Impacts on household fuel consumption from biomass stove programs in India, Nepal, and Peru

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1 Introduction

The majority of households in developing regions depend on solid fuels for their primary energy use, such as cooking and heating (Rehfuess et al., 2006). Cooking with solid fuels in inefficient stoves often results in high levels of indoor air pollution (Armendáriz-Arnez et al., 2010, Pennise et al., 2009), which is associated with several health impacts and estimated to be responsible for ~1.6 million deaths annually (Smith and Mehta, 2003). Solid fuel use can be costly in terms of money and time for fuel gathering/purchasing (García-Frapolli et al., 2010), and in many places contributes to deforestation through the unsustainable harvesting of trees for fuelwood or charcoal production (Masera et al., 2006, Top et al., 2004). There are also considerable climate implications as inefficient cooking technologies and charcoal production produce relatively large quantities of warming species such as methane and black carbon (Johnson et al., 2008, Pennise et al., 2001, Roden et al., 2006).

More efficient stoves and fuels have been primary interventions to address these impacts, with recent interest bringing more attention and resources (Smith, 2010). For example, international efforts such as the Global Alliance for Clean Cookstoves, as well as recently launched national stove programs in India, Peru, and Mexico, amongst others, are seeking to develop and implement more efficient cooking technologies. International carbon markets are also including more cookstove projects. Overall, this growing interest and investment in cookstoves will likely result in more scrutiny, and evaluations to verify that impacts of improved cookstoves are meaningful and real will be critical for justifying continued global investment in stove technologies.

Given the scope of the problem and growing global interest, there are surprisingly few current peer-reviewed estimates of fuel savings from in-home assessments (Bailis et al., 2007, Berrueta et al., 2008, Granderson et al., 2009). In turn, there is limited knowledge of how much fuel is actually being used across different regions and the overall impact stoves are producing. At a program level, improved stove organizations often rely on controlled stove testing to evaluate stove performance and lack estimates for the in-home performance of their stove(s), as in-home assessments require considerably more time and money, and can be more technically complex in terms of study design and data analysis. Unfortunately, controlled testing has been shown not to provide reliable information on fuel consumption or stove performance in the field (Bailis et al., 2007, Berrueta et al., 2008, Johnson et al., 2009).

In response to the need for more field-testing of stove performance, the Partnership for Clean Indoor Air (PCIA), funded by the U.S. Environmental Protection Agency (EPA), sponsored a program to assist Partner Programs in undertaking the Kitchen Performance Test (KPT), which estimates fuels consumption from daily household visits. Here we present the results from these KPTs, with fuel consumption and savings estimates from India, Nepal, and Peru.

2 Methods

2.1 Stove Performance Testing

Stove performance testing can assess a variety of metrics such as fuel efficiency, thermal efficiency, cooking time, ease of use, and emissions. Stove performance on these metrics can be applied to improve stove design and performance, inform stakeholders and potential funders, guide implementation decisions, and support the carbon credit process. The three main stove performance tests that are commonly used are the Water Boiling Test (WBT), Controlled Cooking Test (CCT), and KPT, originally developed by Volunteers in Technical Assistance (Baldwin, 1986), and later updated by the University of California, Berkeley and Aprovecho Research Center for the Shell Foundation's Household Energy and Health Program (www.pciaonline.org/testing).

- The WBT assesses stove performance using standardized cycles of boiling and simmering water under highly controlled conditions. It is generally used for stove design purposes and comparing different stoves using a common protocol.
- The CCT assesses stove performance based on preparation of common foods cooked by local people in a semi-controlled setting. CCTs are designed to compare an improved stove to the stove it is primarily meant to replace while performing the same cooking task.
- The focus of this paper is the KPT, which is the least controlled and most real-world of the three tests. The KPT assesses stove performance in homes during normal daily stove use and evaluates actual impacts on household fuel consumption. It is most commonly used for program level impact evaluation.

2.2 KPT Program Overview

The PCIA Partners selected for this program were from a pool applications seeking to receive KPT training and assistance in carrying out the field campaign. The training and assistance was provided by Berkeley Air Monitoring Group (Berkeley, USA). The first phase of the program consisted of a training workshop at the host organization to cover the theoretical aspects of the KPT, including study design, an overview of stove performance testing, data analysis, report writing, and KPT protocols. The second phase was the field campaign, during which KPTs were conducted at the chosen study sites.

2.2.1 India

The Partner program in India was First Energy, who manufactures and sells the Oorja stove and the biomass pellets used in the stove. The KPT was conducted to evaluate the Oorja stove (see Figure 1) in peri-urban neighborhoods of Kolhapur, Maharashtra. The Oorja stove is a forced-air, gasifier stove, optimized to use pellets made from compressed sugar cane residues.

The stove/fuel combinations in Kolhapur are varied and dynamic, with many families using a mix of fuels and stoves depending on the cooking tasks and fuel availability. The most common fuels are LPG, wood, and dung, with kerosene and pellets also used in some homes. The Oorja is primarily marketed as a less expensive alternative to LPG and generally used as a supplement in homes with LPG or kerosene stoves. As a transition from traditional biomass chulhas to the Oorja was not common, we designed the KPT study to provide a survey of homes primarily using improved sugarcane pellet Oorja stoves, traditional wood-burning chulhas, and LPG stoves. This provided a cross-sectional evaluation of household energy use. Fuel consumption data were collected at the end of the rainy season (October, 2010) in 20 homes primarily using traditional wood-burning chulhas, 7 primarily using LPG, and 25 homes using both Oorjas and LPG. Oorja users were identified from a list of customers supplied by the distributors and non-Oorja users were recruited by visiting households in the same neighborhoods.

2.2.2 Nepal

The Partner Programs in Nepal were the Center for Rural Technology (CRT) and the Energy Sector Assistance Program (ESAP), a unit within the Alternative Energy Promotion Center (AEPC), which hosted the KPT program. The Nepal improved stove assessed for this project came in two models: one-pot or two-pot. The stoves are designed for wood, constructed of clay and with chimneys to vent smoke outside (see Figure 1).

The study site selected for the KPT study was a series of peri-urban communities approximately 5 km west of Dhulikhel, just outside the Kathmandu Valley. Multiple cooking fuels were used in nearly all households, although wood is the dominant fuel source. Most households had small traditional charcoal stoves and an additional traditional open fire for cooking animal food. Corn cobs and bamboo were used as supplements to wood in most households. Electricity and biogas were used in some clusters, and LPG was present, but rarely used. Kerosene was used for lighting but not for cooking. The KPT was cross-sectional, performed at the end of the rainy season (late August, 2010) in 50 baseline households using traditional wood stoves and 50 households with the improved wood stove. The participants with improved stoves had been using them for at least six months.

2.2.3 Peru

The Partner programs in Peru were the Servicio Nacional de Capacitación para la Industria de la Construcción (SENCICO) and the German Agency for International Cooperation (GIZ). The intervention stove was the Inkawasi chimney stove, which is constructed of clay and bricks. It has a metal cooking surface with removable plates, providing holes into which sunken pots can be descended into the combustion chamber (see Figure 1).

Two communities in the northern province of La Libertad were selected for the KPT study site: Santiago de Chuco and Sanagoran. Wood is the primary fuel used in this area, although some homes had LPG stoves that were rarely used. This study was designed to have cross-sectional and paired (before/after) components. The first phase of the study was a cross-sectional evaluation between the communities, with those in Santiago de Chuco using traditional stoves (N=35) and those in Sanagoran using Inkawasis (N=40). The second phase of the study included a paired follow-up in Santiago de Chuco (N=17), where the Inkawasis were installed, as well as an evaluation in Sanagoran to evaluate the impact of maintenance and user training on fuel consumption. The second phase in Sanagoran was cross-sectional, and included a traditional user group (N=15), an Inkawasi group which received stove maintenance but no user training (N=17), and an Inkawasi group which received both stove maintenance and user training (N=20). The Inkawasi group in the first phase in Sanagoran did not receive maintenance or training. All phases of the study were conducted during the dry season, September to December, 2010.

Figure 1. Photos of typical traditional and improved stoves evaluated during the KPT studies.

2.3 Kitchen Performance Test Procedure

2.3.1 KPT Protocols

For all three KPT studies, fuel consumption estimates were collected for over three full days, requiring daily household visits for four days. All fuels used within each household (wood, charcoal, LPG, kerosene, pellets, dung, corn cobs, bamboo, etc.) were weighed daily using Salter Brecknell (Fairmont, MN, USA) ElectroSamson digital hand-held scales (maximum 25 kg; resolution 0.02 kg). Wood moisture was measured daily in fuelwood using households with a digital HRPQ wood moisture meter (Osprey-Talon, USA). A short survey was administered daily to record information about stove/fuel usage, the number and type of meals prepared, and the number of people for which the meals were prepared.

Fuel use and fuel savings were calculated in terms of kilograms per person per day by dividing the kilograms per household per day by the household size. The number of person-meals cooked during each day of the KPT was also determined via the daily KPT survey, and weighting factors were then applied to calculate both standard meals and standard adult equivalents (SAs). Standard meals were calculated using the following weighting factors: breakfast = 1.0, lunch = 1.0, dinner = 1.0, and tea = 0.2. Standard adult (SA) equivalents were determined using FAO standard adult weighting values: <14 years = 0.5, adult female >14 years = 0.8, adult male between 14 and 59 years = 1.0, and adult male >59 years = 0.8 (FAO, 1983). Fuel consumption data is reported per capita on a SA per day basis and per SA-meal. Energy conversions for fuels were assumed as those recommended in the KPT protocols for wood (18 MJ/kg), LPG (48 MJ/kg), and kerosene (44 MJ/kg); and 16 MJ/kg was assumed for Oorja biomass pellets (Mukunda et al., 2010).

2.3.2 Quality Assurance and Control

Quality assurance and control (QA/QC) protocols were followed across the three KPT studies to ensure that accurate and representative data was collected. Participants were instructed not to modify their typical patterns of fuel usage, fuel type, or stove use practices. Surveyors were instructed on appropriate questionnaire techniques. All scales were calibrated using NIST-traceable standardized weights. Duplicate weighings of a 10 kg reference weight were within 1%. Duplicate wood moisture measurements had a standard deviation of 1% in Peru, 3% in India, and 4% in Nepal.

3 Results

3.1 India

The energy consumption estimates for each group are presented in Table 1 and Figure 2. The fuel consumption estimates for the India study are presented based on an energy basis rather than a mass basis since the different fuel types had large differences in energy density. The energy consumption estimates are also presented without relative differences to avoid confusion that reductions in fuel consumption occurred relative to the traditional stoves, as households in the study area were not transitioning from traditional stoves to Oorjas.

Table 1.
Mean fuel consumption estimates for different stove/fuel user groups in India.

Stove/fuel use group	**N**	**SA/home**	**MJ/SA/day**					**MJ/SA-meal**				
			Wood	**LPG**	**Kero**	**Pellets**	**Total**	**Wood**	**LPG**	**Kero**	**Pellets**	**Total**
Chulha	20	4.2±1.3	21±10	1.2±3.1	0.6±2.7	-	**21±11**	6.1±2.6	0.3±0.8	0.2±1.0	-	**6.7±2.7**
LPG	7	4.1±1.7	-	8.9±4.4	-	-	**8.9±4.4**	-	2.3±1.1	-	-	**2.3±1.1**
Oorja	25	4.4±1.4	-	8.7±4.4	-	2.1±1.7	**11±5.9**	-	2.9±3.1	-	1.5±0.8	**4.4±3.3**

Notes: Variability presented as ±1 standard deviation.

The fuel consumption estimates indicate that homes with traditional biomass stoves required approximately double the energy for cooking compared to those using LPG and/or a combination of LPG/Oorja. Figure 2 shows that the cooking energy consumption between exclusive LPG users and those using LPG and the Oorja was similar. Figure 2 also shows that the Oorja was primarily a supplemental technology, as LPG cooking energy was over four times that of the Oorja on a per standard adult basis.

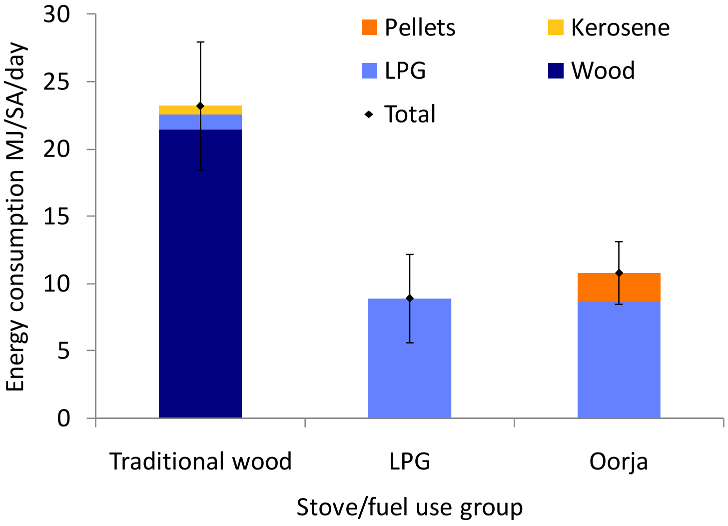

Figure 2. Energy consumption for stove/fuel use groups in India. Error bar represent ±95% confidence intervals.

3.2 Nepal

Household information and fuel consumption estimates for the baseline and improved stove user groups are presented in Table 2 and Figure 3. A primary consideration for comparability of groups was the use of biogas, which was common in the area. The groups were well matched, with 36% of homes in each group reporting use of biogas. There were slightly more standard adults in homes with the improved stoves. The majority of fuel use was regular fuelwood (78-82%) with a small amount of corn cobs, bamboo, and shrubby stalks (listed as “other biomass”) generally used as kindling for lighting the fire. The practice of removing pieces of charcoal from wood fires and using them later was also observed in several homes; however, as this charcoal is derived from the wood consumption, its mass is subsumed within the wood consumption estimates.

Table 2.
Mean fuel consumption estimates for baseline and improved stove users in Nepal.

	N	Percent HH using biogas	SA/home	kg/SA/day		kg/SA-meal	
				Wood	Other biomass	Wood	Other biomass
Baseline	50	36%	3.5±1.6	0.80±0.39	0.23±0.14	0.29±0.15	0.08±0.04
Improved stove	50	36%	4.5±2.4	0.56±0.23	0.13±0.12	0.21±0.11	0.05±0.07
Difference	-	-	**28%**	**-30%**	**-42%**	**-26%**	-34%
t-test p-value	-	-	**0.02**	**<0.01**	**0.01**	**0.01**	0.11

Notes: Variability presented as ±1 standard deviation. Significant differences are highlighted bolded in blue. “Other biomass” refers to corn cobs, bamboo, and shrubby stalks generally used as kindling to start the fire.

The improved stove demonstrated significant wood savings per standard adult (30%) and per standard adult meal (26%), which are generally more robust metrics than simple consumption per household, as they control for differences in household size as well as the amount of cooking. This is especially important here given that there were significantly more standards adults per home in the improved user group.

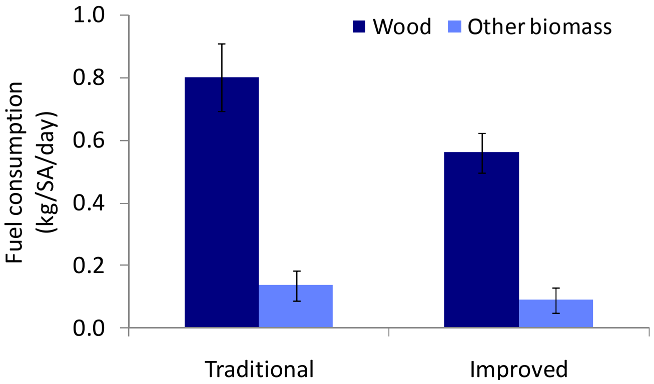

Figure 3. Fuel consumption (kg/SA/day) comparison for traditional and improved stove users in Nepal. Error bars represent ±95% confidence intervals. “Other biomass” refers to corn cobs, bamboo, and shrubby stalks generally used as kindling to start the fire.

3.3 Peru

Tables 3 and 4 present household information and fuel consumption estimates for Santiago de Chuco (before/after study) and Sanagoran (cross-sectional study). Differences in standard adults per home and meals per standard adult in Santiago de Chuco were minimal as these were the same homes being sampled before and after introduction of the Inkawasi stove. The sample groups in Sanagoran were different homes, with the standard adults per home slightly higher in the Inkawasi groups with and without user training.

Tables 3 and 4 and Figure 4 present the fuel consumption estimates for Santiago de Chuco and Sanagoran. The sample size in Santiago de Chuco was relatively small (N=13 paired before/after homes), but the fuelwood savings from Inkawasi use were significant on per capita (38%) and per meal (31%) bases. The Santiago de Chuco participants received stove training and had well-maintained Inkawasis.

Table 3.
Mean fuel consumption estimates for baseline and improved stove users in Santiago de Chuco.

	N	SA/home	kg/SA/day	kg/SA-meal
Baseline	13	2.9±1.0	2.1±0.9	0.67±0.21
Maintained Inkawasi (user training)	13	2.9±0.7	1.3±0.7	0.46±0.20
Difference	-	-3%	**-38%**	**-31%**
t-test p-value	-	0.54	**0.02**	**0.03**

Notes: Variability presented as ±1 standard deviation. Significant differences are highlighted bolded in blue.

The study in Sanagoran was cross-sectional, with groups of traditional users, Inkawasi users with no training or stove maintenance, Inkawasi users who did not receive training but with a maintained stove, and users with both training and a maintained Inkawasi. The impact of training and stove maintenance appears to be strong, as users without either were not found to significantly reduce fuelwood consumption, with those with both training and maintenance demonstrated that largest savings at 66% on a per capita and per meal basis. Those with a maintained Inkawasi but no training also demonstrated significant fuel savings compared to baseline users at 50% on a per capita and per meal basis.

Table 4.
Mean fuel consumption estimates for baseline and improved stove users in Sanagoran.

	N	**SA/home**	**kg/SA/day**	**kg/SA-meal**
Baseline	15	3.3±1.5	3.4±1.3	1.08±0.35
Inkawasi (no maintenance or training)	40	3.0±1.3	2.5±1.6	0.78±0.51
Difference		-10%	-27%	-27%
t-test p-value		0.26	0.26	0.37
Maintained Inkawasi (no user training)	17	4.3±1.6	1.7 ±0.69	0.53±0.19
Difference		32%	**-50%**	**-50%**
t-test p-value		0.06	**<0.01**	**<0.01**
Maintained Inkawasi (user training)	20	3.9±1.5	1.1±0.6	0.37±0.15
Difference		19%	**-66%**	**-66%**
t-test p-value		0.21	**<0.01**	**<0.01**

Notes: Variability presented as ±1 standard deviation. Percentage differences are relative to the baseline scenario. Significant differences are highlighted bolded in blue.

Figure 4 also shows the impact of training and maintenance in Sanagoran (dark blue), with fuel consumption estimates dropping across groups with training and/or maintenance. It is also apparent that baseline fuelwood consumption was significantly lower (Student's t-test; $p<0.01$) in Santiago de Chuco, even though these communities were within ~50 km of one another, with similar climate and geographic conditions. This indicates that a cross-sectional approach between these villages would be inappropriate as the baseline fuel use is not comparable.

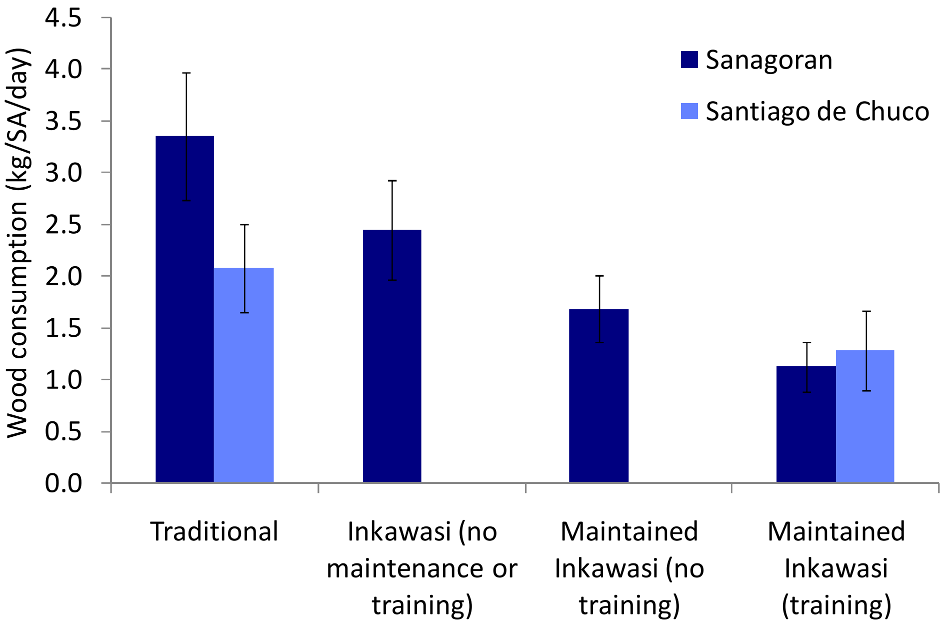

Figure 4. Fuel consumption (kg/SA/day) comparison for traditional and improved stove users in Peru. Error bars represent ±95% confidence intervals.

4 Discussion

4.1 Fuelwood consumption and savings estimates

The baseline per capita fuel consumption estimates reported here fall in-line with previously reported estimates. Figure 5 shows that the baseline fuelwood consumption estimates for Sanagoran and Santiago de Chuco are similar to those from rural Michoacán, Mexico (Berrueta et al., 2008); and those reported here for India and Nepal are also similar to previously reported estimates for India. These estimates suggest substantial differences in baseline fuel consumption between Latin America and India/Nepal. The two to three times higher baseline fuelwood consumption estimates for Latin America (2.1-3.4 kg/SA/day) compared to India/Nepal (1.0-1.4 kg/SA/day) likely arise from differences in dietary patterns, cooking practices, fuel availability, and other factors. The per capita fuel savings estimates found here are also similar for the given regions, with the Inkawasi's 27-66% savings in Peru just below that reported for the Patsari in Mexico (67%) (Berrueta et al., 2008), and the 30% savings of Nepal improved stove somewhat greater than those reported in India (15-19%) (Bailis et al., 2007).

The fuel savings estimates from Peru also provide compelling evidence for the importance of stove maintenance and user training. Figure 4 shows that per capita fuel consumption dropped sequentially across Inkawasi users groups, with the largest savings (66%) achieved by those who had maintained stoves and received user training. This shows that maintenance and training strategies are critical components for stove programs striving to maximize in-home stove performance. These may be especially important for programs which have stoves requiring sustained maintenance, such as large chimney stoves made from local materials, as well as stoves which require significant changes in user behavior to optimize fire tending and cooking practices.

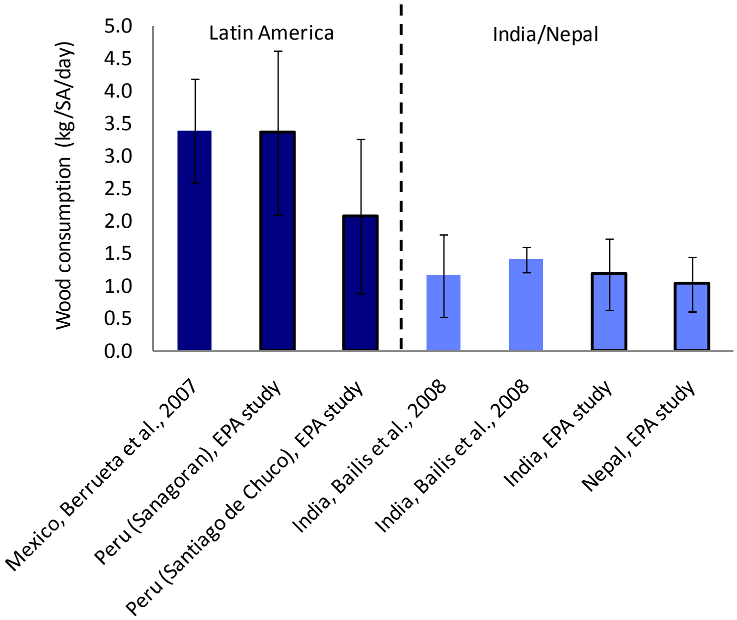

Figure 5. Baseline consumption (kg/SA/day) comparison for exclusive fuelwood users in Latin America and India/Nepal. Estimates from this study have been outlined in black. Error bars represent ±1 standard deviation.

To our knowledge, there are no current peer-reviewed KPT-based estimates of fuelwood consumption from other geographic areas, including Africa, Southeast Asia, and China. Better regional estimates of household energy consumption would help in the development and refinement of fuel use inventories used in climate modeling, country energy balance portfolios, demand on forest and agricultural resources, and methods used for determining carbon offsets from household energy interventions. There are a handful of studies which have reported estimates of fuel consumption using controlled cooking tests (Adkins et al., 2010, Berrueta et al., 2008, Pennise et al., 2010) as well as survey and/or modeling approaches (Habib et al., 2004, Hartter and Boston, 2008), but these can be difficult to translate into reliable household-level estimates.

4.2 Comparison with laboratory testing

The majority of stove testing is conducted under controlled conditions for providing rapid feedback to designers or as a standardized protocol for comparing important performance metrics across different stove technologies. Efficiency and emission metrics derived from controlled testing, however, have been shown to not be predictive of stove performance in homes under normal conditions (Bailis et al., 2007, Berrueta et al., 2008, Johnson et al., 2009, Roden et al., 2009). There are several factors which may contribute to differences between lab and field performance. For example, WBTs are typically conducted with idealized fuel conditions and tending practices, and stove use in homes encompasses a broad spectrum of practices often unrelated to boiling water. CCTs incorporate local fuels and fire tending practices, but still only replicate one cooking activity. Perhaps most critically, neither WBTs nor CCTs can account for the complexity of household stove and fuel use patterns with many improved stoves serving as partial replacement for traditional stoves.

Figure 6 compares the fuel savings estimates of WBTs, CCTs, and the KPTs for the stoves evaluated here. The Nepal improved stove demonstrated slightly higher fuel savings based on the WBT (42±10%) compared to the KPT (30±56%), but the CCT-based savings estimates (28±56%) were in agreement with the KPT estimate. Given the difference in savings estimates for the various Inkawasi user groups in these KPTs, it is difficult to compare the laboratory and field results. For communities that have not received sufficient maintenance and training, the WBT and CCT likely overestimate fuelwood savings, but may underestimate savings in communities where stoves are well maintained and users have received sufficient training. The comparison with the Oorja is different, as it presents a hypothetical scenario for fuel savings given a home transitioning from traditional biomass to a combination of LPG and Oorja use. We have also included a savings estimate from a series of uncontrolled cooking tests, for which users cooked their regular meals on either a traditional biomass (wood/dung) or Oorja stove, which appears to agree with WBT-based savings estimates as well as the hypothetical switch from traditional biomass stoves.

This graph also shows the difference in the variability of fuel savings estimates between the test types. WBTs are highly controlled, with the standard deviation of the fuel savings ranging from 3-23%, whereas uncontrolled KPTs had standard deviations of the fuel savings at 41-61%. The larger variation from uncontrolled testing implies that larger sample sizes are generally needed to reduce uncertainty in fuel consumption estimates for detecting statistically significant differences. A more detailed discussion on sample size is presented in the following section.

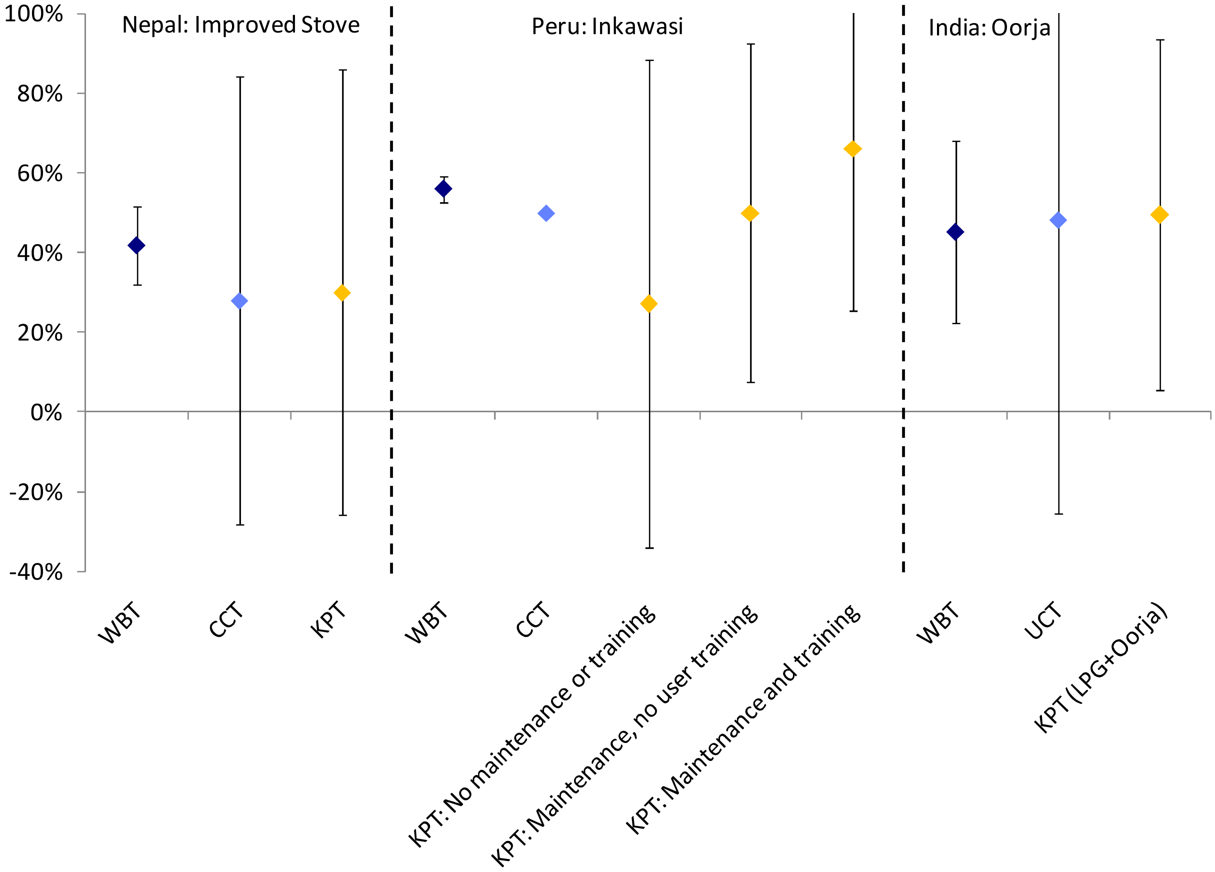

Figure 6. Comparison of fuel savings estimates using controlled tests and KPTs. Variability is expressed as ±1 standard deviation. UCT = Uncontrolled Cooking Test.

4.3 Variability and study design (placeholder section pending GS comments on new offset methodology).

Table X: Placeholder

						Sample sizes need to meet precision guideline			
						CDM	**GS V3 current (Savings)**	**GS V3 original (baseline and project)**	
Location	Sample group	COV baseline	COV project	savings	COV savings	**baseline 90/10**	**savings 90/15**	**baseline 90/15**	**project 90/15**
Peru	Inkawasi (no m, no t)	38%	63%	27%	227%	39	618	18	49
Peru	Inkawasi (m, no t)	38%	41%	50%	85%	39	87	18	21
Peru	Inkawasi (m and t)	38%	49%	66%	62%	39	46	18	30
Peru	Inkawasi (m and t) (paired)	46%	55%	38%	119%	58	170	26	37
India	LPG+Oorja	47%	55%	59%	89%	60	96	27	37
Nepal	Improved wood	48%	41%	30%	186%	63	419	28	20
Mexico	Patsari	24%	43%	59%	50%	15	31	7	23
India (ARTI)	Improved wood	45%	44%	15%	393%	56	1860	25	24
India DA	Improved wood	16%	14%	19%	104%	8	131		
	mean		**45%**	**40%**	**146%**	**42**	**384**	**21**	**30**
	median		**44%**	**38%**	**104%**	**39**	**131**	**22**	**27**
	min		**14%**	**15%**	**50%**	**8**	**31**	**7**	**20**
	max		**63%**	**66%**	**393%**	**63**	**1860**	**28**	**49**

Notes: Variability in fuel savings has been estimated by propagating the error assuming independent sample groups $\left(\sigma_{savings} = \sqrt{\sigma_{base\ line}^2 + \sigma_{project}^2}\right)$, with the exception of the paired Inkawasi group, for which house-by-house fuel savings estimates were available. Coefficient of variation (COV) is the ratio of the standard deviation to the mean: COV = σ/μ.

KPTs are the most time and resource intensive of the standard stove performance tests, and therefore there is considerable interest in optimizing sample design. This can be especially critical for programs seeking carbon credits, as in-home fuel consumption estimates are required as part of the Gold Standard methodology for voluntary carbon credits (Gold Standard, 2010) and are an option for baseline fuel consumption estimates for the Clean Development Mechanism (CDM) method [AMS-II.G. (UNFCCC, 2009)]. The carbon offset methodologies provide precision rules to guide sample sizes. For example, the CDM method requires that projects use the “90/10 rule”, which specifies that samples sizes for a measured parameter should be large enough that the 90% confidence interval[1] should be less than 10% of the mean. When the precision rule is met, the project can use the mean estimate rather than a

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[1] Confidence intervals are a function of variability and sample size. For a normal distribution, $90\%\ CI = \mp 1.645 \frac{\sigma}{\sqrt{N}}$, where σ is the standard deviation, N is sample size, and 1.645 is the z-score for a 90% confidence interval.

conservative confidence bound in the computation of carbon offsets, which provides an incentive to use sufficient sample sizes.

Table X shows the hypothetical sample sizes to meet given precision rules based on the variability from published KPT studies. Those required to meet the CDM method's 90/10 rule for baseline fuel consumption vary from 8-63. The Gold Standard method has a less stringent 90/15 rule, and thus the samples sizes are lower, ranging from 7-49. The Gold Standard method, however, typically requires estimating fuel consumption in the baseline group and project group, whereas the CDM method extrapolates fuel savings by applying an assumed efficiency ratio to only the baseline fuel consumption estimate. Thus the total number of individual fuel consumption estimates required by the Gold Standard method are actually higher than the CDM method. In general, minimum sample sizes of 30-60 should be targeted to meet the given precision rules, with careful analysis of the potential variability that may be encountered for the given project.

In addition to sample size requirements, future KPT efforts may benefit from further evaluation of the sampling period. The current 3-day sampling duration recommended by the KPT protocol is derived from the Berrueta et al. (2008) study, which found that coefficients of variation[2] (COVs) dropped from 54% for one day of fuel consumption estimates to 30% for three full days, with only a marginal reduction to 24% for a full week of estimates. The fuel consumption estimates from this study had COVs of ~40-60%, which are well above the 30% found by Berrueta et al. (2008) for three-day KPTs. The larger variability found during these KPTs suggests that there could be considerable benefit from extending the sampling duration, although more data would be needed to further evaluate the balance between sample duration, variability, and study cost.

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[2] Coefficient of variation is the ratio of the standard deviation to the mean: COV = σ/μ

5 Conclusions and recommendations

5.1 Conclusions

The fuel consumption estimates reported here indicate that the Nepal and Peru stove interventions produce significant fuel savings, and that the combination of Oorja/LPG usage presents an energy consumption scenario substantially lower than use of traditional biomass stoves. The fuel savings of the Inkawasi stove in Peru were highly dependent on the level of stove maintenance and user training, indicating that these are critical factors that need to be addressed for maximum stove performance to be realized. In India, the Oorja stove was used as an alternative to LPG, and thus the comparisons with traditional biomass stoves are speculative, although the fuel consumption estimates clearly suggest that there would be a considerable energy savings if traditional users were able to switch to LPG and Oorja usage.

5.2 Recommendations

- More assessments of in-home fuel consumption across a range of technologies and fuels are needed to better characterize real-world stove performance. A large-scale, global, independent field evaluation of a wide-range of stove technologies, including alternative fuels (e.g. LPG, ethanol, pellets, biogas, kerosene, plant oils), advanced stoves (e.g. forced air, gasifier, TLUD, pyrolytic), rocket stoves, and others would provide a valuable database to compare stove performance under realistic conditions. Concurrently measuring emission factors of health damaging pollutants (e.g. particulate matter and carbon monoxide) and climate forcing species (e.g. methane and black carbon) would help estimate impacts on health and climate.
- Using KPT fuel consumption estimates to map household energy demands across key geographies and demographic strata would help develop and refine fuel use inventories. Such an effort could also be used to inform on potential default, conservative baseline estimates for carbon offset methodologies.
- The KPT provides a good estimate for fuel consumption and savings, but is limited in time and scope. Understanding changes in fuel consumption and stove/fuel use patterns over time can also be critical for the success of a stove program, as well as for carbon offset projects. The development of protocols and monitoring technologies, such as simple stove temperature loggers (e.g the Stove Use Monitoring System [SUMS] (Ruiz-Mercado et al. 2011), can help provide longitudinal information on the adoption and usage rates of given stove technology interventions.
- Future field assessments should be coordinated with laboratory tests to help identify key factors responsible for performance differences and develop testing/assessment approaches which better predict field performance.
- In general there is a need for increasing stove performance testing capacity for programs developing and/or disseminating household energy technologies. Efforts to increase this capacity, especially for KPTs and other in-home assessments, through workshops or training programs, such the one used to help collect the data presented here, would help address this need.

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7 References

Adkins E, Tyler E, Wang J, Siriri D, Modi V. Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. Energy for Sustainable Development. 2010;14:172-85.

Armendáriz-Arnez C, Edwards RD, Johnson M, Rosas IA, Espinosa F, Masera OR. Indoor particle size distributions in homes with open fires and improved Patsari cook stoves. Atmos Environ. 2010;44:2881-6.

Bailis R, Berrueta V, Chengappa C, Dutta K, Edwards R, Masera O, et al. Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health project. Energy for Sustainable Development. 2007;11:57-70.

Baldwin SF. Biomass stoves: Engineering design, development, and dissemination: Center for Energy and Environmental Studies at Princeton University and Volunteers in Technical Assistance; 1986.

Berrueta VM, Edwards RD, Masera OR. Energy performance of wood-burning cookstoves in Michoacan, Mexico. Renewable Energy. 2008;33:859-70.

FAO. Wood fuel surveys. UN Food and Agriculture Organization; 1983.

García-Frapolli E, Schilmann A, Berrueta VM, Riojas-Rodríguez H, Edwards RD, Johnson M, et al. Beyond fuelwood savings: Valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico. Ecological Economics. 2010;69:2598-605.

Gold Standard. Indicative Programme, Baseline, and Monitoring Methodology for Improved Cook-Stoves and Kitchen Regimes. The Gold Standard Foundation; 2010.

Granderson J, Sandhu JS, Vasquez D, Ramirez E, Smith KR. Fuel use and design analysis of improved woodburning cookstoves in the Guatemalan Highlands. Biomass and Bioenergy. 2009;33:306-15.

Habib G, Venkataraman C, Shrivastava M, Banerjee R, Stehr JW, Dickerson RR. New methodology for estimating biofuel consumption for cooking: Atmospheric emissions of black carbon and sulfur dioxide from India. Global Biogeochem Cy. 2004;18:-.

Hartter J, Boston K. Consuming Fuel and Fuelling Consumption: Modelling Human Caloric Demands and Fuelwood Use. Small-Scale Forestry. 2008;7:1-15.

Johnson M, Edwards R, Alatorre Frenk C, Masera O. In-field greenhouse gas emissions from cookstoves in rural Mexican households. Atmos Environ. 2008;42:1206-22.

Johnson M, Edwards R, Berrueta V, Masera O. New Approaches to Performance Testing of Improved Cookstoves. Environ Sci Technol. 2009;44:368-74.

Masera O, Ghilardi A, Drigo R, Trossero MA. WISDOM: A GIS-based supply demand mapping tool for woodfuel management. Biomass Bioenerg. 2006;30:618-37.

Mukunda HS, Dasappa S, Paul PJ, Rajan NKS, Yagnaraman M, Kumar DR, et al. Gasifier stoves - science, technology and field outreach. Curr Sci India. 2010;98:627-38.

Pennise D, Brant S, Agbeve SM, Quaye W, Mengesha F, Tadele W, et al. Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. Energy for Sustainable Development. 2009;13:71-6.

Pennise D, Charron D, Wofchuck T, Rouse J, Hunt A. Evaluation of Manufactured Wood Stoves in Dadaab Refugee Camps, Kenya. United States Agency for International Development; 2010.

Pennise DM, Smith KR, Kithinji JP, Rezende ME, Raad TJ, Zhang JF, et al. Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. J Geophys Res-Atmos. 2001;106:24143-55.

Rehfuess E, Mehta S, Pruss-Ustun A. Assessing household solid fuel use: Multiple implications for the Millennium Development Goals. Environ Health Persp. 2006;114:373-8.

Roden CA, Bond TC, Conway S, Benjamin A, Pinel O. Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. Environ Sci Technol. 2006;40:6750-7.

Roden CA, Bond TC, Conway S, Osorto Pinel AB, MacCarty N, Still D. Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. Atmos Environ. 2009;43:1170-81.

Smith KR. What's Cooking? A Brief Update. Energy for Sustainable Development. 2010;14:251-2.

Smith KR, Mehta S. The burden of disease from indoor air pollution in developing countries: comparison of estimates. International Journal of Hygiene and Environmental Health. 2003;206:279-89.

Top N, Mizoue N, Ito S, Kai S. Spatial analysis of woodfuel supply and demand in Kampong Thom Province, Cambodia. Forest Ecol Manag. 2004;194:369-78.

UNFCCC. AMS-II.G: Switch from Non-Renewable Biomass for Thermal Applications by the User. 2009.