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Measuring and Increasing Adoption Rates of Cookstoves in a Humanitarian Crisis

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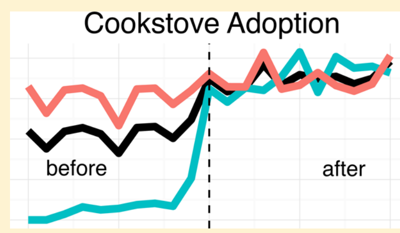
Supporting Information

ABSTRACT: Traditional smoky cooking fires are one of today's greatest environmental threats to human life. These fires, used by 40% of the global population, cause 3.9 million annual premature deaths. "Clean cookstoves" have potential to improve this situation; however, most cookstove programs do not employ objective measurement of adoption to inform design, marketing, subsidies, finance, or dissemination practices. Lack of data prevents insights and may contribute to consistently low adoption rates. In this study, we used sensors and surveys to measure objective versus self-reported adoption of freely-distributed cookstoves in an internally displaced persons camp in Darfur, Sudan. Our data insights demonstrate how to effectively measure and promote adoption, especially in a humanitarian crisis. With sensors, we measured that 71% of participants were cookstove "users" compared to 95% of respondents reporting the improved cookstove was their "primary cookstove." No line of survey questioning, whether direct or indirect, predicted sensor-measured usage. For participants who rarely or never used their cookstoves after initial dissemination ("non-users"), we found significant increases in adoption after a simple followup survey ($p = 0.001$). The followup converted 83% of prior "non-users" to "users" with average daily adoption of 1.7 cooking hours over 2.2 meals. This increased adoption, which we posit resulted from cookstove familiarization and social conformity, was sustained for a 2-week observation period post intervention.



INTRODUCTION

Since the beginning of the modern Darfur conflict in 2003, violence has forced Darfuri families from their homes. Many displaced families have emigrated from their homelands to large Internally Displaced Persons (IDP) camps; current UN figures estimate 2.5 million IDPs in Darfur.[1] In 2005, The University of California, Berkeley and Lawrence Berkeley National Laboratory began a joint effort to design a fuel efficient cookstove for use in Darfuri IDP camps. The impetus for the Berkeley-Darfur Stove (BDS) was to reduce the burden and danger IDP women face when acquiring fuel in and around the camps. The BDS's improved thermal efficiency allows customers to cook food using less fuel than a traditional three-stone fire (TSF) which is locally known as a "ladaya."[2] As of June 2016, 42,000 BDSs have been distributed to households in Darfur. In this and other studies, the average household size measured was appoximately 7.[3] With the 44,284 BDS units disseminated as of Potential Energy's 2015 Impact Report,[4] the BDS is estimated to have reached 310 000 individuals.

Objective monitoring and evaluation is a major barrier to quantifying the impacts of "clean cookstoves" like the BDS. For decades, clean cookstoves have promised to reduce the global burden of disease and drudgery attributable to traditional cooking. Air pollution from traditional cooking methods is the world's largest environmental health risk factor—traditional biomass-fueled cooking is linked with 3.9 million annual premature deaths.[5,6] Clean cookstoves' promise is to displace traditional smoky biomass fires (used by almost half the world's population) with cleaner combustion.[7] However, positive outcomes of clean cookstove interventions are rarely significant or sustained.[8] This is because clean cookstoves have not been widely adopted and they have not sufficiently displaced traditional cookstoves (e.g., "stove stacking").[9]

Stove Use Monitor (SUM) sensors have the potential to objectively inform implementation agencies, policy makers, and analysts about field performance and adoption of cookstoves.[9−14] Many stakeholder agencies are eager to understand which cookstoves, training programs, and marketing methods are effective. However, most cookstove adoption studies use unreliable survey data subject to three problematic sources of error: social desirability or courtesy bias where respondents over-report "ideal" behaviors, recall bias when respondents cannot accurately recall past behavior, and observation bias (the

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"Hawthorne Effect").[9,15−19] By contrast, SUMs provide accurate information about adoption and may eventually improve cooks' health and economic outcomes by creating tighter and more accurate feedback loop between stakeholders in the dissemination space and the customers who use clean cookstoves. If used effectively, SUMs data can inform dissemination stakeholders about which cookstoves are well-adopted, and this information could lead to better cookstoves reaching more customers.

Even when self-reported data is unbiased on average, measurement error in dependent variables (say, expenditures or frequency of symptoms) reduces the precision of estimates, giving reduced statistical power. Unbiased measurement error in independent variables (for example, usage rates) leads to "attenuation bias" that pushes impact estimates toward zero.[20] This effect only worsens when users systematically overstate adoption. Unlike surveys, sensors are unbiased, discrete, and long-lasting. Objective sensor data lead to improvements in our understanding of cookstove adoption and enables insights about cookstove designs, training, or marketing techniques that may increase utilization.

In this study, we add critical information to the small pool of studies objectively measuring cookstove adoption with sensors.[9,12−14,21,22] To our knowledge, other groups have not analyzed adoption of cookstove technologies in an ongoing humanitarian crisis. Evaluation of technologies and techniques that improve living conditions and environmental conditions in humanitarian crises is important but inadequately addressed in the scientific literature. Crises are important case studies because they are regrettably common, are a frequent target market for cookstove dissemination programs, and represent unique social and economic contexts that make non-crises insights potentially nontransferable. In prior studies, sensor data has been compared with survey data.[10,13] In Thomas et al. 2013, sensors measured 40% lower use than surveys, but in Ruiz-Mercado et al. 2013, surveys were found to generally be reliable predictors of sensor-measured behavior. This contradiction points to the need for additional data about what circumstances result in reliable survey data. We extend the literature by testing whether multiple surveying techniques can be combined to better predict sensor-measured behavior. Additionally, we present a novel framework for categorizing stove recipients as "users" or "non-users" and demonstrate the value of this delineation in revealing data insights. Unlike prior work, this study rigorously evaluates causes of sensor damage and loss, and we perform sensitivity analysis for lost data. We also present the first study to our knowledge quantifying the impacts of social pressure on cookstove adoption ("courtesy use"), and we show an example of how sensors revealed user-generated innovations. Lastly, and most importantly, this study adds meaningful data to the literature by assessing the impact of enumeration activities—or the anticipation thereof—on cookstove adoption behavior, and we reveal the potential for low-cost strategies to dramatically increase cookstove adoption.

DESIGN AND METHODS

A detailed description of the design and methods of this experiment is discussed in prior work[14] and in the Supporting Information (SI). For clarity, a brief overview follows.

This work took place in the Al-Salam IDP Camp outside Al-Fashir, North Darfur, Sudan. Sustainable Action Group (SAG), a Sudanese nonprofit that assembles and distributes the BDS in IDP camps, selected participants for this study in the usual procedure for BDS dissemination: 180 participants were selected to receive free BDSs by chief camp administrators ("Omdas") who selected study participants from a comprehensive list of inhabitants. Selected participants were limited to five of the camp's "Administrative Units" representing the geographical and cultural emigration origin of IDPs. In compliance with the University of California, Berkeley's Institutional Review Board approval (CPHS #2013-03-5132), participants were told they would be taking part in a study of the BDS "to improve future BDSs" and that a temperature sensor would be attached to the BDS. However, information about the tracking of cooking behaviors was withheld. All five Units participated in a baseline and followup survey, and three units participated in an additional second followup.

The five Units, each with 36 participants, received their BDSs and took a baseline survey between July 29th and August second of 2013. Serious security concerns precluded enumeration staff from travel and extended stay in the camps, so the baseline survey and all subsequent interactions took place at midday in a women's center in Al-Salam Camp. A phased rollout of the followup survey was conducted four to 12 weeks, depending on Unit, after the baseline. All women were supplied with the date, time, and location of their followup. Women were instructed to bring their cookstoves to the Women's Center for the followup survey. On the appointed day, a survey was conducted and SUMs were removed from cookstoves. Data were discretely downloaded from SUMs using a laptop computer. For three of the five Units, SUMs were reattached and a second followup was conducted 2 weeks after the first followup. The second followup also required bringing the cookstove to the Women's Center so SUMs could be removed, but no additional surveys were conducted. In all cases, women brought their BDSs home from the followup survey(s) and owned the stoves indefinitely thereafter. Additional details about scheduling can be found in the SI.

Building on the methods of others,[9,12,13,21−23] we utilized Maxim's DS1922E-series iButtons as temperature data loggers. SI Figure S1 shows the mounting location of SUMs which was chosen by laboratory cooking experiments to maximize signal (temperature) while still preventing overheating of the sensor.

Surveys in this study were conducted by a team of two redundant enumerators. One enumerator administered the survey using paper and pen while the other used Open Data Kit (ODK) (a smartphone-based survey tool). Data from these two methods were tested against one another for quality control purposes. Data from SUMs and surveys were processed in Version 3 of the open-source statistical computing software R. A further discussion of the algorithm used to label cooking events can be found in Wilson et al., 2015.

RESULTS

SUMs Loss and Bias. The SUMs in this experiment were vulnerable to failure, which may produce SUMs data bias. During the study we discovered that some women innovated by flipping the BDS upside down, filling the bottom with charcoal, and preparing drinks or small meals. The BDS was not designed for this mode of use. The SUM was mounted at the bottom of the BDS to avoid overheating from wood fires (see SI Figure S1), but the bottom of the BDS is precisely where charcoal fires would make the BDS hottest. Of 170 participants with SUMs-equipped cookstoves, 29 participants had thermally damaged SUMs. In followup surveys, participants who reported using charcoal as a primary cooking fuel (for food or drink)

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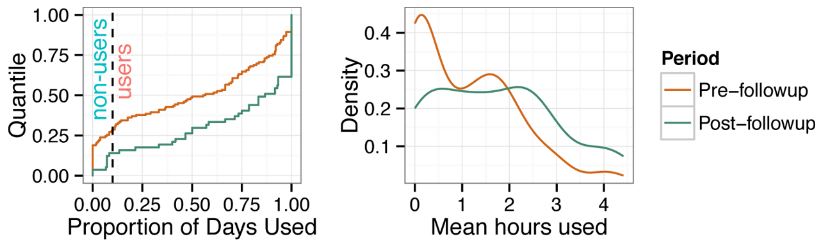

Figure 1. Left: a cumulative distribution function of the proportion of days used as measured by SUMs. Dashed vertical line indicates the 10% of use days delination between "non-users" (left of dashed line) and "users". Right: the probability densities of hours of daily cooking pre and post followup.

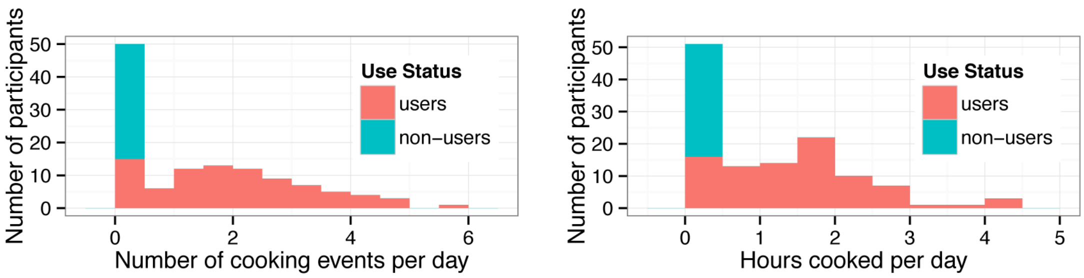

Figure 2. Histograms demonstrate cooking events and hours per day in the pre-followup period. Stacked histograms are coded into user and non-user subgroups.

Table 1. A Summary of SUMs Results[a]

results by unit	Korma	Al-Fashir	Zaghawa	Jebel Si	Tawila	total
pre 1st followup						
users	17	24	16	16	14	87
non-users	9	3	5	10	8	35
hours cooked per day	1.00 (0.99)	1.64 (1.01)	0.98 (0.91)	0.72 (0.84)	1.14 (1.38)	1.10 (1.07)
users	1.52 (0.85)	1.84 (0.87)	1.27 (0.84)	1.15 (0.82)	1.79 (1.37)	1.54 (0.97)
non-users	0.03 (0.07)	0.00 (0.00)	0.03 (0.06)	0.04 (0.09)	0.02 (0.02)	0.03 (0.06)
cooking events per day	1.58 (1.56)	2.10 (1.41)	1.36 (1.32)	0.90 (1.06)	1.33 (1.55)	1.47 (1.43)
users	2.39 (1.33)	2.36 (1.26)	1.77 (1.25)	1.44 (1.04)	2.08 (1.49)	2.04 (1.30)
non-users	0.05 (0.09)	0.00 (0.00)	0.04 (0.07)	0.04 (0.10)	0.03 (0.03)	0.04 (0.07)
post 1st followup						
users			16	14	11	41
non-users			5	8	6	19
hours cooked per day			2.01 (1.10)	1.50 (1.08)	1.67 (1.62)	1.73 (1.26)
users			1.91 (1.15)	1.51 (1.28)	1.77 (1.44)	1.74 (1.26)
non-users			2.32 (0.94)	1.48 (0.69)	1.50 (2.05)	1.70 (1.30)
cooking events per day			2.65 (1.57)	1.97 (1.32)	1.62 (1.83)	2.11 (1.60)
users			2.51 (1.68)	1.84 (1.45)	1.70 (1.74)	2.06 (1.62)
non-users			3.11 (1.15)	2.21 (1.12)	1.47 (2.15)	2.21 (1.57)

[a]Note that "user" and "non-user" are defined in the context of the pre-followup period. Data format is mean (standard deviation).

were 2.8 times more likely (p = 0.01, Fisher test) to thermally damage their SUMs as participants who did not report using charcoal as a primary fuel. A summary of SUMs failures by Administrative Unit is presented in SI Table S2.

Because data were unrecoverable from thermally damaged SUMs, this study has possible bias. We posit that adopters of the BDS are more likely to damage SUMs and therefore adopters are underrepresented in surviving SUMs data. Put another way, it would be difficult to thermally damage a SUM mounted on a BDS that was never used for cooking. Therefore, data loss from thermal damage represents a nonrandom sampling bias in SUMs data and a probable downward bias on sensor-measured adoption rates. Accordingly, SUMs-derived data presented in this study are a conservative estimate of adoption throughout the entire experimental population. Other less prevalent causes of SUMs loss were observed, namely misplaced and faulty sensors (before distribution and baseline survey), one stolen stove, and a small number of women not returning for followup surveys. These data are summarized in detail in SI Table S2. However, we assume nonthermal damage loss factors do not meaningfully bias data. Unless otherwise noted, quantitative SUMs data presented throughout this study are derived from surviving SUMs.

Defining "User" and "Non-User" Groups. To perform more meaningful analyses, we classified participants into two groups based on their pre-followup BDS adoption: "users" and "non-users." First, using SUMs data for each participant, we computed the proportion of cookstove ownership days where at least one cooking event was observed. The "pre-followup period" analyzed was defined from 1 day after the participant's baseline survey until 2 days before the participant's follow up survey (to avoid effects near the followup discussed later). This

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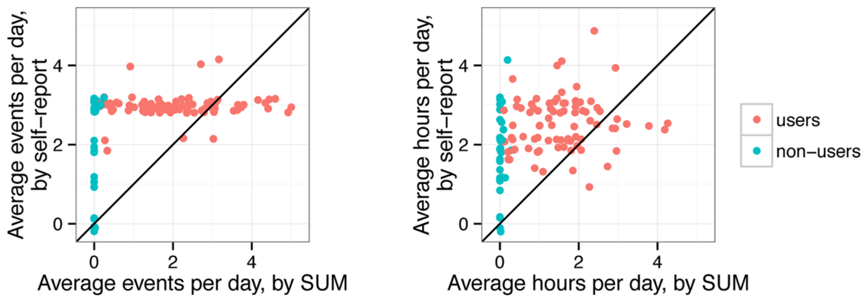

Figure 3. Daily events (left) and hours of BDS use (right) are shown as scatter plots of SUMs-measured versus self-reported data. The scatter plots include the 1:1 line that data would fall on if users' self-reports perfectly agreed with the SUMs algorithm. To avoid overplotting, plot points are "jittered.".

variable, termed "proportion of days used" is plotted as a cumulative distribution function in Figure 1. An arbitrary delineation was drawn at 10% of days used, and participants utilizing the BDS more than 10% BDS ownership days in this period were classified as "users." Although the quantitative delineation between users and non-users was arbitrary, it is useful to characterize study participants in terms of women who generally tried out the BDS before their follow up survey (users) and those who very rarely or never used the BDS before the follow up survey (non-users). It is important to note that we do not intend to conflate the term "user" to mean "successful adopter." We would not be satisfied, and we suspect that neither would most customers, if a cookstove was only useful 3 days out of a month. In that way, 10% is not a meaningful cutoff for a program's success in any health, environmental, or economic benefit sense. However, as will be shown, the "user" and "non-user" delineation is useful in comparing when and how cookstoves are adopted. Unless otherwise specified, "user" and "non-user" classification refers to pre-followup behavior.

Pre-Followup Adoption Measured by SUMs and Surveys. In the pre-followup period, 87 of 122 (71%) participants with surviving SUMs were classified as users of the BDS. Remembering that SUMs thermal damage presents a downward bias on this study, if all thermally damaged SUMs were presumed to belong to "users," the study-wide adoption rate would be 77% users.

The proportion of users varied widely and significantly by Administrative Unit (p = 0.004; Fisher's exact test) with Al-Fashir Rural having the highest rate of users at 89% and Jebel Si having the lowest at 62%. Study-wide, a typical user utilized her BDS 1.54 (SD = 0.97) hours per day over 2.04 (SD = 1.30) cooking events; these data are displayed as histograms in Figure 2. Including non-users, the study-wide average adoption rates were 1.10 (SD = 1.07) hours and 1.47 (SD = 1.43) events of daily cooking. A summary of SUMs-measured adoption is shown in Table 1. Although ownership periods were relatively short compared with other longitudinal studies,[9,12] users showed no significant linear trend in average hours cooked per day over the pre-followup ownership period (estimated increase of 0.0002 h/day; p = 0.84).

Participants reported high rates of BDS adoption regardless of their SUMs-measured usage: 95% of participants reported using the BDS as their "primary stove." As shown in Figure 3, nearly all users reported using the BDS three times a day on a "normal day." This is compared to a SUMs-measured daily cooking events of 2.04 events for users and 0.04 (median of 0) daily events for non-users. 77% of users and 86% of non-users over-reported cooking events. Of the 62 participants who used the BDS an average of less than once per day, only five actually reported doing so. Both users and non-users over-reported cooking hours with 85% of users and 86% of non-users over-reporting. All told, over-reporting represents 1.2 h and 1.3 events of daily cooking overestimation.

Because of the disagreement between SUMs and surveys, we explored whether calculation errors or ambiguity in the wording of the question "On a 'normal day,' how many times/hours do you use your BDS?" could explain the observed differences. Because of the question's design, answering in a way that would perfectly correlate with SUMs would require respondents to time-average usage and then report their average daily use, recalling over long periods and aggregating many data points, a task that has been shown in the Development Economics literature to be error prone.[20,24] Aside from recall and averaging errors, we posited that women may over-report if they interpret the question to only consider usage days rather than all ownership days. If this different interpretation was used, surveys would overstate usage relative to the sensors. To test these possibilities, we checked whether SUMs data correlated with another way we asked about usage: for an exhaustive list of meal types, we asked how many times in a normal week a meal was prepared with the BDS and how long each meal took to cook on the BDS. The sum of weekly occurrences is termed "Computed Events" and the sum of the product of meal durations and weekly occurrences is termed "Computed Hours." These data are shown in a correlation table with SUMs data in Table 2. Although these variables do not rely as heavily on cooks' recall, calculations, or question interpretation as the "normal day" questions, they correlate even more weakly with SUMs data.

Impacts of Enumeration Activities on Adoption. Figure 4 illustrates the effect of enumeration activities on adoption for the three Units tracked after the first followup. Beginning roughly 2 days before the scheduled followup, non-users begin to adopt their BDSs. After followup, enumeration activities had a statistically significant positive impact on the non-user group, increasing hours of daily cooking by 1.6 h (p < 0.001, paired t test) and no meaningful impact on the user group, increasing hours of daily cooking by only 10 min. Compared with the pre-followup period, non-users also increased adoption of the BDS in terms of events, with an average increase of 2.1 events per day. As a reminder, "users" and "non-users" are classified solely by their BDS adoption *before* the followup survey. A summary of results both pre- and post-followup is shown in Table 1.

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Environ. Sci. Technol. 2016, 50, 8393−8399

Table 2. Correlation Coefficients Tabulated for SUMs and Survey-Based Measures of Adoption

	SUMs (Events)	SUMs (Hours)	Survey ("Normal" Events)	Survey ("Normal" Hours)	Survey (Computed Events)	Survey (Computed Hours)
Survey (Computed Hours)	0.10	0.10	0.51	0.45	0.82	1.00
Survey (Computed Events)	0.13	0.16	0.61	0.48	1.00	
Survey ("Normal" Hours)	0.35	0.36	0.67	1.00		
Survey ("Normal" Events)	0.33	0.33	1.00			
SUMs (Hours)	0.95	1.00				
SUMs (Events)	1.00					

cor: 1.00, 0.75, 0.50, 0.25

DISCUSSION

Although the BDSs were distributed free of charge, it was relatively well-adopted among recipients, with 71% of surviving SUMs classifying cooks as "users." The (downward) bias caused by thermally damaged SUMs resulting from inverted BDS charcoal fires means that up to 77% of participants were potential "users" in the pre-followup period. Among "non-users," pre-followup behavior is characterized by little or no BDS utilization whatsoever. There is little evidence that non-users try and then abandon the BDS. Rather, non-users seem to neglect using the BDS altogether until just days before the followup survey. It should be noted that all modes of clean cookstove adoption cannot automatically be considered exposure-reducing and beneficial to health; improper cookstove operation, movement of a cleaner cookstove to a less-ventilated environment, or increased overall fuel consumption via stove stacking could all contribute to increased exposure relative to baseline.

Other studies have found that socioeconomic and educational factors are the most important predictors of cookstove adoption,[25] and this trend likely holds in our study as well. Namely, Al-Fashir Rural Unit, which exhibited the highest rates of adoption, is comprised of inhabitants who have emigrated to Al-Salam IDP Camp from periurban settlements near North Darfur's capital. Although socioeconomic and educational factors were not measured explicitly in surveys, Al-Fashir Rural residents were likely to have been exposed to better educational and work opportunities than residents from other Units representing poorer rural parts of Darfur.

As found in other studies of health-related technologies,[10,11,26,27] study participants tended to over-report cookstove adoption. In this study, average self-reported used was roughly twice SUMs data in terms of hours and events of cooking per day. However, because there is little correlation between SUMs and survey data, it is somewhat misleading to think of reporting as a 2-fold overestimation. For example, almost all women surveyed (83%) report using the BDS three times per day—every meal. In other words, it is incorrect to think that women inflate their adoption by 2-fold; instead, nearly uniformly, women report using the BDS for all daily meals, but across the sample, women actually use their BDSs for about half of all meals. Though we attempted to adjust for users' inability to average over large time periods by calculating adoption from other questions, no manner of questioning or reinterpretation of reporting periods correlated well with SUMs-measured behavior, leading us to believe that many participants intentionally misrepresent cookstove adoption when surveyed.

We were surprised by the strong influence of survey enumeration activities on the "non-user" group. As easily seen in Figure 4, non-users exhibit a strong up-tick in adoption starting 2 days before their scheduled followup survey. This effect is seen in all Units that were observed until a second followup, and this effect spanned a range of socio-economic levels and cultural or geographic origin (as indicated by Administrative Unit) and pre-followup ownership duration.

We posit that non-users may feel social pressure to use their BDS before the followup survey; perhaps it would be embarrassing to bring a shiny, clean, unused, donated stove

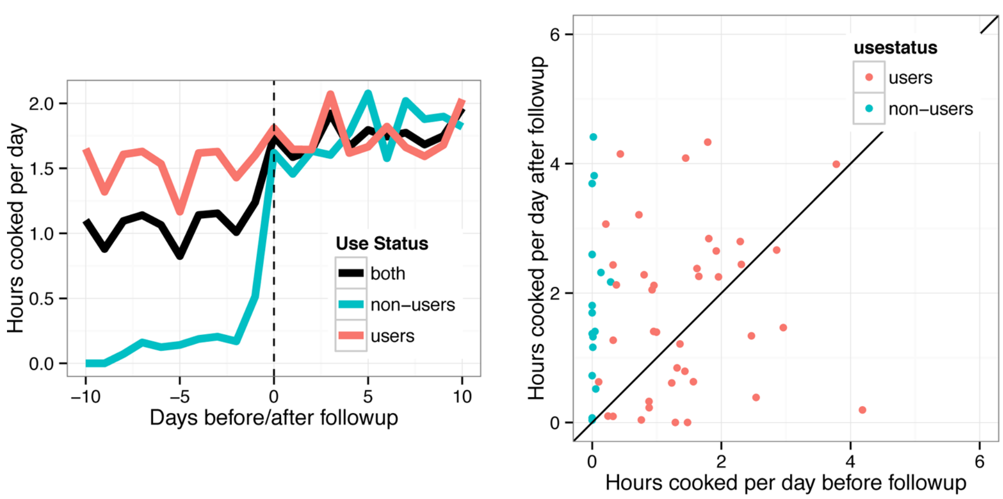

Figure 4. Left: average hours of daily cooking per day in the 10 days preceding and tailing the followup. Right: post followup versus pre followup SUMs data of hours of cooking per day. Points falling along the 1:1 line represent participants whose behavior was unchanged by the followup. Participants above the 1:1 line use their stove more after the followup, and participants below the 1:1 line use their stove less after the followup.

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back to the women's center. Or, perhaps, non-users felt the need to educate themselves about the BDS before returning for the followup survey. Regardless of motivation, in the days leading up to the followup survey, the non-user group strongly exhibits what we refer to as "courtesy use." This spike in usage in reaction to or anticipation of direct observation (sometimes called "reactivity" by other researchers) is consistent with other studies in the developing and developed world.[11,28−31]

However, what was not expected was the non-user group's sustained adoption in the 2 weeks after followup survey enumeration. Because enumeration activities were not instructive or coercive, one would expect women who did not adopt the BDS would continue to neglect it after the follow up survey. Quite to the contrary, upon returning home, non-users' cookstove utilization became indistinguishable (mean 1.77 h, standard error 0.31) from their "user" peers (mean 1.74 h, standard error 0.22). In fact, using the same definition of "user" as the pre-followup period (BDS use on ≥10% of ownership days), 83% of previous non-users transitioned to "post-followup users." Additionally, population wide, 86% of participants would be classified as users in the post-followup period compared with 71% in the pre-followup period.

We propose three hypotheses that may explain the phenomenon of non-user conversion. First, non-users rarely or never used their BDSs until just before the followup, so this group may never have realized the benefits of the BDS. Perhaps, after finally trialling the BDS as a courtesy immediately before the followup, non-users realized they enjoyed the BDS and subsequently continued use after the followup. Second, it is possible that peer pressure at the followup survey influenced non-users; one can imagine non-users walking and talking with their user peers to the Women's Center. At the Women's Center, although surveys were private, women may have seen peers with well-used cookstoves. Non-users may have over-heard others others talking, truthfully or not, about enjoying the BDS and thus felt more comfortable trying the BDS. Finally, SUMs vs surveys suggest that many non-users told mistruths during the followup survey about how often they use the BDS. This deceit, although untrue, could have built non-users' self-efficacy as a BDS adopter and helped non-users visualize themselves as BDS adopters, inducing adoption after returning home.[32] Alternatively, deceit may generate unpleasant cognitive dissonance, which participants may resolve through adoption consistent with their self-reports.[33,34] These theories were not tested in this study, but suggest potential contributors to post-followup adoption.

In this study, we presented cookstove adoption and reporting behaviors for recipients of the BDS, joining a small set of studies that have been able to combine traditional self-reported data with objective sensor-based measurements. Our analysis is unusual in part because of its context: despite the distribution of tens of thousands of BDS cookstoves in IDP camps to date, the challenging operating environment that makes aid needed also leads to data scarcity and other monitoring challenges.

The relevance of our results is not limited to the IDP context. Free distribution of improved cookstoves is commonplace, and may be accompanied by a desire among recipients to report behaviors preferred by distributors. However, the impacts of free distributions on survey bias have yet to be rigorously studied. Indeed, this study contributes evidence of the discrepancies between self-reported and sensor-detected usage, and affirms the need for sensor-based inquiry when impact must be accurately measured. More exploration is need of factors that could predict or facilitate higher accuracy of self-report data even when compliance with a normative behavior is low.

Additionally, we were able to use sensors to show an example of how monitoring activities can themselves alter the behaviors being monitored: usage spiked just before a followup visit, and for many previously non-users, the uptick was sustained for the following 2 weeks. This discovery may have useful implications for optimal followup after distribution and provide insight about strategies for inexpensive "light-touch" interventions to increase cookstove adoption.

Our findings do not suggest that sensors can or should replace self-reported data more generally. Sensors can be costly to implement and can only cover a small fraction of the types of data that may be relevant for analysis. Still, it is important to consider which types of data are most likely to be reliable and whether objective data sources may complement survey data in a given context. In this IDP context, it is apparent that surveys are extremely unreliable means of measuring technology adoption.

In summary, these data highlight the weaknesses of self-reported adoption data, the importance of objective sensor-based validation of adoption and impacts, and reengaging technology recipients, especially those with low uptake. This work has shown that effective monitoring and evaluation can have dramatic positive impacts on adoption, potentially leading to better health and economic outcomes for customers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b02899.

> A full acknowledgment of participants in this study as well as an expanded Background section that discuses the Berkeley-Darfur Stove's context and supporting figures and tables referenced in the main text. These supporting figures and tables are intended to give the reader additional insight into study timeline and design (including phased rollout), stove use monitor (SUM) failures, and the internally displaced persons context (PDF)

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Notes

The authors declare no competing financial interest.

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