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Sensors show long-term dis-adoption of purchased improved cookstoves in rural India, while surveys miss it entirely

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Key terms: sensor, survey, stove usage, dis-adoption, purchased cookstove, stove use monitors

Abstract

User surveys alone do not accurately measure the actual use of improved cookstoves in the field. We present the results of comparing survey-reported and sensor-recorded cooking events, or durations of use, of improved cookstoves in two monitoring studies, in rural Maharashtra, India. The first was a free trial of the Berkeley-India Stove (BIS) provided to 159 households where we monitored cookstove usage for an average of 10 days (SD=4.5) (termed "free-trial study"). In the second study, we monitored 91 households' usage of the BIS for an average of 468 days (SD=153) after they purchased it at a subsidized price of about one third of the households' monthly income (termed "post-purchase study"). The studies lasted from February 2019 to March 2021. We found that 34% of households (n=88) over-reported BIS usage in the free-trial study and 46% and 28% of households over-reported BIS usage in the first (n=75) and second (n=69) surveys of the post-purchase study, respectively. The average over-

reporting in both studies decreased when households were asked about their usage in a binary question format, but this method provided less granularity. Notably, in the post-purchase study, sensors showed that most households dis-adopted the cookstove even though they purchased it with their own money. Surveys failed to detect the long-term declining trend in cookstove usage. In fact, surveys indicated that cookstoves' adoption remained unchanged during the study. Households tended to report nominal responses for use such as 0, 7, or 14 cooking events per week (corresponding to 0, 1, or 2 times per day), indicating the difficulty of recalling exact days of use in a week. Additionally, we found that surveys may also provide misleading qualitative findings on user-reported cookstove benefits without the support of sensor data, causing us to overestimate impact. Some households with zero sensor-recorded usage reported cookstove fuel savings, quick cooking, and less smoke. These findings suggest that surveys may be unreliable or insufficient to provide solid foundational data for subsidies based on the ability of a stove to reduce damage to health or reduce emissions in real-world implementations.

1. Introduction and background

Three billion people worldwide rely on biomass to meet household energy needs and prepare their daily meals (Stoner et al. 2021). A vast majority burn solid biomass fuels (e.g., coal, wood, dung, crop residues) using fires or inefficient cookstoves, which drives an unsustainable dependence on sources of woody biomass and produces extreme levels of pollutants that affect climate and human health. Women are disproportionately affected as they predominantly bear the burden of cooking and collecting fuelwood (Smith et al., 2014). Exposure to indoor solid fuel combustion is the world's deadliest environmental health threat, responsible for 3-4 million premature deaths per year (Forouzanfar et al. 2016). In India alone, 760 million people use solid fuels, and half a million premature deaths occur each year from exposure to indoor solid fuel combustion (Balakrishnan et al., 2019). In the state of Maharashtra, two-thirds of the rural population (about 10 million households) (Government of India 2012; International Institute for Population Sciences, 2015) use fuelwood for cooking, with 24% of collected fuelwood unsustainably harvested (Bailis et al., 2015).

Efforts to address this global issue often consist of introducing energy-efficient biomass cookstoves, termed "improved cookstoves", and healthier fuels, such as liquid petroleum gas (LPG). While improved cookstoves offer many benefits, impact is only realized if the stoves are regularly used. Improved cookstove programs have failed to reach desired levels of adoption (Gould and Urpelainen, 2018; Pillarisetti et al., 2014), plagued with problems of inadequate improved cookstove performance in the field, the stove design requiring burdensome behavior changes for the user, and missteps in program implementation and organization (Khandelwal et al., 2017).

Moreover, cookstoves programs often use unreliable and short-term methods to measure impact. Existing methodologies (Gold Standard, n.d.; UN, 2021) used to verify carbon emission reductions from cookstoves projects on the carbon offset market do not require emissions testing or usage monitoring which may result in inaccurate estimations (Johnson, Edwards, and Masera 2010; Freeman and Zerriffi 2014; Sanford and Burney 2015). The minimum requirement for verification in carbon offset methodologies (Gold Standard, n.d.; UN 2021) is to collect survey data on cookstove usage, allowing projects to claim up to 75% of continuous usage, potentially over-reporting emissions reductions significantly.

Previous studies have shown that it is critical to measure cookstove usage via sensors, also known as stove use monitors, as traditional methods of interviews can inaccurately represent actual usage because households commonly over-report their usage (Thomas et al. 2013; Daniel L. Wilson et al. 2016; 2018; Ramanathan et al. 2017). Over-reporting of intervention usage via surveys has also been shown for other interventions, such as water treatment (Thomas et al., 2013). Surveys can provide critical qualitative information such as user design preferences, household information, and insights into usage (Stanistreet et al., 2015), but they can fail to accurately measure quantitative patterns, especially over long periods. In contrast, sensors provide reliable, quantitative data of users' actual usage and can eliminate the different biases associated with interviews (e.g., recall bias, courtesy bias, and the Hawthorne effect) (Thomas et al., 2013; Wilson et al., 2016; Simons et al., 2017). While some studies have found better agreement between survey-reported and sensor-recorded usage, potentially due to survey question format, survey data provided much lower granularity (Ruiz-Mercado, 2011; Piedrahita et al., 2016).

Despite previous mixed methods studies' findings, surveys are still widely used as a method to measure cookstove usage. In a systematic review examining the factors that influence cookstove adoption in 32 improved cookstoves studies, none of the studies used sensors (Lewis and Pattanayak, 2012). In another review assessing the effects of behavior change strategies on cookstove adoption in studies published from spring 2013 to summer 2020, only four out of the 40 studies measured adoption with sensors (Furszyfer Del Rio et al. 2020). Similarly, another review also examined behavior change strategies used in cookstove adoption studies, in which five out of the 18 studies used sensors (Lindgren 2020).

Among the previous studies that have monitored usage with sensors, most are for durations shorter than 2 months (Burwen and Levine, 2012; Brant et al., 2012; Thomas et al., 2013; Hankey et al., 2015; Lozier et al., 2016; Wilson et al., 2016, 2018; Ventrella and MacCarty, 2019). To our knowledge, only a few studies report results from continuously monitoring usage for at least 6 months (Pillarisetti et al., 2019; Simons et al., 2017; Ramanathan et al. 2017) and beyond that, only three studies that continuously monitored usage for at least 1 year (Carrión et al., 2020; Pillarisetti et al., 2014; Piedrahita et al., 2016). Of these longer studies, Pillarisetti et al. (2014) and Carrion et al. (2020) found a decline in improved cookstove use via sensors over the course of the study, although they did not present analyses comparing survey-reported and sensor-recorded usage. Piedrahita et al. (2016) found as small as 2.4-6.8% discrepancies between aggregated survey-reported and sensor-recorded usage; however, they found temporal survey and sensor data agreement to decrease throughout the study. Owing to the urgency of identifying effective actions on climate change, there is an urgent need for more long-term continuous monitoring studies. Studies that use short-term or unreliable methods to measure usage may be failing to capture dis-adoption (also called disadoption or discontinuance in some literature (Ruiz-Mercado et al. 2011; Carrión et al. 2020; Alem, Hassen, and Köhlin 2014)).

This paper summarizes the results of comparing survey-reported and sensor-recorded use from two improved cookstoves monitoring studies in Maharashtra, India between February 2019 and March 2021. The first was a free trial of the Berkeley-India Stove (BIS) provided to 159 households where we monitored cookstove usage for an average of 10 days (SD=4.5) (termed "free-trial study"). The second was a study where we monitored 91 households' usage of the BIS for an average of 468 days (SD=153) after they purchased it at a subsidized price of about one third of the households' monthly income (termed "post-purchase study").

Unlike prior works, we provide meaningful insight into the behavior of users who purchased cookstoves at a significant price relative to their monthly income. Ramanathan et al. 2017 presents a climate credit-incentived study in which they measured the use of purchased improved cookstoves over a 9-month period; however, women took out loans to purchase the cookstove and 80% said they purchased it because of the promised climate credit payments. To our knowledge, there is only one prior study in the published peer-reviewed literature on extended continuous cookstove-sensor monitoring duration beyond 1 year (Piedrahita et al. 2016) that compares sensor- and survey-recorded usage; however, it studied the stacking of stoves, and the stoves were given free. We demonstrate the inaccuracy of using surveys alone to measure cookstoves' usage over time and highlight the importance of using sensors to accurately measure usage over a long-term period. In this paper, we define dis-adoption as the disuse of the improved cookstove, like Carrión et al. 2020. We do not provide a quantitative definition as dis-adoption is a complex process. We observe that dis-adoption can be intermittent; there might be periods of dis-adoption followed by periods of use. A detailed longitudinal analysis of the patterns of cookstove dis-adoption, as well as exploring potential reasons for dis-adoption using survey responses, will be presented in an upcoming paper. This paper does not speculate on the causes of dis-adoption, nor does it analyze reasons for why the surveys were unreliable. To our knowledge, there is no prior published study on measured adoption and use of purchased improved biomass cookstoves without the use of climate credit incentivization.

2. Design and Methods

2.1 Study Design

All fieldwork interactions with the study participants were in compliance with the University of California, Berkeley's Institutional Review Board approval (CPHS # 2017-07-10101). For all surveys (Section 2.5), we interviewed the female primary cook (above age 18) of each household. For stove-use monitoring (Section 2.6), participants were told that we would be "gathering data from a small temperature sensor in the new cookstove" but were not explicitly told that we would compare survey responses to measured temperature data.

The study design consisted of three main parts: 1) public informational meetings about the BIS (see Section 2.2) in villages, 2) the free-trial study, and 3) the post-purchase study. We held open public meetings where we presented the BIS to all attendees in the NGO-selected villages. We offered a free, no-obligation, 1-week trial to use the cookstove. At the end of the trial, households had the option to return the cookstove and purchase a new identical cookstove at a subsidized price. The decision to not give the cookstoves away for free, which is typically done in most cookstoves projects, was based on two main reasons: 1) to demonstrate a sustainable business model for future scaled implementation; and 2) it has been shown that when cookstoves are given for free, it can impact the user's perception of the cookstove's value (Barnes, Kumar, and Openshaw 2012). However, interviews revealed that households could not afford the BIS at full price (23 USD including transportation, packaging, and labor), as they had a median monthly household income of 2,500 INR (approximately 36 USD). We sold the cookstoves at about a 50% subsidized price (800 INR, 11 USD) on an interest-free 3- to 6-month installment plan, depending on the household.

2.2 Improved Cookstove

The BIS (shown in Figure 1A and 1B) was derived from the Berkeley-Darfur Stove (BDS), which was invented by researchers at Lawrence Berkeley National Laboratory (LBNL) and UC Berkeley in 2005 and was initially designed for use in Darfur during a humanitarian crisis where women faced hardship and danger from fuelwood collection (Amrose et al. 2008). The BDS has been shown to reduce fuelwood usage in laboratory-based experiments by approximately 35% and particulate matter measuring 2.5 microns or less ($PM_{2.5}$) emissions by approximately 50% compared to a three-stone fire (Jetter et al. 2012; Preble et al. 2014) which is the baseline stove in Darfur. Field tests showed that the BDS demonstrated 50% fuelwood savings compared to the three-stone fire (Galitsky et al. 2006). We hypothesized that, based on the substantial fuelwood savings the BDS provided, that a stove based on this design would likely reduce the burden and hardship of the women in rural Maharashtra, where fuelwood use for cooking is widespread. Leveraging existing partnerships between the Gadgil Lab and organizations in Maharashtra, we aimed to adapt the cookstove design—based on user-feedback and cultural appropriateness—for cooks in rural Maharashtra who were using fuelwood.
In June and July 2018, the LOLT and IITB CTARA research teams participated in an iterative design adjustment to develop the BIS design based on user-feedback and cultural appropriateness. LOLT and IITB CTARA were the public-facing part of the design adjustment to get feedback from users and focus groups. UC Berkeley and the manufacturers (Shri Hari

Industries) undertook the technical modifications according to feasibility and cost. The iterative process included three main steps: 1) usage of the cookstove via 5- to 10-day trial periods (n=30); 2) user feedback consisting of 1-on-1 interviews (n=30) and focus group discussions (six groups); and 3) minor design changes. Throughout this design adjustment process, we recognized the importance of adjusting the cookstove design to local cooking practices (Khandelwal et al. 2017) and we paid particular attention to stove features shown to be valued by users (Thacker, Barger, and Mattson 2014; Mukhopadhyay et al. 2012). Our goal was to identify minor design changes that fit the following criteria: 1) met user preferences based on their local cooking practices; 2) were feasible to complete, both economically and within a specific timeframe; and 3) did not reduce the stoves' energy efficiency. See SI (S1.1) for more details.

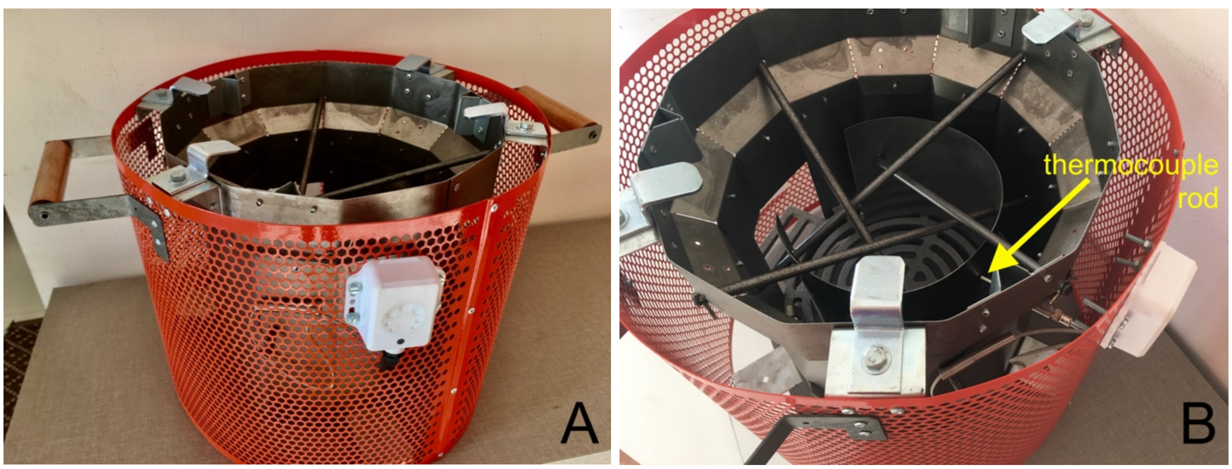

Figure 1A (Left): Side view of BIS with Geocene sensor, the white box, attached to outer wall; **Figure 1B (Right):** Top view of BIS showing a steel tube (shown by the yellow arrow) holding the thermocouple touching the firebox wall.

2.3 Study Site

Both the free-trial and the post-purchase studies took place in the Raigad and Thane Districts of Maharashtra, India, about 60 km east and 90 km northeast, respectively, of Mumbai, between February 2019 to March 2021. We worked in collaboration with the Centre for Technology Alternatives for Rural Areas at the Indian Institute of Technology, Bombay (IITB

CTARA), and the local NGO, Light of Life Trust (LOLT) near the villages in the study. The districts were identified based on where IITB CTARA and LOLT had existing presences in lower income, rural communities that had reported local fuelwood scarcity and poor LPG fuel access. Study participants in both studies lived in 17 villages in Raigad District and 3 villages in Thane District; in both districts, the study villages were within approximately 30 km of their nearest neighboring village. A timeline of the work presented in this paper can be found in the SI (S2).

We observed an average fuelwood collection trip of 3.3 h in time (n=3), 3.5 km in distance (n=3), and woodpile weights (n=14) of 33 $\pm$ 5.4 kg carried on women's heads (shown in Figure 2). Women (n=40) reported making fuelwood collection trips like this at least once per day in the non-rainy season (October – May). We hypothesized that an improved biomass cookstove with high fuel-efficiency, such as the BIS would be beneficial to villages with these characteristics.

Figure 2: Women carrying fuelwood on their heads during a fuelwood collection trip near Raigad District, Maharashtra, March 2019.

2.4 Study Participants

In our two studies (free-trial and post-purchase), 159 households participated in the free-trial study, with 48 of these households purchasing the cookstoves and participating in the post-purchase study. An additional 43 households that did not participate in the free-trial study wanted to purchase the cookstoves, having heard of the cookstoves via word of mouth, and participated in the post-purchase study. The total number of households in the post-purchase study was 91. Separately, some households purchased the cookstoves, but we did not monitor them owing to limitation on number of sensors. See SI (S1.2) for more details.

2.5 Survey Collection

As mentioned above, we monitored 159 households' (that participated in the free-trial study) cookstove usage with the sensors. However, our research team was only able to collect survey-reported quantitative use for 88 of those 159 households at the end of the free 1-week trials. We have binary-use survey reports for 120 of those 159 households (see Section 3.1.1).

For the post-purchase study, the research team interviewed all 91 households for baseline information at the time of the purchase of the stove. There were two more follow-up surveys conducted throughout the study: Follow-up 1 (n=75) at 3-5 months and Follow-up 2 (n=69) at about 1 year after purchase, depending on the household, as the households purchased their cookstoves at different dates. Survey questions consisted of household attributes, household members' occupations and education levels, fuelwood collection, BIS usage, and BIS advantages and disadvantages. Again, for all surveys, we interviewed the female primary cooks (above age 18) of each household. Survey questions on BIS usage were derived from methods used in Wilson et al. 2016 and Ruiz-Mercado 2011. Additionally, we worked with IITB CTARA, LOLT, and another local organization, Neerman, to develop the surveys, translate them (to the local language, Marathi), pre-test them, and make sure they were interpretable by survey respondents. There were 51 households in the post-purchase study that were interviewed in both follow-up surveys. Due to the remoteness of the villages, it presented challenges in reaching all households for each follow-up survey. We faced road closures due to monsoons and household members were often not home. Additionally, due to the COVID-19 Pandemic beginning in March 2020, we had to reduce the number of follow-up surveys initially planned and were unable to reach some households for second follow-up surveys.

2.6 Stove Use Monitoring

We used temperature data loggers, Geocene Dot sensors (Wilson, Williams, and Pillarisetti, 2020), to measure BIS usage quantitatively for both the free-trial study and the post-purchase study. We were unable to extensively measure concurrent traditional or baseline cookstove usage due to the limited number of sensors. The sensors (the white boxes shown in Figure 1A) were attached to the outer wall of the cookstoves. The sensors have a thermocouple which touched the inner firebox of the cookstove, shown in Figure 1B, and recorded the temperature of the inside firebox every 5 minutes. The temperature of the cookstove firebox is a well-established proxy for usage (Ruiz-Mercado, 2011). The sensor boxes and thermocouples were bolted to the cookstove wall and firebox, respectively, making them very stable and difficult to remove. We found all retrieved sensor boxes and thermocouples still bolted to cookstove at the time of sensor collection. We found some sensors (<5) damaged, in which case we did not use these data in our analyses.

For the free-trial study (n=159), the mean monitoring period was 10 days (SD=4.5), and the median was 9 days. There was variation in the lengths of the monitoring periods due to the ability of the research team to reach villages to collect the cookstoves. For the post-purchase study (n=91), the mean monitoring period was 468 days (SD=153 days), and the median monitoring period was 518 days. Households' cookstoves were also monitored for different lengths of time because households had different purchase dates and different sensor retrieval dates. Sensor retrieval and data collection were difficult due to unexpected challenges with fieldwork; some households moved during the study period, and the COVID-19 Pandemic began in the middle of the study. About 25% of sensors remain in the field, either lost or unable to be retrieved. These households may have a shorter monitoring period compared to other households, which presents a nonrandom bias in data loss, since most of the lost sensors are from the Thane District.

Approximately 13 million data points were collected during the post-purchase study, which represents about 48,000 stove-days. We used the "FireFinder" algorithm presented in Wilson, Williams, and Pillarisetti 2020 to identify periods of "cooking" based on the temperature sensor data. One "cooking event" is defined as having a minimum period of 10 minutes and separated by more than 10 minutes between adjacent cooking events. These parameters were determined based on pre-study field observations and interviews on cooking practices.

3. Results

3.1 Survey Usage Questions

3.1.1 Binary Question Format

The research team asked 120 households in the free-trial study about their cookstove use in a binary question format: "Did you use the BIS in the trial?" Table 1A shows the results comparing the trial households' responses and the sensor-recorded usage. We found that 90% of households' responses matched their sensor-recorded usage, of which the majority were users, and 10% of households' responses did not match their sensor-recorded usage. A match is defined as when a household that responded "no", had zero cooking events, and a household that responded "yes" had at least one cooking event. We define "user" as a household having used the cookstove at least once and "non-user" as a household that never used the cookstove.

For the post-purchase study, the research team similarly asked households about their cookstove usage in a binary question format in both follow-up surveys: 1) "Have you used the BIS at least once in the last month?" (Asked in both follow-up surveys), and 2) "Have you used the BIS at least once in the last year?" (Asked only in Follow-up 2). We then compared the households' responses to their sensor-recorded usage. Table 1B and Table 1C show the results from Question 1 in which households replied yes or no, and whether the sensor showed any use for the previous month from the interview date. We found that for Question 1 in Follow-up 1 (n=75), 83% of households' responses matched their sensor-recorded usage, split about equally between users and non-users, and 17% of household's responses did not match their sensor-recorded usage. For Follow-up 2 (n=69), 78% of households' responses matched their sensor-recorded usage, with three times more non-users than users, and 23% of households' responses did not match their sensor-recorded usage. Table 1D shows the results of Question 2 where 90% of households' responses matched their sensor-recorded usage, and 10% of households' responses did not match their sensor-recorded usage.

A. Free-trial data			
		Sensor-recorded usage	
		Yes	No
Survey-reported usage	Yes	74%	7.5%
	No	2.5%	16%

B. Post-purchase Follow-up 1 (1mo)			
		Sensor-recorded usage	
		Yes	No
Survey-reported usage	Yes	41%	11%
	No	6%	42%

C. Post-purchase Follow-up 2 (1mo)			
		Sensor-recorded usage	
		Yes	No
Survey-reported usage	Yes	18%	20%
	No	3%	60%

D. Post-purchase Follow-up 2 (1y)			
		Sensor-recorded usage	
		Yes	No
Survey-reported usage	Yes	58%	3%
	No	7%	32%

Table 1: Results of sensor-recorded usage versus survey-recorded usage for binary questions. **Table 1A (Top Right):** "Have you used the BIS at least once within the last week? Trial data, n=120. **Table 1B (Top Left):** "Have you used the BIS at least once within the last month?" Follow-up 1, n=75**; Table 1C (Top Right):** "Have you used the BIS at least once within the last month?" Follow-up 2, n=69; **Table 1D (Bottom Left):** "Have you used the BIS at least once within the last year?" Follow-up 2, n=69.

3.1.2 Quantitative Question Format

The research team asked 88 households in the free-trial study (average monitoring period: 10d, SD=4.5) about their cookstove use in a quantitative format, "How many days in the trial did you use the cookstove at least once?" We compared the households' reported usage from this question to their sensor-recorded usage during the trial. For the free-trial study, we arbitrarily defined accurate reporting as falling within ±30% of the sensor-recorded usage to allow for some recall bias. We define over-reporting as falling above the +30% boundary and under-reporting as falling below the -30% boundary. Figure 3A shows the results; 49% of households accurately reported their usage, 34% over-reported their usage, and 17% under-reported their usage. It is possible that under-reporting was due to survey respondents (female primary cooks) being unaware of other household members using the cookstove. We also calculated the average deviation from the solid 1:1 survey-to-sensor line shown in Figure 3 to understand how divergent households' survey-reported usage was from their actual sensor-recorded usage. The average deviation was 1.61 days (SD=2.6).

The research team similarly asked households in the post-purchase study (average monitoring period: 468d, SD=153) about their usage in a quantitative format: "What is the average number of times per week that you have used the BIS in the last month?" (Asked in both follow-up surveys). We compared the households' reported usage from this question to a 4-week average of sensor-recorded usage leading up to the interview date. For the post-purchase study, we arbitrarily defined accurate reporting as falling within ±10% of the sensor-recorded usage to allow for some recall bias. We define over-reporting as falling above the +10% boundary and under-reporting as falling below the -10% boundary. The results are shown in Figure 3B and Figure 3C for both follow-up surveys. For Follow-up 1 (n=75), we found that 44% of households accurately reported their usage, 46% of households over-reported their usage, and 10% of households under-reported their usage. For Follow-up 2 (n=69), we found that 64% of households accurately reported their usage, 28% of households over-reported their usage, and 8% of households under-reported their usage. We also compared the households' reported usage to their sensor-recorded usage from the last 1 week to see if there would be higher agreement, and we found results within 5% of the 4-week average of sensor-recorded usage. Additionally, for Follow-up 1, the average deviation was 4.5 cooking events (SD=5) and for Follow-up 2, the average deviation was 3.5 cooking events (SD=6.5).

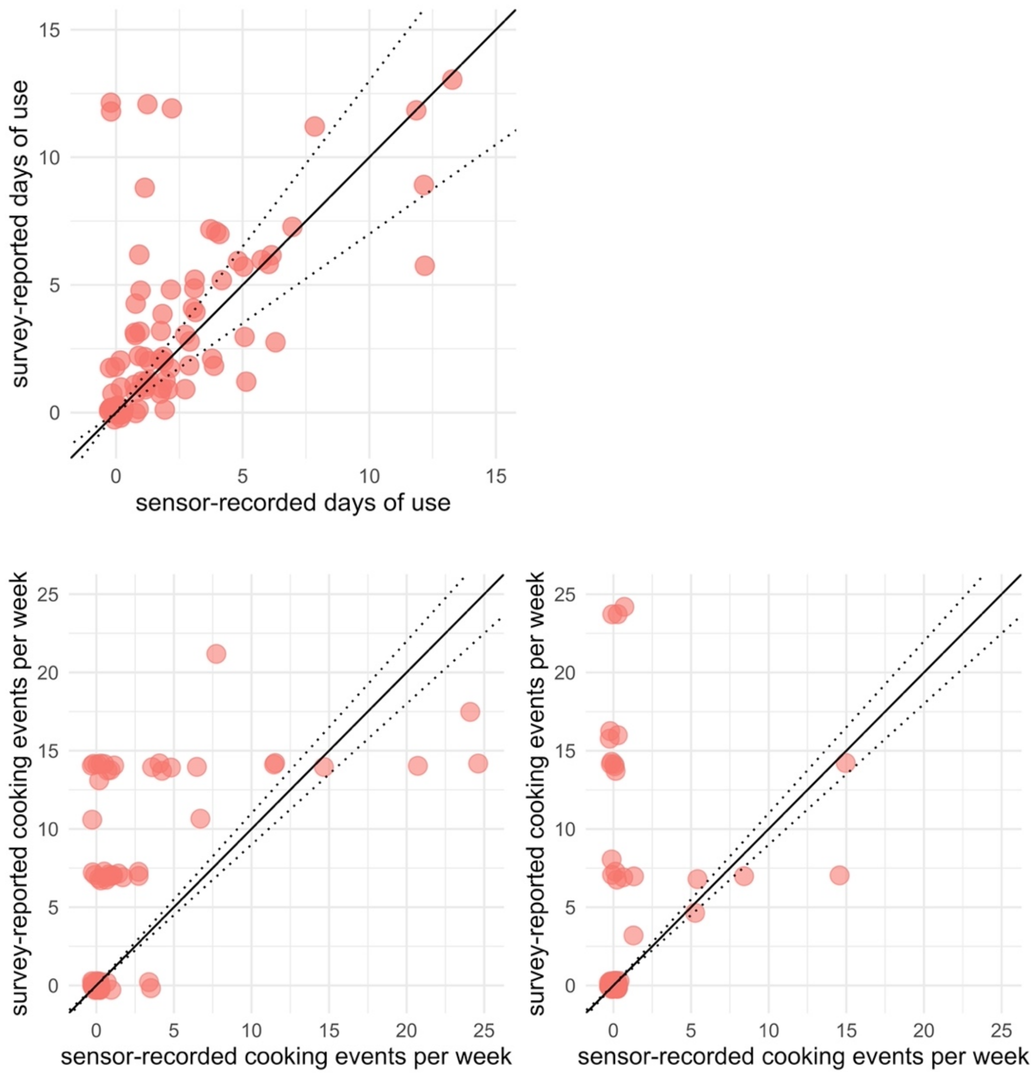

Figure 3: Survey-reported vs. sensor-recorded usage for households in each Follow-up for the long-term study and the trial. The solid 1:1 line represents where survey-reported usage equals sensor-recorded usage. The dotted lines are ±30% of the solid lines for Figure 3A and ±10% of the solid lines for Figures 3B & 3C. Each red point represents a household. **Figure 3A (Top Left):** Trial data (n=88). **Figure 3B (Bottom Left):** Follow-up 1 (n=75). **Figure 3C (Bottom Right):** Follow-up 2 (n=69). Note that points in all plots are "jittered" to avoid overplotting.

We ran a linear regression of survey-reported use versus sensor-recorded use for each plot in Figure 3. For the free-trial study in Figure 3A, there is a statistically significant positive slope of 0.72 (p <0.001), but with an R^2=0.35. For Follow-up 1 in the post-purchase study (Figure 3B), there is a statistically significant positive slope of 0.64 (p <0.001), but with an

R^2=0.29. For Follow-up 2 (Figure 3C), there is a statistically insignificant positive slope of 0.48 (p = 0.10), but with an R^2=0.043. The low R^2 values indicate a very poor correlation between survey- and sensor-recorded usage. This indicates that one could not use the linear regression relationship to translate survey-recorded data into sensor-recorded usage (actual usage).

We removed all the households that did not use the cookstove at least once (non-users) from the linear regression analyses to determine if correlations would improve. There was no improvement in R^2 values except a slight increase for the free-trial data, with a statistically significant positive slope of 0.67 (p <0.001), with an R^2=0.36. For Follow-up 1, there is a statistically significant positive slope of 0.37 (p =0.005), with an R^2=0.22. For Follow-up 2, there is a statistically insignificant positive coefficient of 0.13 (p = 0.75), with an R^2=0.01. Still, the low R^2 values indicate a very poor correlation between survey- and sensor-recorded usage, even with removing the non-users from the regression analyses.

3.2 Long-term decline in sensor-recorded usage

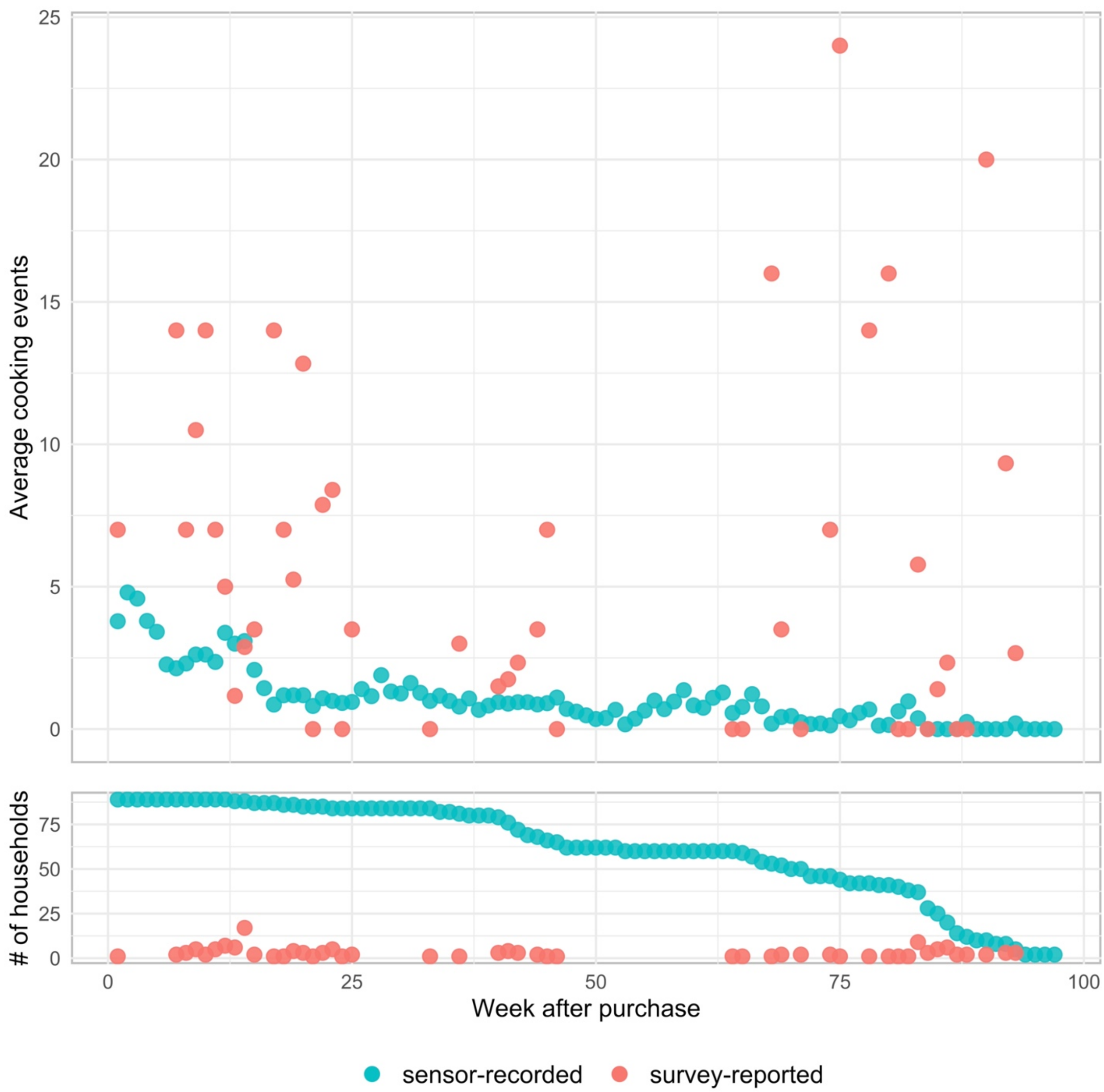

Figure 4. Upper panel: Average cooking events per week after purchase across all households in the post-purchase study for sensor-recorded usage (blue) and survey-reported usage (red). **Lower panel:** Number of households whose cookstoves were monitored on the week after purchase (blue) and number of households interviewed on that week after purchase (red).

We compared the longitudinal sensor-recorded use to the longitudinal survey-reported use for the post-purchase study. In summary, we found that weekly usage stabilized at approximately 20 weeks; however, a more detailed analysis of the longitudinal sensor-recorded use will be presented in an upcoming paper. The number of cooking events, averaged across all households per week after purchase, is shown in Figure 4 for both the sensor-recorded usage, shown in blue, and the survey-reported usage, shown in red. Because each household had a different start date, we averaged cooking events for households' respective week after purchase, instead of date. For the survey-reported usage, we averaged households' responses to the quantitative usage question, "What is the average number of times per week that you have used the BIS in the last month?" mentioned above (Section 3.1.2) and plotted their response on the week after purchase that they were interviewed. The lower panel of Figure 4 shows for each week after purchase, the number of households whose cookstoves were monitored, shown in blue, and the number of households interviewed and asked about their usage, shown in red. While we have the sensor-recorded usage for 97 weeks (at 5-min intervals), we only have survey-reported usage for 43 weeks of the study. There are two large gaps of at least 10 missing weeks of survey-reported data for weeks 26 through 35 and weeks 93 through 97.

Additionally, the number of monitored cookstoves also decreased throughout the study due to sensor loss during the COVID-19 pandemic. We were also unable to conduct as many surveys as we had previously planned due to the pandemic. The number of households whose cookstoves were monitored with sensors for a single week of the study started at 91 households at the beginning of the study to two households at the end of study, whereas the number of households with survey-reported use for a single week of the study ranged anywhere from one to 17 households at different weeks of the study. The average number of households that were monitored with sensors for a single of week of the study was 61 households (SD=26) and the average number of households with survey-reported usage for a single week of study was 2.8 households (SD=2.9).

The sensor data showed a lower overall weekly use compared to the survey data over the course of the study. The sensor data showed a 97-week average of 1.06 cooking events per week (SD=1.04) and a median of 0.86 cooking events per week. However, the survey data showed a 43-week (total weeks of available data) average of 5.8 cooking events per week (SD=5.9) and a median of 3.5 cooking events per week, which is 5.5 times the average weekly usage as the sensor data. Moreover, the survey data shows a higher average weekly use than the sensor data for about 70% of the total weeks when there is both sensor and survey data available.

From the sensor data, we found an overall decreasing trend in BIS usage over the course of the study. Less than 10% of the households were using the cookstove by the end of the study. We observed that sensor data transitioned from 4.0 cooking events per week (n=91) on week 1 to 0.15 cooking events per week (n=41) on week 80, on average. About 54% of the rate of change of the moving average (1-month window) of the sensor data is negative and about 6% is zero. Importantly, the survey data did not show the same overall decreasing trend in the BIS usage over the course of the study. Instead, survey data showed 7.0 cooking events per week (n=1) on week 1 compared to 14 cooking events per week (n=2) on week 92, on average. About 38% of the rate of change of the moving average (1-month window) of the survey data is negative and about 23% is zero.

3.3 Distribution of Responses

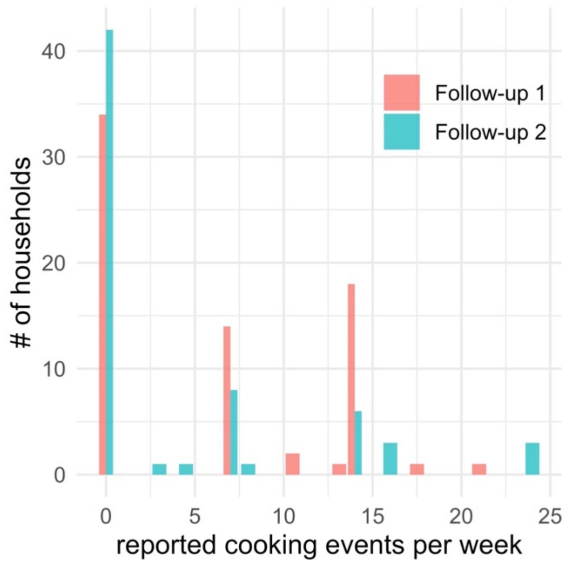

Figure 5. Distribution of household's responses to the question: "What is the average number of times per week that you have used the BIS in the last month?" in red for Follow-up 1 (n=75) and blue for Follow-up 2 (n=69).

We discovered that households were reporting nominal values of usage in the post-purchase study for the quantitative usage question (Section 3.1.2), potentially due to the difficulty of recalling how many times per week one uses the cookstove. For instance, it may be easier for households to estimate that one uses the cookstove 0, 1, or 2 times per day, which would translate to using it 0, 7, or 14 times per week, respectively, rather than recalling exactly how many times one used the cookstove. Figure 5 shows the distribution of the reported cooking events per week for both follow-up surveys in the post-purchase study. There are peaks at 0, 7, and 14 cooking events per week for both Follow-up 1 and Follow-up 2. For Follow-up 1 (n=75), 48% of households reported zero cooking events per week, 20% reported seven cooking events per week, and 25% reported 14 cooking events per week, with the remaining 7% reporting other values. For Follow-up 2 (n=69), 66% of households reported zero cooking events per week, 12%

reported seven cooking events per week, and 8% reported 14 cooking events per week, with the remaining 14% reporting other values.

3.4 Weekly Usage of Accurate and Inaccurate Reporters

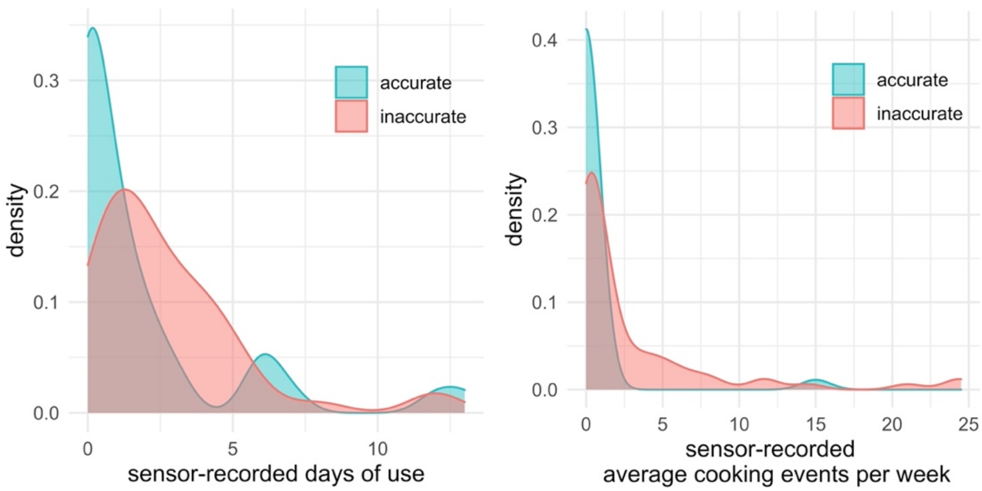

Figure 6. Density plots of households' sensor-recorded average cooking events per week, separated by accurate (defined as survey data agreeing within ±30% of sensor data for the free-trial study and within ±10% of sensor data for the post-purchase study – see Section 3.1.2) reporters (blue) and inaccurate reporters (pink). Density plots integrate to 1; smooth curves are generated to fit the data and guide the eye better. **Figure 6A** (Left): Free-trial data (n=88). **Figure 6B** (Right): Combined responses for Follow-up 1 & Follow-up 2 combined (n=144).

We compared the distributions of households' average weekly usage between the accurate and inaccurate reporters, for the free-trial study shown in Figure 6A and for the post-purchase study shown in Figure 6B (see SI for Figure 6B split into Follow-up 1 and Follow-up 2 plots). Accuracy is defined as survey data agreeing within ±30% of sensor data for the free-trial study and within ±10% of sensor data for the post-purchase study (see Section 3.1.2). The only place where we found extremely high agreement between survey and sensor data is among the answers given by non-users. When we compared the answers given by users with the measurements by sensors, the agreement is close to meaningless. For the free-trial study, about half of the accuracy is coming from non-users. There were 23% non-users and 77% users; among the non-users, 73% reported accurately and 27% inaccurately. Among the users, 32% reported accurately, and 68% inaccurately.

For the post-purchase study, the accurate reporting is mostly from the non-users. For Follow-up 1, there were 52% non-users and 48% users. Among the non-users, 77% reported accurately and 23% inaccurately. Among the users, 3% reported accurately and 97% inaccurately. For Follow-up 2, there were 82% non-users and 18% users. Among the non-users, 75% reported accurately and 25% inaccurately. Among the users, 8% reported accurately, and 92% inaccurately.

3.5 Household Response Consistency Between Surveys

We also analyzed the consistency of households' reporting between follow-up surveys in the post-purchase study. Fifty-one out of the total 91 households were interviewed in both Follow-up 1 and Follow-up 2. Of these 51 households, 63% were consistent with their reporting between surveys, meaning they either accurately reported (39%) on both surveys, over-reported (16%) on both surveys, or under-reported on both surveys (8%). However, all the households that accurately reported on both surveys were non-users. The other 37% of the 51 households were inconsistent with their reporting between surveys, meaning they either accurately reported, over-reported, or under-reported on the first survey and then did not respond the same on the second survey. The inconsistent-reporting households fell into four categories: accurate then over-report (8%), over-report then accurate (8%), over-report then under-report (17%), and under-report then over-report (4%).

3.6 Household Qualitative Responses

		Percent of total interviewed households that:			
Reported advantage	Follow-up survey #	Reported the advantage	Reported the advantage **and** reported using the stove via surveys	Reported the advantage **and** shows sensor-recorded usage	Reported the advantage, but were non-users
Fuel savings	1 (n=75)	55%	39%	32%	23%
	2 (n=69)	44%	22%	9%	35%
Quick cooking	1 (n=75)	29%	27%	21%	8%
	2 (n=69)	35%	17%	7%	28%
Less smoke	1 (n=75)	14%	11%	9%	5%
	2 (n=69)	41%	23%	9%	32%

Table 2. Percent of total households that reported an advantage (column 3) as well as their reported use (column 4) and sensor-recorded use (columns 5 and 6).

Follow-up surveys in the post-purchase study also included qualitative questions regarding advantages and disadvantages of the BIS. Households were asked what advantages and difficulties they experienced while using the BIS. Table 2 provides the number of households that reported fuelwood savings, quick cooking, and less smoke (compared to their traditional cookstoves) as advantages. For each reported advantage, we compared the number of households that reported using the stove to the number of households that used the cookstove according to the sensors. The percent of households that reported the advantage (column 3) is higher than the percent of households that reported the advantage and reported using the stove (column 4) for all rows, which shows that some households reported the advantage but also indicated that they did not use the stove. This result shows the inconsistency between households' responses. Column 5 shows the percent of households that reported the advantage and their sensors confirmed their usage; this column represents the data we might rely on for understanding advantages. We also found that as many as 35% of total interviewed households (column 6), reported an advantage, but were non-users, as confirmed by the sensors. A potential explanation is that these households were reporting what they heard from their neighbors by word of mouth, or perceived these benefits to be possible, but their lack of sensor-recorded usage shows that they did not experience the benefits themselves. Without the sensor data, we might have erroneously used the results shown in columns 3 and 4 to gather information that we considered reliable about reported advantages of the BIS. However, we know from the sensor data that some of the sources of this information includes households that did not use the stove.

4. Discussion

Similar to other studies (Thomas et al. 2013; Wilson et al. 2016), households over-reported improved cookstove usage. We found that over-reporting was common in both the free-trial study (average length: 10-day, SD=4.5) and the post-purchase study (average length: 468-day, SD=153 days), which might indicate that over-reporting is an issue regardless of the length of the study and common even when households purchase the cookstove.

We explored whether survey-reported usage was more accurate with different question formats, which has been explored in a few other studies (Ruiz-Mercado 2011; Thomas et al. 2013; Wilson et al. 2016; Piedrahita et al. 2016) with mixed results. Using the binary question format instead of quantitative question format, the accuracy of households' responses increased by 46%, 39%, 14% for the free-trial survey, post-purchase Follow-up 1, and post-purchase Follow-up 2, respectively. This may be indicative of the difficulty of recalling a quantitative value of cookstove usage. However, using the binary question format to measure cookstove usage over a long-term period presents challenges. The binary question format decreases the granularity of usage; thus, if increased granularity is necessary, then this survey method may require increased field visits.

When households were asked about their usage in a quantitative question format, we found that 34%, 46%, and 28% of households over-reported their usage for the free-trial survey, post-purchase Follow-up 1, and post-purchase Follow-up 2, respectively. We also found no correlation between survey- and sensor-recorded data for any survey ($R^2 < 0.40$), indicating that there is no linear relationship one could use to translate survey-recorded usage into sensor-recorded usage.

Most notably, we found that surveys were unable to accurately capture the average long-term decline in cookstove usage over the course of the post-purchase study. Survey data showed 5.5 times the average weekly usage as the sensor data. Moreover, for about 70% of the total weeks, the survey data showed higher weekly use than the sensor data, and of course, surveys did not provide the same granularity in data collection frequency nor the same number of monitored households as sensors did. Piedrahita et al. (2016) found that agreement between survey-reported and sensor-recorded usage decreased throughout the course of the study and that surveys provided poor granularity compared to sensors. Our results back up Piedrahita et al. (2016) findings in a new setting and markedly, for households that purchased their cookstoves for one-third their monthly income. We found that sensors showed that most households dis-adopted the cookstove—less than 10% of households were using the BIS by the end of the study, whereas surveys showed similar levels of average use at the beginning and the end of the study. Without sensors, and relying only on surveys, we may have falsely concluded sustained cookstoves adoption and thus would have highly over-estimated the long-term benefits of its use.

Additionally, on examining the distribution of households' reported usage values in the post-purchase study, we found peaks at nominal values, 0, 7, and 14 times per week (corresponding to 0, 1, and 2 times per day). This is indicative of recall bias as households may default to such values if they are not able to recall the exact weekly usage values. This shows that even if households are attempting to report their usage, their best guess is to report a nominal value of usage. Thus, getting accurate, quantitative values of usage is difficult via surveys, especially over a long-term period.

When we analyzed the consistency of households' responses between follow-up surveys in the post-purchase study, we found that 39% of households reported accurately on both surveys, 16% over-reported on both surveys, and 8% under-reported on both surveys. Understanding how individual households may tend to respond is useful for field staff to potentially conclude which households are reliable. Thus, they may weigh some interviewees' responses differently.

While surveys may not be accurate in collecting quantitative values, they may be invaluable for qualitative understanding and insights. Surveys were essential to our understanding of how to change the design of the BIS to fit the cultural cooking practices of the region, as well as to understand the potential of the cookstove to alleviate the burden of fuelwood collection on women. In the upcoming paper that provides the longitudinal analysis of the sensor data, we will also present survey responses for insight into reasons for dis-adoption. However, we found that households in the post-purchase study reported on cookstove advantages even when their sensor-recorded usage indicated no usage, which may be indicative of courtesy bias. Households may be reporting certain cookstove advantages that they've heard from their neighbors, regardless of their own usage. Without the sensors, we may rely on these qualitative responses when the households did not use the stoves and, therefore, we may mistakenly weigh certain advantages and disadvantages over others. This action may falsely influence our implementation strategies, our impact reports, and our design changes, which highlights the importance of using sensors to support qualitative survey responses.

In summary, we confirmed the findings of prior studies (Ruiz-Mercado 2011; Thomas et al. 2013; Piedrahita et al. 2016; Wilson et al. 2016, 2018; Ramanathan et al. 2017) that surveys alone are not sufficient to evaluate the adoption of a cookstove in field, even in a new context where households purchased the cookstove. Moreover, surveys alone are not sufficient for either qualitative or quantitative findings, nor can they capture the longitudinal trends of cookstove usage that sensors can capture. If we had relied on only surveys to report usage, we would have over-reported usage by 28-46%, missed the dis-adoption of the cookstove over time, and thus would have significantly overclaimed the carbon credits having used voluntary market methodologies. We also would have overclaimed the benefits to women's quality of life. Thus, sensors should become the required standard to measure cookstoves usage whenever affordable.

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