Air Pollution and Impact Analysis of a Pilot Stove Intervention

Report to the Ministry of Health and Inter-Ministerial Clean Stove Initiative of the Lao People's Democratic Republic

Final Report

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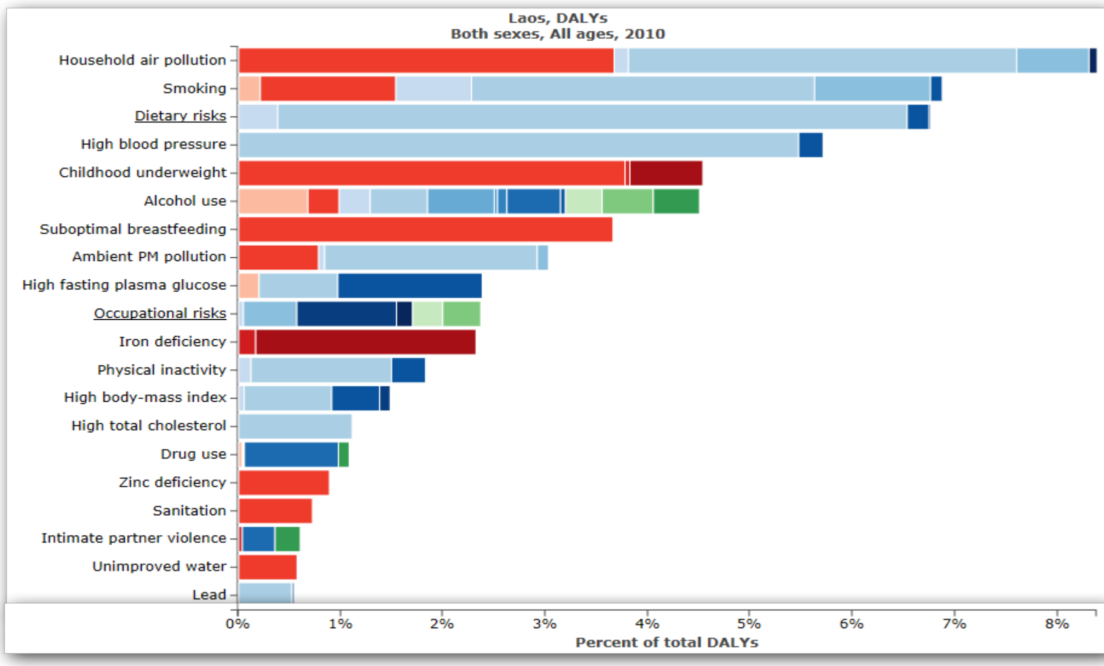
Preface

Household air pollution (HAP) from burning of solid fuel for cooking in traditional stoves is estimated to be responsible for about four million premature deaths annually in the world. In Lao People's Democratic Republic (PDR), where about 19 of 20 households cook with biomass fuels, it is thought to be responsible for about 5.8 thousand premature deaths a year, of which about 1,100 are due to pneumonia in children under five years. As shown in Figure P-1, HAP is ranked first of some 60 risk factors examined as a cause of ill-health in Lao PDR, being responsible for over 8 percent of total lost disability-adjusted life years (DALYs) in the country.

Figure P-1. Top 20 causes of lost DALYs in Lao PDR in 2010. HAP ill-health is mostly due to pneumonia in children under five, and cardiovascular and chronic lung diseases in adults. From http://vizhub.healthdata.org/gbd-compare/ .



Unfortunately, the burden is only slowly declining over time: ~2.5 percent per year since 1990.[2] This slow improvement and remaining large burden in many countries has led to global efforts to develop cleaner-burning biomass stoves for dissemination in rural areas to substitute for traditional stoves that tend to be highly polluting because of poor combustion conditions. If such advanced stoves could be shown to effectively and reliably lower pollution exposures and consequent health risks in the population, they could potentially be promoted as part of a package of national health promotion programs in Lao PDR and other countries.

Funded by the World Bank and with in-country partners (see author page), the Household Energy, Climate, and Health Research Group of the University of California Berkeley and the Berkeley Air Monitoring Group conducted an investigation of the effectiveness of a pilot stove intervention in Lao PDR in early 2015, which involved field, lab, and analysis work of several kinds to determine its field

[2] Further information about HAP and other causes of ill-health in Lao PDR can be found at http://www.healthdata.org/results/country-profiles

performance in terms of several parameters including air pollution, stove usage, and fuel consumption. This report to the Lao Ministry of Health and Inter-Ministerial Clean Stove Initiative Taskforce summarizes the results in a way that is hoped to assist in its assessment of whether this type of advanced stove might be appropriate for a large-scale introduction in the country to improve health.

Executive Summary

This study evaluated the usage, air pollution, and fuel-use performance of an introduced advanced biomass stove (African Clean Energy (ACE)-1) based on measurements in 72 households in three villages of the Xonboury District of Savannakhet Province in early 2015. This amounted to 23 percent of all the households in these villages. The report describes comparisons between household measurements conducted before stove introduction and those conducted approximately two weeks after introduction in the same households. Based on the best available health effects information, the report also estimates the potential health benefits of a large-scale introduction of this ACE-1 stove in Lao People's Democratic Republic (PDR) compared to traditional biomass stoves, assuming the new ACE-1 stoves were to perform similarly in the large program.

Due to time constraints, this study was limited in sample size and geographic and seasonal representation and was also only able to examine short-term pollution and fuel-use effects from the new stove less than a month after introduction. Most health benefits, however, require long-term reduction in air pollution, which was not directly measured in this study.

Major findings about the ACE-1 stove intervention revealed by this study are

- When introduced and promoted, it was readily taken up by the villagers and apparently used for nearly all cooking in the first weeks
- When used as the only cookstove, it reduced average kitchen pollution levels by about a factor of four compared to the traditional open biomass stoves.
- When used exclusively, it reduced fuel consumption per person by about 40 percent.
- When used exclusively, it reduced personal air pollution exposures of the cook also by about 40 percent – this is the most important metric for health.
- If this performance were maintained for three years with 75 percent long-term adoption and usage, dissemination to 25,000 households in similar Lao villages would reduce premature deaths by about 22 and disability-adjusted life years (DALYs) by about 1,200 in this population, with about half of the mortality benefit accruing from decreased child pneumonia and the rest from reduction in adult chronic diseases. (about 70 percent of the reduced DALYs would be in children). Assuming different lifetimes and/or usage rates would alter these estimates.
- Village outdoor pollution levels were apparently not affected even though nearly one-quarter of the households took on cleaner-burning ACE-1 stoves, which limits the maximum exposure reduction that can occur for anyone in the village because of smoke coming from neighbors' stoves.
- This implies that greater health benefit is likely to accrue if a larger proportion of households in a village adopt cleaner-burning stoves than achieved in this study.

- Pollution exposures, although substantially improved, did not come down to WHO guidelines or typical national standards for pollution.
- Although this intervention could achieve some heath improvement, about 87 percent of the total health impact of the stove pollution still remains when the stove is being used as intended because of the remaining pollution exposure.
- As is common with new technologies, there was evidence of stacking in many households in the initial weeks, i.e. some remaining use of the traditional stove. Only a longer study could determine the reasons for and duration of this practice.
- Although continuing monitoring is needed to firmly establish trends, many stoves apparently has had serious technical problems and, within a few months, usage rates declined substantially to no more than 75% of meals on average in the study households.
- This calls into question what the stove lifetime and usage are likely to be in the longer term for this stove, at least without major efforts to provide local servicing and repair facilities.

There are potentially other socioeconomic benefits of using ACE-1 stoves but this report only focuses on health impacts due to air pollution. Advanced biomass stoves like the ACE-1 may also have safety benefits compared to open cookfires, but these were not evaluated here. A decision whether to go ahead with a large-scale stove program as a health intervention should consider not only these findings, but also what alternative health investments are available in the country.

Introduction

This report assesses the impacts of the introduction of an advanced biomass stove called the African Clean Energy (ACE)-1[3] as part of the Lao Cookstove Pilot Intervention Study.[4] The analyses here are based primarily on measurements in 72 households in three villages in Xonboury District in Savannakhet Province over about three months conducted before and after the introduction of the advanced stove. The socio-demographic conditions of the villages are summarized in the Appendix Table 1.[5] This report provides results of several kinds, as indicated in the table of contents.

The basic design was a before and after study, with household measurements made before the introduction of the stove and after approximately two weeks of use. The full details of the methods and results are presented in the Appendix to this main report. See the Appendix Figures 1 and 2 for the flow charts of which measurements were undertaken in which subsets of households in what sequence.

As the field team encouraged each household to use the new stoves during the study period, this evaluation can be considered to be in an "efficacy" mode, i.e. the intervention is given the best chance to succeed through promotion by the field staff at each house.[6]

Results

Unless stated otherwise, the results reported here are based on paired analyses, i.e., a comparison of each house before introduction of the ACE-1 stove and after. This reduces unmeasured variability by keeping most household and demographic parameters constant and thus improves the ability to detect differences with statistical significance solely due to the stove introduction. Similarly, where possible, analyses are based on 48-hour measurements, which reduces variations due to natural alterations in household behavior from day to day.

Finally, as discussed in detail in the Appendices, we report as primary results those measurements using gravimetric methods (pumps and filters) as these are considered the highest quality ("gold standard"). The exception being section 2 (below), where data from a continuous but non-gravimetric monitor are needed to capture variations during the day.

1) Kitchen Air Pollution (KAP)

Figure 1 shows all the data for 48-hour kitchen concentrations both before and after in the 29 homes with complete gravimetric data. It shows that there was some overlap in the before and after

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[3] ACE 1 Ultra-Clean Biomass Cookstove, manufactured by African Clean Energy, Lesotho, and purchased in late 2014. The specifications of this stove, reasons behind it being chosen, and details of its dissemination in Lao PDR are reported by SNV Lao PDR Renewable Energy Sector, Vientiane. http://www.advancedcleancooking.org.

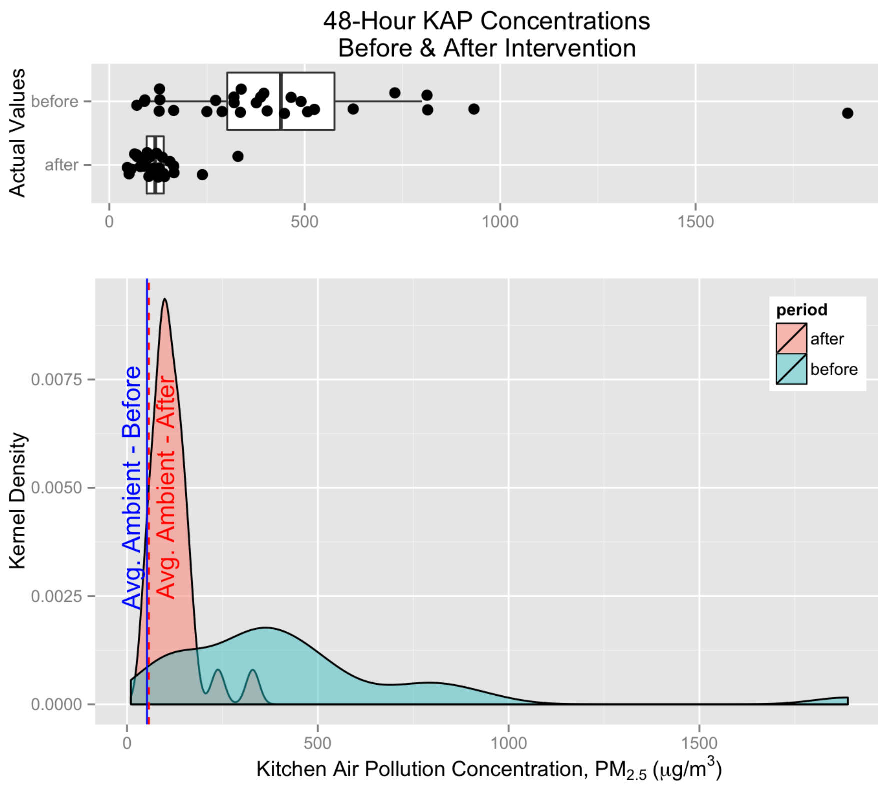
[4] For a description of the overall project, see reports, presentations and video in https://www.astae.net/

[5] Details are found in the separate report: Boatman M, et al. (2015): "Clean Cookstove Social Acceptability Assessment, Lao People's Democratic Republic Clean Stove Initiative Phase 2". Prepared for the World Bank.

[6] Efficacy trials are sometimes contrasted to "effectiveness" trials that evaluate lower but perhaps more realistic levels of promotion as might accompany a widespread intervention. There is no strict difference between the two, however, as even large disseminations can be accompanied by strong promotional efforts.

groups – some kitchens before the intervention had lower $PM_{2.5}$ levels[7] than some kitchens did after intervention, and vice versa. There is more variation in $PM_{2.5}$ level among the 29 homes' kitchen before the intervention than after, presumably due to more variability in the way open fires are fueled and used than the new stoves.

Figure 1. Distributions of paired 48-hour kitchen $PM_{2.5}$ concentrations (KAP). The horizontal axis shows the level of $PM_{2.5}$ in μg/m³ and the vertical axis shows relative frequency of the measurements (kernel density). Vertical lines show outdoor ambient average $PM_{2.5}$ concentrations during each period, Superimposed are boxplots that show individual sample. Means on the boxplots are represented by a vertical line, 95 percent confidence intervals of the means are indicated by the edges of each box, and whiskers show the standard deviation.



Before introduction of the ACE-1, KAP levels in these 29 households averaged 439 μg/m³ and afterwards they lowered to 118 μg/m³, nearly a factor of 4 improvement – see Table 1. The variation decreased substantially as well, with the max household level declining by nearly a factor of 6 (from 1889 to 329 μg/m³) as can be visualized by the much longer "tail" in Figure 1 for the before data.

[7] Particulate matter less than 2.5 micron in size, which is thought to be the best indicator of the health risk of pollution from combustion.

Table 1. Summary statistics for paired 48-hour KAP concentration measurements.

KAP Measurements - Paired 48-Hour Averages									
	n	Mean (μg/m³)	Lower 95% Confidence Interval (CI) (μg/m³)	Upper 95% CI (μg/m³)	Max (μg/m³)	Min (μg/m³)	Med (μg/m³)	SD (μg/m³)	COV
Before	*29*	439	301	576	1889	71	376	361	0.82
After	*29*	118	96	139	329	46	103	58	0.49

Average $PM_{2.5}$ was calculated from 96-hour continuous measurements using the University of California, Berkeley Particle and Temperature Sensor (UCB-PATS) monitor (light-scattering, not gravimetric) only. Visual observation of the time-series trace allowed us to understand whether KAP variations during the day before and after ACE-1 dissemination in the same households (see section 2) were similar (See Appendix). Relying on these instead of the gravimetric results, allows an assessment of KAP for a larger sample size (53 instead of 29) as shown in Table 2. This indicates that the households in which gravimetric monitoring was done had a somewhat larger reduction in KAP than was indicated by results with a larger sample size using light-scattering monitors. Here the reduction is about 58 percent, compared to 73 percent for households with either gravimetric or UCB measurements, although the starting ("before") levels are quite similar (459 vrs 439 μg/m³). We have no reason to think this difference is due to bias (different kinds of households or systematic error in the light-scattering devices) and is likely due to natural variation in these relatively small samples. Nevertheless, we use only the gravimetric results as a summary.

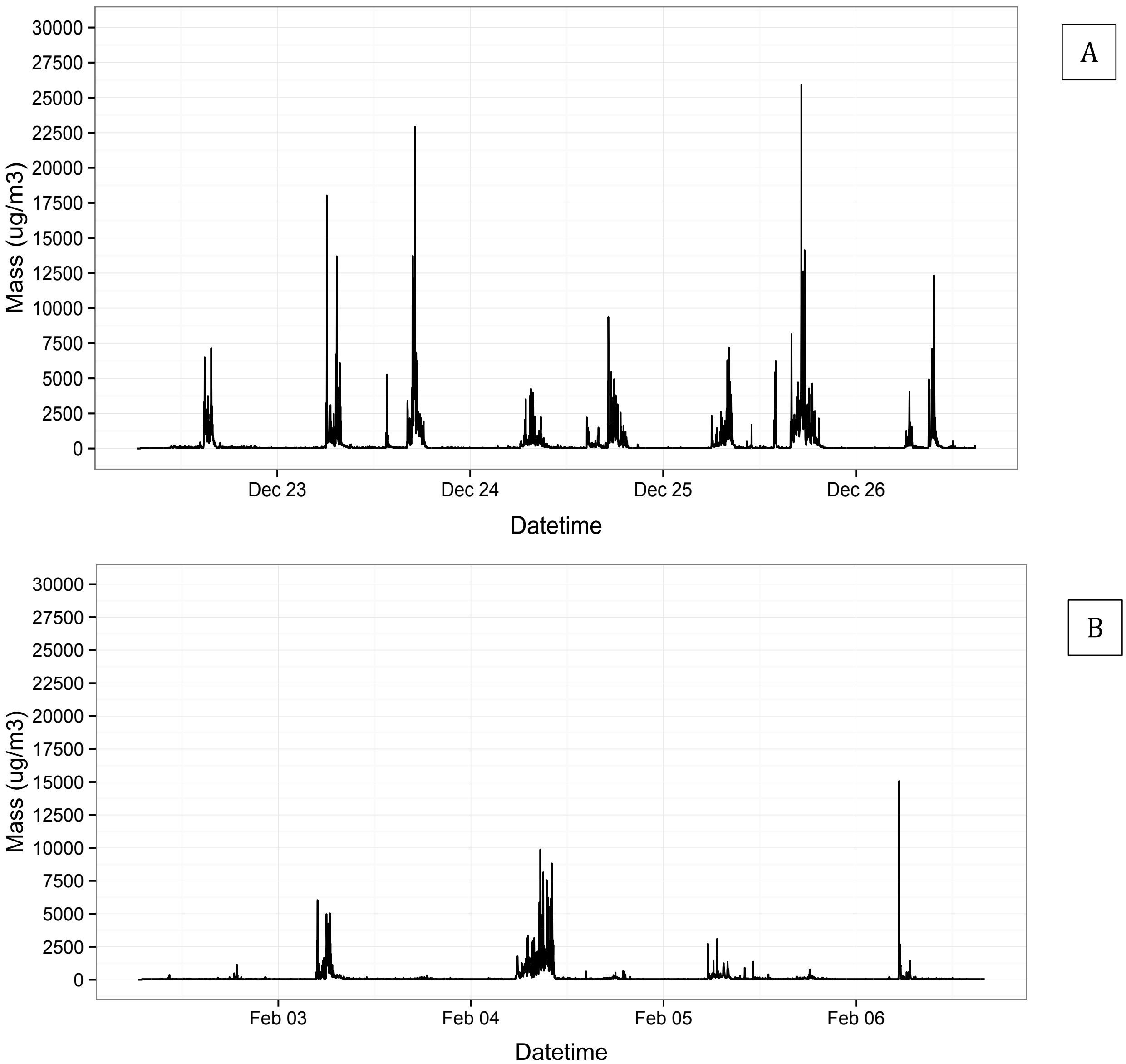
Table 2. Summary statistics for four-day KAP measurements using UCB-PATS

UCB KAP Measurements - All Households									
	n	Mean (μg/m³)	Lower 95% CI (μg/m³)	Upper 95% CI (μg/m³)	Max (μg/m³)	Min (μg/m³)	Med (μg/m³)	SD (μg/m³)	COV
Before	*53*	459	336	582	2530	60	362	446	0.97
After	*53*	192	138	246	1292	44	143	196	1.02

2) KAP variations during the day based on UCB-PATS

Daily patterns of particulate matter KAP before and after the intervention remained somewhat similar; an example of one household is shown in Figure 2. The peak KAP concentrations are clearly lower during the monitoring after the advanced cookstove introduction (Figure 2b). The total number and duration of elevated KAP events also appear reduced during the monitoring after the advanced cookstove introduction. Possible explanations include less frequent cooking, cooking elsewhere in the home, cooking different types of food, or the combined effect of significantly lower emissions from the ACE-1 stove and high ventilation reducing the KAP from cooking events to only slightly elevate above ambient levels, as seems to be the case for the small PM signal seen in a few February evenings (Figure 2b).

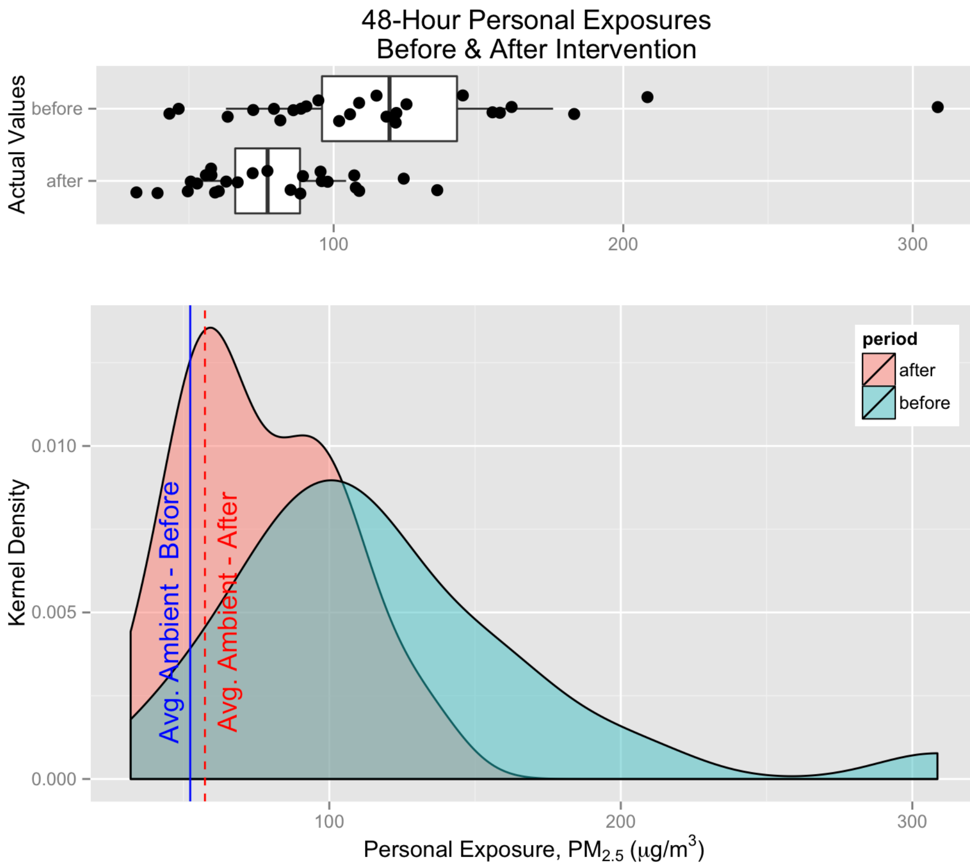
Figure 2. $PM_{2.5}$ KAP concentrations over 96 hours in one household measured by UCB in a study kitchen (a) before the ACE-1 dissemination and (b) after the ACE-1 dissemination.



3) Personal exposures to the cook

Personal exposures to the main cook, usually the wife of the household head, but in about 20 percent of households the woman head of household, are measured by asking her to wear a pump and filter for 48 hours. These were accomplished once before and once after the stove introduction. The results are shown in Figure 3, which shows the distributions for both the before and after measurements. Note that, again, there was much remaining overlap between the two groups before and after, i.e. some households after intervention had more exposure that some households before the intervention, and vice versa. In other words, the stove introduction did not create completely different (non-overlapping) exposure patterns.

Figure 3. Distributions of paired 48-hour personal $PM_{2.5}$ exposure values. The horizontal axis shows the level of $PM_{2.5}$ in µg/m³ and the vertical axis shows frequency of measurements (kernel density). Vertical lines show outdoor ambient average $PM_{2.5}$ concentrations during each period. Superimposed are boxplots, also differentiated by sampling period, that show individual sample. Means on the boxplots are represented by a vertical line, 95 percent confidence intervals of the means are indicated by the edges of each box, and whiskers show the standard deviation.



Statistically, however, the results show a mean reduction from 119 µg/m³ to 77 µg/m³ – see Table 3. As with KAP levels, the maximum level decreased to a greater extent (309 to 136) and overall variation was substantially less after the intervention. These changes in the mean exposures are the primary outcomes of the study for determining the health impacts of the stove. See Section 9.

Table 3. Summary statistics for paired 48-hour Personal Exposure measurements.

Personal $PM_{2.5}$ Exposure Measurements - Paired 48-Hour Averages									
	n	**Mean (µg/m³)**	**Lower 95% CI (µg/m³)**	**Upper 95% CI (µg/m³)**	**Max (µg/m³)**	**Min (µg/m³)**	**Med (µg/m³)**	**SD (µg/m³)**	**COV**
Before	*25*	119	96	143	309	43	109	57	0.47
After	*25*	77	66	88	136	32	72	27	0.35

4) Kitchen exposure factor (KEF)

As personal exposures are the best indicator of health risk, but also the most difficult to measure, it is useful to examine how well KAP alone represents exposure. As placing fixed monitors on the kitchen wall is much easier, less intrusive, and cheaper than personal monitoring, finding a strong relationship between these two could simplify future field studies. This relationship is indicated by the Kitchen Exposure Factor (KEF), which is simply the exposure divided by the KAP over the same period in the same household.

Table 4 shows that the mean KEF among households at baseline was 0.33 (95% Confidence Interval (CI): 0.25 - 0.41) and, when linearly modeled, was found to be a statistically insignificant relationship (p=0.83). The mean Kitchen Exposure Factor among households after receiving the ACE-1 intervention jumped to 0.69 (95% CI: 0.56 - 0.81) and became nearly significant using the standard criterion of 0.05 (p=0.11). More detailed information can be found in the Appendix, but unfortunately simple KEF does not seem stable enough under traditional conditions in these villages to allow KAP to be a useful surrogate for personal exposure. A more sophisticated modeling of KEF will be reported separately.

Table 4. Mean relationships between paired 48-hour Exposure and KAP, tested for trend by linear regression.

Linear Regression of 48-Hour Personal Exposure against KAP Concentration – Kitchen Exposure Factor

"Before" Data				
Slope	Intercept	p-value of slope	Mean KEF	95% CI
0.005	105	0.83	33 percent	8 percent
"After" Data				
Slope	Intercept	p-value of slope	Mean KEF	95% CI
0.157	56.6	0.11	69 percent	13 percent

5) Changes in ambient (outdoor) $PM_{2.5}$ in the villages

Budget constraints and initial difficulties with equipment resulted in fewer ambient measurements in the villages than would have been optimal, but, as shown in Table 5, a relatively small (5 μg/m^3) and statistically insignificant difference was found before and after in spite of the introduction of cleaner stoves in 23 percent of village households, ranging 18-30 percent by village. As there was also some shift in season with consequent differences in temperature, rainfall, wind direction and speed, which also affect ambient pollution, however, it is difficult to interpret the results.

Table 5. Summary statistics for ambient $PM_{2.5}$ concentrations in the study villages.

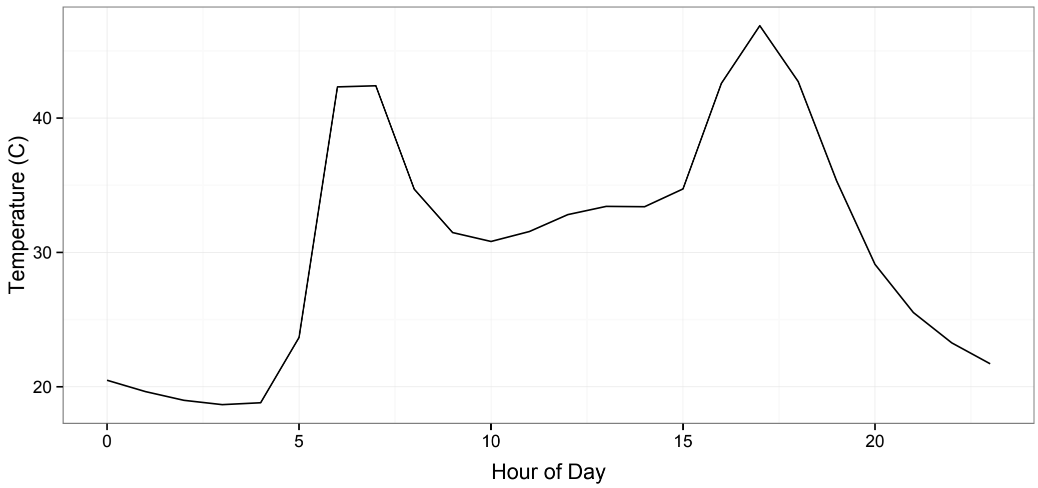
Ambient/Outdoor $PM_{2.5}$ Concentrations

	n	Mean (μg/m^3)	Lower 95% CI (μg/m^3)	Upper 95% CI (μg/m^3)	Max (μg/m^3)	Min (μg/m^3)	Med (μg/m^3)	SD (μg/m^3)	COV
Before	*7*	52	38	67	73	26	50	16	0.30
After	*14*	57	38	77	153	15	57	34	0.59

6) Stove usage and stacking (multiple stoves in use)

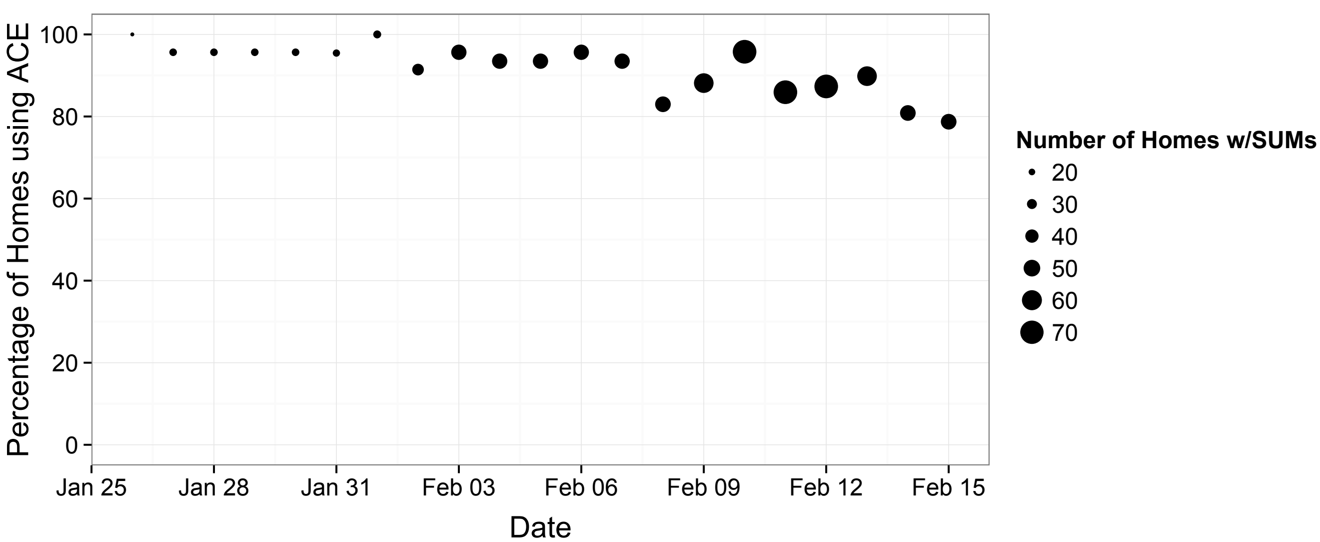
Deployment of Stove Use Monitors (SUMs) allowed direct measurement of stove usage and trends. As seen in Figure 4, cooking events were clustered around morning (5-9 am) and evening (4-8 pm) periods and were consistent across villages (See Appendix). Similar trends were noted in both pre- and post-intervention periods indicating that, at least for monitored stoves, periods of use occurred during roughly the same time windows.

Figure 4. The mean temperature by hour of day across all SUMs and households for the entire study period. The bimodal distribution strongly indicates two distinct daily cooking periods: 5-9 am and 4-8 pm.



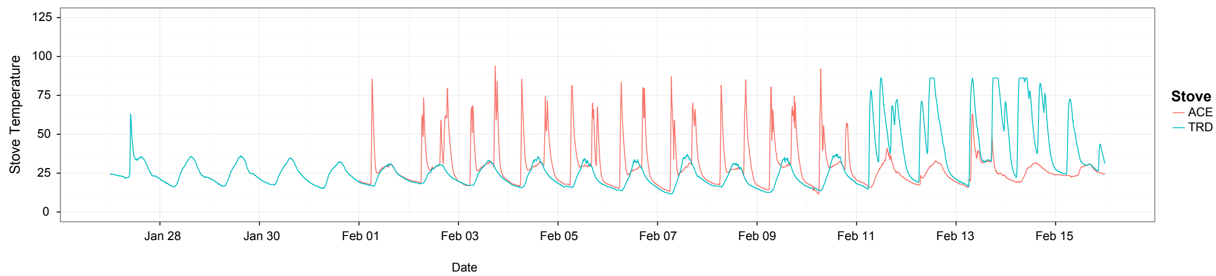
The proportion of homes using the ACE-1 remained high throughout the post-intervention period, though declining over time. As shown in Figure 5, on average, across the study, 92 percent of households used the ACE-1 every day; the lowest proportion of use occurred on the last day of monitoring, when 79 percent (37 out of the 47 monitored homes) used the stove.

Figure 5. The percentage of homes using the ACE-1 stove during post-intervention SUMS monitoring. The size of the circles indicates the number of homes being monitored at each given point, which first increased as more stoves were introduced and then decreased as the monitoring period came to a close. Overall usage of the ACE-1 remained high throughout the monitoring period.



Of the 17 households where SUMs were in place to measure both the ACE-1 and the traditional stove, 5 did not record any use of the monitored traditional stove during the post-intervention measurement period. From the remaining 12 homes, mixed usage was monitored for on average 4 days during the post-intervention period (Range 1-13, Standard Deviation (SD) 3.3). See details in Appendix Tables 15 and 16. Houses exhibiting stacking could be generally placed into one of three categories: "Initial mixed use, followed by ACE-1 use", "Mixed use throughout", and "Mixed use with reversion." 45 percent of homes began with mixed use, and then switched to exclusive use of the ACE-1 amongst monitored stoves; 27 percent exhibited mixed use behaviors throughout; and 36 percent used the ACE-1 and the reverted back to their traditional stove. An example of the third type is seen in Figure 6.

Figure 6. Example of stove stacking from the current study. In this case, exclusive use of the ACE-1 is replaced with mixed use and then exclusive use of the traditional stove.



It is important to note, however, that the effect of stacking was not measured accurately during post-intervention monitoring since households were asked to use only their ACE-1 stoves. Thus, the true mean post-intervention levels for the average household are likely higher than shown given that some households would be using their old stoves.

A quick survey of all 72 households was undertaken in June, 2015, about five months after introduction of the stoves. Table 6 shows the summary results and more details are in the Appendix.

Table 6. Self-Reported ACE-1 Usage after 5 Months (n=72)

Typical Usage	Number of households
Never	11 (15%)
A few times per week	6 (8%)
One or more meals per day	14 (19%)
Every meal	41 (57%)

After five months, self-reported usage was apparently consistent with nearly three-quarters of meals in the 72 households being cooked on the ACE-1 stove.[8] This implies that at least one-quarter of meals were being cooked on the traditional polluting stoves.[9] Unfortunately, the quick survey was not able to determine the degree of stacking occurring in households, i.e., the degree to which ACE-1 stove use occurred simultaneously with use of traditional stoves. As elaborated in the Appendix, the survey also revealed a number of technical problems that plagued the stoves and reduced usage.

[8] Depending on the interpretation of "one or more meals" and "a few times a week"
[9] See report of June disseminator http://www.advancedcleancooking.org.

7) Differences in fuel use based on cross-sectional measurements

Kitchen performance tests (KPTs)[10] were carried out using a cross-sectional study design because, due to the urgency of placing stoves into the village, there was no time to do pre-intervention KPTs in the same households. Approximately 2 months after ACE-1 stove dissemination, stove fuel consumption in the 72 ACE-1 households was compared to 72 neighborhood control homes with traditional cookstoves.

All fuels to be used on the household stoves were weighed at the beginning and end of the three consecutive 24-hour monitoring periods. Moisture levels in the wood fuel were adjusted for in the analysis and a short questionnaire during the monitoring period was administered each day of the total three days.

Table 7 shows fuel use measured during the three-day KPT. Only one household partly used charcoal, which was treated as wood in the analysis, otherwise wood was the exclusive fuel used on the household stoves in both study groups. Analysis shows a large statistically significant difference in both wood fuel and total energy consumption between the study groups. Households (HH) with the ACE-1 stoves used on average 59 percent less wood fuel per day and 42 percent less fuel energy (MJ) per 'standard adult (SA)[11] per day than the homes using traditional cooking methods. Both results were statistically significant (p=<0.001). See Appendix for more details of methods and results.

Table 7: Stove fuel use comparing ACE-1 to control households. SA = standard adult equivalent

	Wood			**Total Energy**	
	kg/HH-day	**kg/SA-day**		**MJ/HH-day**	**MJ/SA-day**
Control					
Mean	5.5	1.3		98.8	23.5
SD	2.5	0.6		44.7	11.3
COV	45percent	48percent		45 percent	48 percent
ACE-1					
Mean	2.3	0.8		40.6	13.7
SD	1.4	0.5		24.9	8.6
COV	61 percent	63 percent		61 percent	63 percent
percent difference	-59	-42		-59	-42
p-value*	<0.001	<0.001		<0.001	<0.001

*Independent samples T-test. N=72 in both study groups

8) Effect on black carbon KAP and personal exposure

Particles from combustion contain a percentage of black carbon (BC), a dark carbon-rich component, which has a disproportionate impact on climate warming. To determine the exact

[10] Details in Appendix

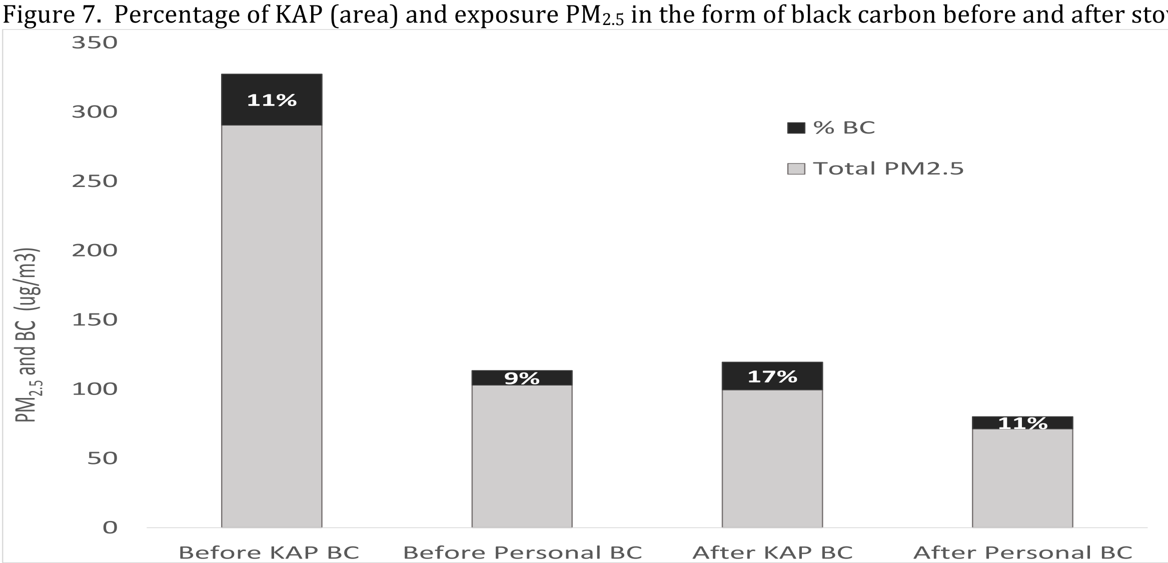
[11] "Standard adult" equivalence factors defined in terms of sex and age. See Appendix. Gender and age fraction of standard adult: child 0-14 years = 0.5; female over 14 years = 0.8; male 15-59 years = 1; and male over 59 years = 0.8.

climate impact, however, depends also on the organic fraction of the emitted particles, which tends to be light colored and thus actually cools the climate, partly or completely masking the warming caused to the BC component. The total warming commitment of biomass combustion also includes contributions from other products of incomplete combustion, such as methane and carbon monoxide, as well as the component of carbon dioxide coming from non-renewably harvested wood.

We did not conduct actual emission measurements, which would be needed to directly ascertain climate impacts. By examining the way light is absorbed on filters taken in the study, however, we made a rough estimate of their black carbon content in $PM_{2.5}$ in kitchens and in personal exposures (see Appendix). Figure 7 shows that introduction of the ACE-1 stove cut BC concentrations in kitchens nearly in half. This was largely due to the overall reduction in $PM_{2.5}$ kitchens impacting the BC concentrations as well, however. Of total $PM_{2.5}$ measured in kitchens, a greater fraction was actually BC in the after monitoring than the before monitoring, 17 percent and 11 percent, respectively, i.e. per unit mass, the particles from the ACE-1 were more warming that those from the traditional stoves, although there was less total amount of them.

The concentration of BC measured during personal exposure did not change as much as the KAP BC levels – from a bit more than 10 μg/m^3 to a little less than 9 μg/m^3, a change that was not statistically significant (see Appendix). The fraction of $PM_{2.5}$ found to be BC in the exposure measurements were smaller both before and after than the respective KAP fraction, suggesting that the women were exposed to sources of $PM_{2.5}$ exposure other than the cookstove that have a higher organic fraction than the $PM_{2.5}$ found in the kitchen. Possible sources are tobacco smoke and trash burning.

Figure 7. Percentage of KAP (area) and exposure $PM_{2.5}$ in the form of black carbon before and after stove dissemination.



9) Imputed health impacts: Averted DALYs and premature deaths

It is possible to estimate the health benefits of a stove introduction using Household Air Pollution Intervention Tool (HAPIT)[12], a web-based application developed by University of California,

[12] https://hapit.shinyapps.io/HAPIT/

Berkeley. This tool has built into it the most recent 2010 quantitative estimates of the health impacts of air pollution across four major disease categories in adults and one in children and calculates changes according to inputs of measured exposure changes and background disease conditions in ~60 nations, including Lao PDR.

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

- Personal exposure of the cook before and after introduction (as measured in this study) mirror those of other adults and children less than five year of age in the household. (No health effects in school age children have yet been firmly established for household air pollution.)
- The stove's performance in this study will be duplicated in the districts where the large-scale dissemination will be conducted
- The stove's performance measured in this study after two to three- weeks of use will be maintained for at least three years across all seasons.
- There will be no stacking (simultaneous use of the traditional woodstove during use of the ACE stove).
- The program disseminates 25,000 stoves, all installed instantaneously on the first day (January 1) of the first year. (larger programs would scale proportionally)

Estimates from HAPIT suggest that a dissemination of 25,000 ACE stoves in Lao PDR – assuming 100 percent stove usage and a 3-year stove lifetime – would avert between 730 and 2,660 total DALYs[13] and between 14 and 50 premature deaths, given the exposure levels and reductions measured and modeled during this analysis.[14]

On the other hand, if only 50 percent usage was achieved in the long term, the benefits would be roughly half those from 100 percent usage.

Taking the roughly 75 percent usage found in this study and a 3-year stove lifetime, between 535 and 2,005 DALYs and between 12-39 premature deaths could be averted by a 25,000-stove program in Lao. These results are reported in the last columns of Table 8 along with the central estimates. See Appendix for estimates under other scenarios.

Breakdowns of averted DALYs and premature deaths by disease type for each scenario described are also shown in Table 8. These disease types are acute lower respiratory infections (ALRI: mostly pneumonia) in children less than five years and adult chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), lung cancer (LC) and stroke. See more information in the Appendix.

In addition to the reduction in the health impacts, HAPIT also calculates the remaining ill-health that is left due to air pollution exposures even after the intervention, i.e., what additional could have been achieved if there had been 100 percent penetration of a truly clean cooking option in the villages, such as gas or

[13] Disability-adjusted life year – standard global health metric for comparisons across diseases, risk factors, and populations. It combines the impacts of premature death as well as illness. See Lim et al., 2012.

[14] The range derives from the measured variation in exposures during the study.

electric cooking. Figure 8 shows the full analysis for both a 3-year at 75 percent usage, illustrating that about 87 percent of the health impact from using the traditional cookstoves would still be untouched.

Averted DALYs and premature deaths by disease for an exposure reduction from 119 μg/m^3 to 77 μg/m^3 25,000 Lao households; 75% usage; no stacking; 3-year lifetime												
	ALRI		COPD		IHD		Lung Cancer		Stroke		Total	
	DALYs	Deaths	DALYs	Deaths	DALYs	Deaths	DALYs	Deaths	DALYs	Deaths	DALYs	Deaths
Central Estimate	885	10	95	2	125	5	35	1	80	4	1220	22
Lower Interval	400	5	25	1	60	3	15	1	35	2	535	12
Upper Interval	1450	17	150	4	205	9	55	2	145	7	2005	39

Table 8. Estimates of averted premature deaths and DALYs attributable to an ACE-1 stove intervention (assuming 75% usage and a 3-year lifetime) in 25,000 Lao households currently using open woodstoves for cooking. The higher and lower estimates derive from the measured variability in exposures.

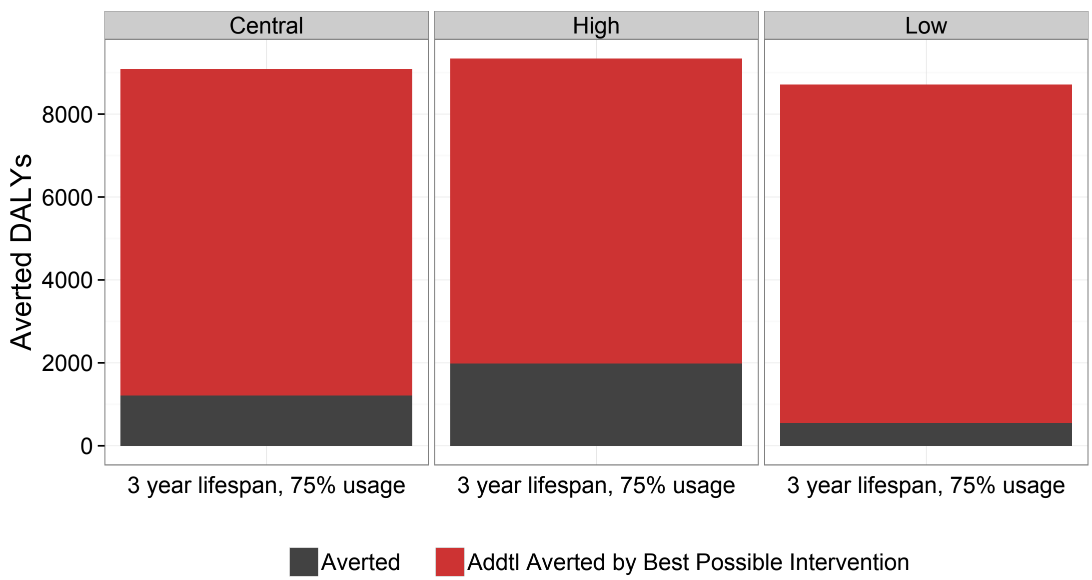


Figure 8. Estimates of averted DALYs attributable to an ACE-1 stove intervention (assuming 75% usage and a 3-year lifetime) in 25,000 Lao households currently using open woodstoves for cooking and the amount of ill-health still occurring because of the remaining household air pollution from the cookstove. The high and low estimates derive from the measured variability in exposures.

HAPIT additionally can estimate program cost-effectiveness using a simple financial accounting approach that does not take into account household participation, discounting, adjustments such as tax breaks, and monetization of such benefits as reduced time spent acquiring fuel. It basically assumes 100 percent support by some donor or government agency, which is not necessarily what would occur in a program funded by private investors in Lao PDR. A sample health cost-effectiveness analysis performed under these simplifying assumptions is included in the Appendix.

Summary and conclusion

This section is divided into four sections reflecting the primary results of interest in deciding whether to go ahead with a large-scale stove program.

Fuel Use

An important potential benefit of an advanced biomass stove is lower fuel use since it can translate to less time in fuel gathering and, where fuel is purchased, money savings. It may also have environmental benefits for the local habitat, although this seems unlikely in the area of Lao PDR where the study was done, which is not in danger of deforestation. Finally, even if there is no improvement in combustion, less fuel use alone will lower stove pollution emissions.

Based on the cross-sectional measurements in the study area, compared to traditional stoves, the ACE-1 stove seemed to require significantly less fuel for the same tasks; about 40 percent less per capita in Table 6.

This quite encouraging result should be considered in context, however. Unlike other parts of this work, the fuel use tests were not conducted on a before and after basis with the same households. The cross-sectional results that are reported here, by comparison, estimate changes that may not be as accurate, although given their size it is still likely that there is a real improvement. In addition, the kitchen performance tests are not done blindly, i.e. the household knows that they are occurring and thus may change behavior. Finally, as is true for all the measurements done in this study, fuel use was measured only once when the introduced stoves were relatively new. Without longer term studies, however, it is difficult to know to what extent such fuel performance would be maintained over years and across different seasons with changing biomass characteristics (type, moisture content, etc.).

Air pollution

Table 9 shows the most important results of the study, the reductions in 48-hour kitchen and personal $PM_{2.5}$, which were both highly significant. Kitchen levels lowered by more than 320 $\mu g/m^3$; exposures were lower and the difference pre- and post-intervention was less than that of the difference in KAP because people do not spend all day in the kitchen, but move around to other locations around the household and village where the pollution levels are less than in the kitchen, where the most polluting source, the cookstove, is located. In this study, the best indication of the exposure in these other locations is the ambient level (Table 5), which was somewhat more than 50 $\mu g/m^3$ on average. To reduce exposures much more, therefore, may require a larger fraction of households in the area to give up traditional stoves and consistently use cleaner stoves and/or fuels, since much of the village ambient pollution is likely due to the cumulative effect of many biomass stoves in use.

Table 9. Summary changes in 48-hour personal exposures and KAP concentrations calculated using the concentrations summarized in Tables 1 & 3. With statistical tests.

Difference Between 48-Hour Average Before and After Concentrations				
	Mean Difference (μg/m^3)	Lower 95% CI (μg/m^3)	Upper 95% CI (μg/m^3)	p-value (paired)
Personal	42	19	65	$p < 0.001$
KAP	321	188	454	$p < 0.001$

The level of personal exposure achieved in households using the advanced stove (77 μg/m^3– Table 3) is well above the Air Quality Guideline (AQG) recommended by WHO of 10 μg/m^3 or the US national standard of 12 μg/m^3, both annual averages. It is more than twice the Interim Target- I in the WHO AQGs (35 μg/m^3) set as the highest that should be allowed for any population. Nevertheless, it is significantly better than in the households when they were using simple open biomass cookstoves.

We did not measure stove emissions per se, but among the metrics in our study, changes in KAP levels could be expected to most closely track changes in emissions, although also being affected by other factors including changes in burning time of the cookstove and possible changes in kitchen characteristics like ventilation rates. The reduction in KAP levels averaged 73%. Given that fuel use was 42% less, on average, this implies that the emissions per unit fuel declined by about half ((1-0.42)/(1-0.73)).

Among advanced biomass stoves that have been formally tested, the Philips forced draft stove is closest to the ACE-1. In lab tests, the Philips showed an approximate 80% reduction in $PM_{2.5}$ per unit dry woodfuel compared to an open 3-rock wood stove (the closest among those tested to the open cookfires in Lao). As is often found, this probably indicates substantially better performance in the lab than achieved in the field in our study, a conclusion tempered, however, by the many assumptions necessary to make this comparison.[15]

A remaining question is how these reductions might be affected by household and socio-economic factors, e.g., do households with greater education achieve better results. Although there was relatively little differences of these types among the households in the study, tentative trends in exposure did seem to emerge according to socio-demographic variables, but sample size did not allow for statistical tests and so should be treated with caution.

During pre-intervention measurement, both exposure and KEF appeared to decrease with increasing household education level and increasing kitchen size. The associations with education became less steep during post-intervention monitoring while both associations with kitchen size seemingly reversed. Again, these are not robust conclusions at present due to high homogeneity among

[15] Jetter J, Zhao Y, Smith KR, Khan B, Yelverton T, DeCarlo P, Hays M, 2012, Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards, Environmental Science and Technology. 46,10827–10834.

households and consequent inability to discern trends with statistical significance at these sample sizes. See Appendix for more discussion.

Average pre-intervention personal exposures and KEFs were also greater in homes where smoking was present in the kitchen, but were not significant. The association between KEF and kitchen smoking remained after the intervention, while the relationship between exposure and kitchen smoking became less clear. Average ambient $PM_{2.5}$ concentrations varied only slightly between villages and sample periods, and are unlikely to introduce substantial bias into the analysis.

Imputed health benefits from a large-scale stove intervention

What health benefits could be expected from a proposed 25,000-stove intervention by the Lao government or others under the following conditions:

- In an area similar in cooking habits, fuel use, housing conditions, and climate to the study area
- With a stove that performed as well as the ACE-1 in this study over its lifetime
- There was no stacking (simultaneous use of the traditional biomass stove)

Under these conditions, the program results in between 535-2005 averted DALYs (~70 percent in children) and 12-39 averted premature deaths (half in children). Although these improvements are important, about 87 percent of the ill-health would remain from air pollution exposures after the intervention in this population compared to what could be achieved by a truly clean cooking technology, such as gas or electricity. Changes in assumptions about lifetime and usage would alter these results substantially, however.

Stove Use

The most troublesome results of the stove intervention relate to the apparent major decline in usage of the stove in the months after the primary monitoring was done. Unfortunately, however, due to impending deadlines that forced a much shorter field assessment than originally planned, there were no systematic measurements in those months. Surveys were conducted, however, that indicate a major drop in usage, apparently mostly due to technical failures of the stoves. Without more detailed field work, however, it is not possible to tell how much of the drop in usage was due to each of quite different reasons:

- Failure of the stoves that could have been fixed if local repair facilities were available
- Failure that would have required the replacement of the stove
- Other reasons such as dissatisfaction among users in the stove performance or usability.

No matter how efficient and clean a new stove, it brings no benefits if not used. This, of course, is premised on the observation and common sense that if the new stove is not being used people are still cooking and must have reverted to their old stove to do so. Ideally, both the intervention and primary traditional stoves would be systematically followed for many months more with more information gathered about reasons for non-use and, of course, for any future implementation.

Conclusion [same as in Executive Summary]

Due to time constraints, this study was limited in sample size and geographic and seasonal representation and was also only able to examine short-term pollution and fuel-use effects from the new stove less than a month after introduction. Most health benefits, however, require long-term reduction in air pollution, which was not directly measured in this study.

Major findings about the ACE-1 stove intervention revealed by this study are

- When introduced and promoted, it was readily taken up by the villagers and apparently used for nearly all cooking in the first weeks
- When used as the only cookstove, it reduced average kitchen pollution levels by about a factor of four compared to the traditional open biomass stoves.
- When used exclusively, it reduced fuel consumption per person by about 40 percent.
- When used exclusively, it reduced personal air pollution exposures of the cook also by about 40 percent – this is the most important metric for health.
- If this performance were maintained for three years with 75 percent long-term adoption and usage, dissemination to 25,000 households in similar Lao villages would reduce premature deaths by about 22 and disability-adjusted life years (DALYs) by about 1,200 in this population, with about half of the mortality benefit accruing from decreased child pneumonia and the rest from reduction in adult chronic diseases. (about 70 percent of the reduced DALYs would be in children). Assuming different lifetimes and/or usage rates would alter these estimates.
- Village outdoor pollution levels were apparently not affected even though nearly one-quarter of the households took on cleaner-burning ACE-1 stoves, which limits the maximum exposure reduction that can occur for anyone in the village because of smoke coming from neighbors' stoves.
- This implies that greater health benefit is likely to accrue if a larger proportion of households in a village adopt cleaner-burning stoves than achieved in this study.
- Pollution exposures, although substantially improved, did not come down to WHO guidelines or typical national standards for pollution.
- Although this intervention could achieve some heath improvement, about 87 percent of the total health impact of the stove pollution still remains when the stove is being used as intended because of the remaining pollution exposure.
- As is common with new technologies, there was evidence of stacking in many households in the initial weeks, i.e. some remaining use of the traditional stove. Only a longer study could determine the reasons for and duration of this practice.
- Although continuing monitoring is needed to firmly establish trends, many stoves apparently has had serious technical problems and, within a few months, usage rates declined substantially to no more than 75% of meals on average in the study households.
- This calls into question what the stove lifetime and usage are likely to be in the longer term for this stove, at least without major efforts to provide local servicing and repair facilities.

There are potentially other socioeconomic benefits of using ACE-1 stoves but this report only focuses on health impacts due to air pollution. Advanced biomass stoves like the ACE-1 may also have safety benefits compared to open cookfires, but these were not evaluated here. A decision whether to go ahead with a large-scale stove program as a health intervention should consider not only these findings, but also what alternative health investments are available in the country.

Appendix [see separate file/document)