation and auscultation to assess respiratory and cardiovascular improvements (similar to the study of Dohoo et al (2012)) and related those improvements to the overall impact on the Cambodian economy and productivity.

3. This study was due to its small sample size not able to look into the effect of stove stacking on HAP. It is recommended that this is studied in a follow-up study by dividing the project population in 2 groups, one that relies solely on biogas and one that is using a baseline stove on regular basis.

9. References

Australian Government. (2007). *Best Practice Regulation Handbook.* Canberra.

Berkeley Air Monitoring Group. (2012). *Stove Performance Inventory Report.* Berkeley. Retrieved from http://cleancookstoves.org/resources_files/stove-performance-inventory-pdf.pdf

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, M. P., Berntsen, T., & DeAngelo, B. J. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research*, 5380-552.

Buysman, E. (2015). *Carbon Monitoring and User Survey 2014.* Phnom Penh: NBP.

Buysman, E., & Mol, A. (2013). Market-based biogas sector development in least developed countries - The case of Cambodia. *Energy Policy*, 44-51.

CAI. (2010). *Particulate Matter (PM) Standards in Asia.* Clean Air Initiative for Asian Cities.

Copenhagen Consensus Center. (2015, August 3). *Post-2015 Consensus - Air Pollution Assessment.* Retrieved from Copenhagen Consensus Center: http://www.copenhagenconsensus.com/publication/post-2015-consensus-air-pollution-assessment-larsen

Derbyshire, W. (2015). *Cambodia - In Depth Study on Electricity Cost and Supplies.* G-PSF Project.

Dohoo, C., Guernsey, J. R., Critchley, K., & Leeuwen, J. V. (2012). Pilot Study on the Impact of Biogas as a Fuel source on Respiratory Health of Women on Rural Kenyan Smallholder Dairy Farms. *Journal of Environmental and Public Health*, 9.

GACC. (2015, June 15). *Alliance Convenes Group of Global Researchers Examining the Impacts of Clean Cooking on Children's Health*. Retrieved from Global Alliance for Clean Cookstoves: http://cleancookstoves.org/binary-data/ATTACHMENT/file/000/000/231-1.pdf

GACC. (2015, June 4). *Country profile Cambodia*. Retrieved from Global Alliance for Clean Cookstoves (GACC): http://www.cleancookstoves.org/country-profiles/48-cambodia.html

IHME. (2013). *GBD Cambodia.* Seattle: Institute of Health Metric and Evaluation.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis.* IPCC.

IPCC. (2014). *Chapter 8 of the 5th Assessment: Anthropogenic and Natural Radiative Forcing.* Geneva: IPCC.

Kloog, I., Ridgway, B., Koutrakis, P., Coull, B. A., & Schwarts, J. D. (2013). Long- and Short-Term Exposure to PM2.5 and Mortality. *Epidemiology*, 555-561.

Kooijman, P. (2014). *Pro-poor Biodigester - Carbon Baseline & Market study.* Phnom Penh: SNV.

Martin, W., Glass, R., Houman, A., Balbus, J., Collins, F., Curtis, S., . . . Keown, S. (2013). Household Air Pollution in Low- and Middle-Income Countries: Health Risks and Research Priorities. *PLOS Medicine*, Volume 10.

MCraken, J., Schwartz, J., Diaz, A., Bruce, N., & Smith, K. R. (2013). Longitudinal Relationship between Personal CO and Personal PM2.5 among Women Cooking with Woodfired Cookstoves in Guatemala. *PLOS one, 8*(2).

Murray, C., & Acharya, A. (1998). Understanding DALYs (disability-adjusted life years). *Health Economics*, 703-730.

Net Balance. (2014). *The Real Value of Robust Climate Action: Impact Investment Far Greater Than Previously Understood.* Zurich: The Gold Standard Foundation. Retrieved from http://www.goldstandard.org/wp-content/uploads/2014/05/GoldStandard_ImpactInvestment.pdf

Neupane, M., Basnyat, B., Fischer, R., Froeschl, G., Wolbers, M., & A. Rehfuess, E. (2015). Sustained use of biogas fuel and blood pressure among women in rural Nepal. *Environmental Research*, 343-351.

Newby, D. E., Mannucci, P. M., Tell, G. S., Bacccarelli, A. A., Brooks, R. D., Donaldson, K., . . . Franchini, M. (2014). Expert position paper on air pollution and cardiovascular diseas. *European Heart Journal*.

Northcross, A., Chowdhury, Z., McCracken, J., Canuz, E., & Smith, K. R. (2010). Estimating personal PM2.5 exposures using CO measurements in Guatemalan households cooking with fuel wood. *Journal of Envivonmental Monitoring*, 873-878.

Pokhrel, A. K., Pokhrel, A., N Bates, M., Acharya, J., Valentiner-Brath, P., K Chandyo, R., . . . R Smith, K. (2015). PM2.5 in household kitchens of Bhaktapur, Nepal, using four different cooking fuels. *Atmospheric Environment*, N/A.

San, V., Ly, D., & Check, N. I. (2013). Assessment of Sutainable Energy Potential of Non-Plantation Biomass Resources in Sameakki Meanchey District in Kampong Chhnang Province, Cambodia. *International Journal of Environmental and Rural Development*, 173-178.

SIWI. (2007). *Making Water a Part of Economic Development.* Retrieved from http://www.who.int/water_sanitation_health/waterandmacroecon.pdf

Smith, K. S. (2015). Changing Paradigms in Clean Cooking. *EcoHealth*, 196-199.

SNV. (2015, June 17). *Advanced Clean Cooking Solutions*. Retrieved from http://www.advancedcleancooking.org

SNV. (2015, June 16). *Biogas*. Retrieved from SNV: http://www.snvworld.org/en/biogas

UNEP. (2015, June 23). *Black Carbon*. Retrieved from UNEP: http://www.unep.org/transport/gfei/autotool/understanding_the_problem/Black%20Carbon.pdf

WHO. (2014). *WHO Guidelines for Indoor Air Quality: household fuel combustion.* Geneva: WHO.

WHO. (2015, July 27). *Global Health Observatory Data Respiratory.* Retrieved from World Health Organisation: http://apps.who.int/gho/data/node.country.country-KHM?lang=en

Zhou, Y., Zou, Y., Li, X., Chen, s., Zhou, Z., He, F., . . . Ran, P. (2014). Lung Function and Incidence of Chronic Pulmonary Disease after Improved Cooking Fuels and Kitchen Ventilation: a9-year Prospective Cohort Study. *PLOS Medicine, 11*(3).

10. Appendix

Annex I: Share of benefits accrued of the digester population 2006- 2014 at the end of 2014

The digesters built in the period 2006 to 2014 attain between 56.4% and 67.13% of the benefits. The digesters built in year 2006 attain between 83.75% to 85.00% of the benefits; while for the digesters built in 2014 only 0% to 30% of the benefits are attained, or 15% on average when assuming an equal distribution of digesters construction over the year.

Year	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013 (A)**	**2014 (B)**	**Units (C)**	**(B*C) Year y**	**(A*C) Year y+1**
2006	30%	42%	55%	67.50%	80%	81.25%	82.50%	83.75%	85.00%	294	249.9	246.225
2007		30%	42%	55%	67.50%	80%	81.25%	82.50%	83.75%	1150	963.125	948.75
2008			30%	42%	55%	67.50%	80.00%	81.25%	82.50%	2340	1930.5	1901.25
2009				30%	42%	55%	67.50%	80.00%	81.25%	2616	2125.5	2092.8
2010					30%	42%	55.00%	67.50%	80.00%	3744	2995.2	2527.2
2011						30%	42.00%	55.00%	67.50%	4826	3257.55	2654.3
2012							30.00%	42.00%	55.00%	4201	2310.55	1764.42
2013								30.00%	42.00%	1115	468.3	334.5
2014									30.00%	1831	549.3	0
									sum	**22117**	**14850**	**12469**
									Weighted attainable benefit		**67.143%**	**56.379%**
									Year on EPA cessation lag		4	3

This method only applies to chronic diseases. The next table shows the outcome of the average benefits in year 3 with year 4:

ALRI DALYs <5	ALRI Deaths <5	COPD DALYs	COPD Deaths	IHD DALYs	IHD Deaths	Lung Cancer DALYs	Lung Cancer Deaths	Stroke DALYs	Stroke Deaths	Total DALYs	Total Deaths
925	**11**	**113.5**	**2**	**195**	**8**	**48.5**	**2**	**160**	**6.5**	**1442**	**29.5**

Annex II: Share of benefits accrued in 2020 of the digester population at the end of 2014

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019 (A)	2020 (B)	Units (C)	(B*C) Year y	(A*C) Year y+1
2006	30%	42%	55%	67.50%	80%	81.25%	82.50%	83.75%	85.00%	86.25%	87.50%	88.75%	90.00%	91.25%	92.50%	294.0	272.0	268.3
2007		30%	42%	55%	67.50%	80%	81.25%	82.50%	83.75%	85.00%	86.25%	87.50%	88.75%	90.00%	91.25%	1150.0	1049.4	1035.0
2008			30%	42%	55%	67.50%	80.00%	81.25%	82.50%	83.75%	85.00%	86.25%	87.50%	88.75%	90.00%	2340.0	2106.0	2076.8
2009				30%	42%	55%	67.50%	80.00%	81.25%	82.50%	83.75%	85.00%	86.25%	87.50%	88.75%	2616.0	2321.7	2289.0
2010					30%	42%	55.00%	67.50%	80.00%	81.25%	82.50%	83.75%	85.00%	86.25%	87.50%	3744.0	3276.0	3229.2
2011						30%	42.00%	55.00%	67.50%	80.00%	81.25%	82.50%	83.75%	85.00%	86.25%	4826.0	4162.4	4102.1
2012							30.00%	42.00%	55.00%	67.50%	80.00%	81.25%	82.50%	83.75%	85.00%	4201.0	3570.9	3518.3
2013								30.00%	42.00%	55.00%	67.50%	80.00%	81.25%	82.50%	83.75%	1115.0	933.8	919.9
2014									30.00%	42.00%	55.00%	67.50%	80.00%	81.25%	82.50%	1831.0	1510.6	1487.7
														sum		22117	19203	18926
														Weighted attainable benefit			86.82%	85.57%
														Year on EPA cessation lag			9	9

	2006-2014 population	Usage rate	ALRI DALYs <5	ALRI Deaths <5	COPD DALYs	COPD Deaths	IHD DALYs	IHD Deaths	Lung Cancer DALYs	Lung Cancer Deaths	Stroke DALYs	Stroke Deaths	Total DALYs	Total Deaths
Existign	2006-2014	88%	925	11	113.5	2	195	8	48.5	2	160	6.5	1442	29.5
Future	2015-2020	82%	278.0	3.3	34.1	0.6	58.6	2.4	14.6	0.6	48.1	2.0	433.3	8.9
Total	2020		1203.0	14.3	147.6	2.6	253.6	10.4	63.1	2.6	208.1	8.5	1875.3	38.4

Annex III: Benefits accrued of the 2015-2020 digesters in 2020

	2015	2016	2017	2018	2019 (a)	2020 (b)	Units (c)	(B*C) Year y	(A*C) Year y+1
2015	30%	42%	55%	67.50%	80%	81.25%	2000	1625.0	1600.0
2016		30%	42%	55%	67.50%	80%	2200	1760.0	1485.0
2017			30%	42%	55%	67.50%	2400	1620.0	1320.0
2018				30%	42%	55%	2600	1430.0	1092.0
2019					30%	42%	2800	1176.0	840.0
2020						30%	3000	900.0	0.0
					sum		15000	8511	6337
					Weighted attainable benefit			56.74%	42.25%
					Year on EPA cessation lag			3	2

Benefits accrued from the 2015-2020 digesters in 2020:

	ALRI DALYs <5	ALRI Deaths <5	COPD DALYs	COPD Deaths	IHD DALYs	IHD Deaths	Lung Cancer DALYs	Lung Cancer Deaths	Stroke DALYs	Stroke Deaths	Total DALYs	Total Deaths
Average	425	5	48.5	1	82.5	3.5	21	1	66.5	2.5	643.5	13

Overall benefits 2006-2020

Digester population	**ALRI DALYs <5**	**ALRI Deaths <5**	**COPD DALYs**	**COPD Deaths**	**IHD DALYs**	**IHD Deaths**	**Lung Cancer DALYs**	**Lung Cancer Deaths**	**Stroke DALYs**	**Stroke Deaths**	**Total DALYs**	**Total Deaths**
2006-2014 in 2020	1203	14	148	3	254	10	63	3	208	8	1875	38
2015-2020	425	5	49	1	83	4	21	1	67	3	644	13
SUM	1628	19	196	4	336	14	84	4	275	11	2519	51

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