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Effects of USB port access on advanced cookstove adoption

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ABSTRACT

Three billion people cook using traditional fires, and exposure to smoke from cooking remains a persistent and significant environmental health risk factor: household air pollution is estimated to cause 3–4 million premature deaths per year. "Improved cookstoves" could reduce the health risks associated with cooking, but the performance of most improved cookstoves is insufficient to result in meaningful health benefits, and global adoption of low-emission cookstoves remains low. However, a new class of advanced cookstoves equipped with thermoelectric generators could improve both emissions performance and adoption leading to better health outcomes. These cookstoves use electrical power provided by a thermoelectric generator to power combustion-improving fans while powering outboard USB charging ports. In communities lacking electricity access, USB levels of power could provide much-needed off-grid charging for mobile phones, small lights, and other loads. However, there is a risk that instead of being used primarily as a cooking tool, these cookstoves could be used solely as fire-powered USB chargers. Without displacing traditional cookstoves, "charging-only" adoption would result in a net increase in emissions exposure. In this study, we used custom Advanced Stove Use Monitor (ASUM) sensors to measure adoption of TEG-equipped cookstoves in 72 rural homes without electricity access in Odisha, India. To measure the impacts of the USB charging port, we randomized whether recipients received a cookstove with USB ports enabled or disabled. We found that access to USB charging ports significant increased adoption of cookstoves in "cooking" use modes; USB-enabled cookstoves were used for cooking 3.5X more than identical cookstoves with disabled USB ports. This substantial increase in cooking came with a relatively small marginal use of the cookstove in a "charging-only" mode; just 11% of total cookstove use was in this mode. As with past work, data showed that surveys of user behavior do not correlate well with sensor-measured behavior. The trial cookstove was much smaller and more cumbersome than traditional cookstoves, but still, we found that users were willing to prepare fuel and found the cookstove useful for light cooking tasks. Access to USB charging served as a catalyst for adoption of advanced cookstoves as cooking tools and did not increase undesirable "charging only" adoption modes. This work suggests that these kinds of USB-enabled cookstoves could be an important tool to improve biomass combustion, increase adoption, and realize meaningful health benefits.

1. Introduction

Two fifths of the global population cooks on smoky traditional fires fueled by wood, dung, charcoal, crop residues, and other forms of biomass (The World Bank, 2011), and although the proportion of the planet using the fuels has decreased since 1980, population growth has maintained the total number of users relatively constant at 2.8 billion (Bonjour et al., 2013). Globally, exposure to biomass cooking smoke is one of today's greatest environmental health risk factors; it's estimated that cooking smoke causes some 3–4 million premature deaths annually (Forouzanfar et al., 2015; Lim et al., 2013; Smith et al., 2014). Additionally, biomass cooking contributes meaningfully to the total anthropogenic burden of atmospheric aerosols, especially black carbon (Bonjour et al., 2013; Bond et al., 2004). To combat this crisis of cooking, "clean cookstoves," which emit less harmful emissions per meal, have been suggested as a tool to reduce the dangers of cooking.

Presently, a new class of clean cookstoves are entering the market. These new cookstoves rely on forced air provided by electric fans. When

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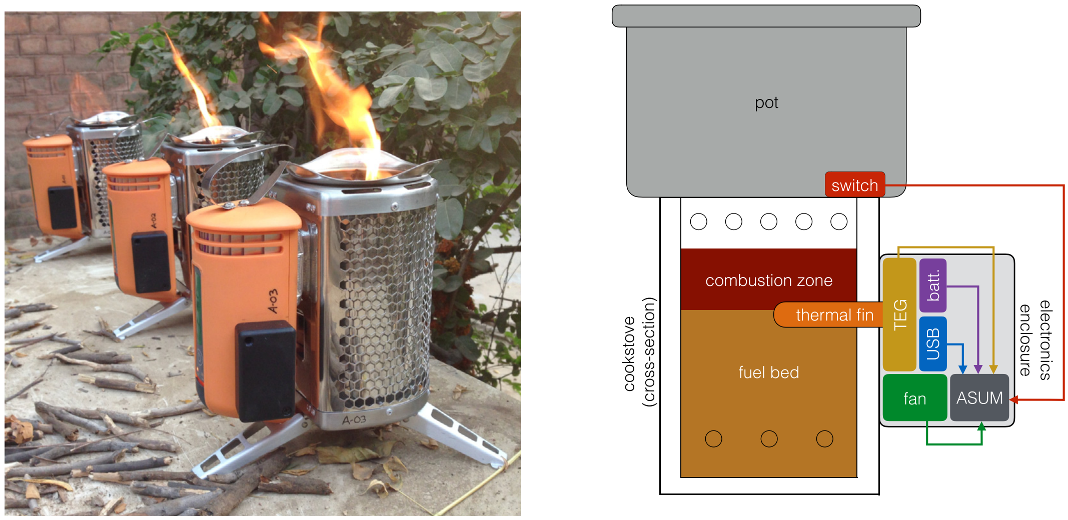

Fig. 1. Left: three Shakti Chulhis undergo quality control testing before distribution. Right: a schematic of the Shakti Chulhi and ASUM. The ASUM is integrated within Shakti Chulhi's electronics enclosure. The ASUM collects voltage information from the cookstove's TEG, fan, USB port, battery, and a pot proximity switch.

designed well, forced air cookstoves can improve combustion of biomass and greatly reduce harmful emissions (Jetter et al., 2012; Just et al., 2013; MacCarty et al., 2010; Rapp et al., 2016). Some forced air cookstoves use traditional wall plugs to power their fans, but an increasingly large number utilize thermoelectric generators (TEG) to generate electrical power (Horman et al., 2013; Champier et al., 2010; Gao et al., 2016; O'Hanley, 2009; Mal et al., 2014, 2015). Thermoelectric generators operate on the Seebeck Effect: a thermal gradient applied across a junction of dissimilar conductors will create a voltage difference, and this voltage difference can be employed to perform useful work (Priya and Inman, 2009). While the primary purpose of TEGs on cookstoves is to improve combustion (typically by powering a fan), most TEG cookstoves can generate surplus electrical power beyond what is necessary to improve combustion. Increasingly, manufacturers have installed outboard Universal Serial Bus (USB) ports. These stoves with USB ports are marketed to customers without access to grid power so that customers can charge small electronics such as mobile phones or lights.

Off-grid charging is a disruptive technology and an important benefit for many customers. In India, 700 million people (54%) rely primarily on open biomass-fired “chulhas” for their daily cooking (Smith and Sagar, 2014). However, at the same time, mobile phone ownership and penetration of low-energy appliances such as LED lights and radios is booming (Rai, 2016; Chaurey and Kandpal, 2009; Lam et al., 2012). In fact, mobile phones have become so ubiquitous that our research team could not find a household in this study (which took place in one of the most rural and poor parts of India) that did not own a mobile phone. By contrast, 20% of all Indians and 30% of rural Indians do not have access to grid electricity (Access to Electricity, 2017).

The disparity between the ubiquity of small battery-operated devices and access to electricity has created a cottage industry of charging services. Many Indians who own mobile phones and other devices will

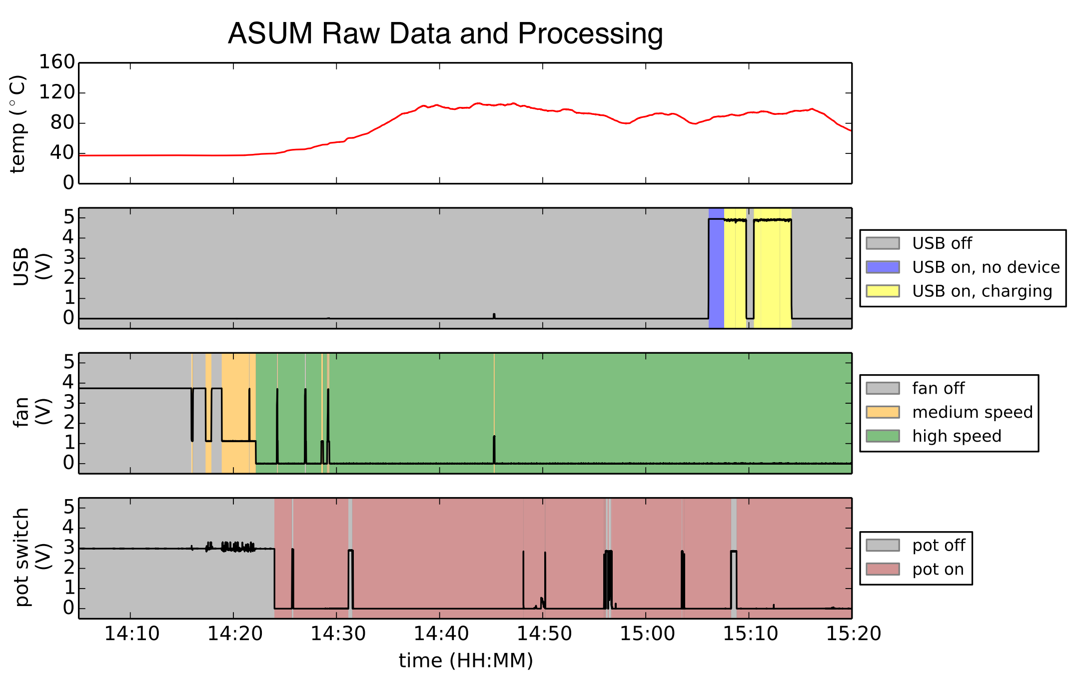

Fig. 2. ASUM raw data is shown as line plots. Results of processing are shown as colored regions representing different states. Combinations of states are used to create use modes. For example, if the pot is off while the USB is charging a phone, this would be the “pot off and changing” use mode.

Table 1
Baseline survey summary. Household demographics, economic status indicators, fuel sourcing behavior, and device charging behavior. Sample size n = 72 for with n = 36 in both USB and no USB groups.

category	metric	USB		no USB		total	
		mean	SD	mean	SD	mean	SD
demographics	total household members	3.8	1.4	4.9	1.6	4.4	1.6
demographics	women in household	1.4	0.7	1.3	0.5	1.4	0.6
demographics	men in household	1.2	0.7	1.3	0.6	1.2	0.7
demographics	girls (< 14 yo) in household	0.6	0.9	1.2	1.3	0.9	1.1
demographics	boys (< 14 yo) in household	0.5	0.7	1.1	1.3	0.8	1.1
demographics	cook age (field staff estimate)	32.1	7.2	33.1	6.4	32.6	6.8
wealth	phones per household	1.1	0.2	1.0	0.2	1.0	0.2
wealth	rooms per household	2.3	1.0	2.5	0.8	2.4	0.9
wealth	prop. w/separate kitchen	36%	–	31%	–	33%	–
fuel sourcing	weekly fuel collection trips	2.2	0.7	2.1	0.7	2.1	0.7
fuel sourcing	fuel collection hours per trip	5.3	1.8	6.0	1.6	5.6	1.7
fuel sourcing	weekly fuel expenses (INR)	36.1	46.9	53.3	5.8	40.4	40.8
fuel sourcing	prop. collecting fuel	86%	–	92%	–	89%	–
fuel sourcing	prop. purchasing fuel	3%	–	0%	–	1%	–
fuel sourcing	prop. collecting & purchasing fuel	11%	–	8%	–	10%	–
charging	prop. paying to charge devices	70%	–	69%	–	69%	–
charging	charging at neighbor's home	72%	–	89%	–	81%	–
charging	charging at a business	28%	–	11%	–	19%	–
charging	weekly paid device charges	1.8	0.8	2.2	1.1	2.0	0.9
charging	cost per device charge (INR)	6.8	3.5	7.2	2.5	7.0	3.0

charge their phones at a local market, at a neighbor's house who has electricity, or at a kiosk. This process of out-of-home charging can be expensive and time consuming; our survey found fees of 7 INR (0.10 USD) per charge of a mobile phone. This equates to roughly 28 USD/kWh, or about 450 times the price of residential consumer grid electricity in Delhi.

With the new availability of USB ports on TEG-enabled cookstoves, stakeholders are curious about how these USB ports influence adoption. The capability of off-grid charging could conceivably affect cookstove adoption in three categorical ways: (i) the willingness to pay for a cookstove, (ii) the impacts of USB on adoption of the cookstove as a cooking tool, and (iii) the extent to which USB access creates a perverse incentive to use the cookstove solely as a fire-powered charger. The possibility of TEG cookstoves leading to cookstove "misuse" is of great concern to policy makers and stakeholders in the cookstove space. If a customer chooses to use a cookstove solely for charging purposes, she might expose herself and her family to higher daily doses of harmful emissions than if she never obtained the "clean cookstove" in the first place – even a very clean cookstove will contribute to increased exposure if the cookstove is not displacing dirtier cooking technology for the purpose of making meals. The emergence of TEG cookstoves on the global marketplace and the potential risks associated with this technology highlights the need to understand TEG-enabled USB charging impacts on cookstove adoption.

In this study, we explore how the presence of USB ports on fan-powered cookstoves influences adoption. We measure the impacts of USB charging ports on the number of fires made in the cookstove, and we also measure whether those fires were used for cooking or not. We compare data about cookstove adoption measured in surveys and by sensors, and, finally, we explore customers' perception and willingness to pay for USB and non-USB cookstoves.

2. Design and methods

2.1. Cookstove and sensor

We designed and studied a customized version of BioLite's TEG-enabled "CampStove." This cookstove, which is designed for remote backpacking, is equipped with a thermoelectric generator, fan, USB port, and a 600 mAh 3.7 V lithium ion backup battery. The TEG module provides 2 W of electrical power, or enough to charge a typical 10 kJ simple mobile phone battery from empty to full in about 1.4 h. The team gave this cookstove a Hindi nickname, "Shakti Chulhi," which translates loosely as "Little Cookstove With Power." This cookstove is of the top-lighting up-draft (TLUD) variety that requires fuel to be broken into small pieces. The Shakti Chulhi is significantly smaller than traditional earthen chulha cookstoves, and it also produces lower firepower, making it a poor direct replacement for womens' primary cooking appliance. This choice of a small cookstove was made intentionally; because Shakti Chulhi was unlikely to serve as a total replacement of the primary cookstove, we hope this study will serve as a worst-case scenario when analyzing charging-without-cooking behavior. Shakti Chulhi was distributed without instruction or coercion to discontinue use of the families' traditional cookstove, so its use was expected to complement, not replace, use of the traditional cookstove (i.e. "stove stacking" (Pillarisetti et al., 2014; Lewis and Pattanayak, 2012; Johnson and Chiang, 2015)).

Cookstoves were also outfitted with a custom sensor, called the Advanced Stove Use Monitor (ASUM), which was designed for this study by the research team. The ASUM is an evolution of the Stove Use Monitor (SUM) sensors typically used to track cookstove adoption (Pillarisetti et al., 2014; Ruiz-Mercado et al., 2008, 2011, 2012, 2013; Thomas et al., 2013, 2016; Wilson et al., 2016). In contrast to traditional SUMs which solely rely on temperature as a proxy for cookstove adoption, ASUMs have the ability to monitor whether the USB port is charging a device, if there is a pot on the cookstove, the fan's speed, and TEG output voltage (a proxy for TEG power). All data is written to an on-board micro SD card between 10 Hz and 0.1 Hz, depending on firmware configuration. A photograph and schematic representation of the Shakti Chulhi and ASUM is shown in Fig. 1, and a demonstration of the data measured by the ASUM are shown in Fig. 2.

2.2. Study population and design

Our study was based in the rural and exceptionally-poor district of Kalahandi in Odisha, India. We partnered with a local Non-

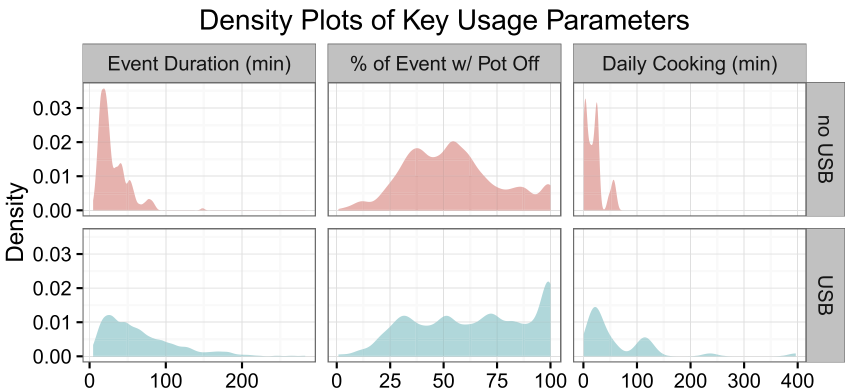

Fig. 3. Density plots of key adoption parameters of both non-USB (top row) and USB stoves (bottom row). All density plots integrate to 1. From the left-most column to right, densities of cooking events, the percentage of cooking event time with the pot off of the cookstove, and average daily cooking minutes for USB and non-USB stoves.

Governmental Organization (NGO) called Antodaya that has more than 20 years of experience working with villages on health and energy initiatives in Kalahandi. Antodaya employed four Odia-speaking enumerators who originate largely from the villages around Bhawanipatna, the District's main city. Enumerators underwent three days of intensive training covering two primary topics: proper use and maintenance of the trial cookstove, and enumeration of the survey instrument.

Antodaya was responsible for identifying 72 participating families from three villages in Kalahandi (24 participants per village). Participants were screened against the following criteria: (i) the household used biomass as their primary cooking fuel to cook food, (ii) the household had no reliable source of electricity, and (iii) and the household owned at least one mobile phone that can be charged via USB power. A summary of household demographics, economic indicators, fuel gathering behaviors, and device charging behaviors are enumerated in Table 1.

Table 1 shows that households in this study were composed of 4.4 members on average with 2.6 adults and 1.7 children under 14. Participants' economic status is indicated by living in 2.4-room homes, owning 1.0 cell phones per household, and 33% of households having a separate kitchen structure. All households burned wood in traditional chulhas as their primary method of cooking both food and tea. Wood is both scavenged and purchased. For households scavenging wood, fuel collectors take 2.1 trips per week, and each trip lasts 5.6 h for a total weekly fuel collection duration of about 11.8 h. More than two-thirds (69%) of households pay to charge one or more mobile devices, and they purchase paid charges twice per week for 7 INR ($0.10 USD) per charge. Participants typically charge their devices at a neighbor's house who might have a solar panel or grid hookup (81%), but some participants (19%) charge their mobile phone at a local business while visiting town or the market. It is worth noting in Table 1 that there is a potential internal validity issue in this study resulting from the randomly-selected non-USB households have 1.1 more occupants (4.9 for non-USB vs. 3.8 for USB).

As an incentive to participate and as part of the experimental design, all participants were allowed to keep two small LED lights, a USB cord and wall charger, a small pot and kadai (frying pan), and 2 kg of chopped wood. The total value of all these incentives was roughly INR 400 (6 USD). Chopped wood was given as an incentive because Shakti Chulhi is a top-loading stove that requires prepared fuels. The fuel for Shakti Chulhi needs to be broken or cut into small pieces (roughly the size of a pinky finger as explained during training) to fit into the cookstove. Based on previous work with cookstoves in Darfur, Sudan (Wilson et al., 2016), the research team anticipated some reluctance towards initial adoption of the cookstove exacerbated by the fact that Shakti Chulhi requires fuel preparation. The small starter sample of prepared fuel would give customers time to realize Shakti Chulhi's benefits before facing the task of chopping their own wood. The sample wood represented a mixture of commonly-available woods in Kalahandi including *Cleistanthus collinus*, *Grewia asiatica*, and *Shorea robusta*.

Participants in the study received a 2-week free trial of the Shakti Chulhi. After arriving at a community center at a predetermined time, 24 women (at each village) participated in a raffle to determine which participants would receive USB and non-USB cookstoves. Other than the presence of absence of the USB port, all the 12 USB and 12 non-USB cookstoves were visually and functionally identical. After the raffle, cookstoves and additional materials were disseminated to participants, and all participants engaged in a 30-min cook-off and training session. Randomized women from the USB and non-USB groups were provided with ingredients to prepare chai (tea) or upma (porridge). All participants received identical fire tending and stove operation training with the exception that the USB group received addition instruction on the cookstove's charging capabilities. A graphical cookstove operation pamphlet was included with the training materials. After the training, a 10-min baseline survey was performed. Approximately two weeks later, women returned the cookstove, and participated in a 20-min followup survey. Both surveys were designed to measure knowledge, attitudes, and practices regarding cooking with Shakti Chulhi as well as willingness to pay. Willingness to pay was assessed using a rudimentary self-assessment; the cook was asked to answer how much she would be willing to pay for the cookstove were it for sale at the local market with the caveat that the cookstove was not for sale after the survey (to discourage haggling techniques).

As previously mentioned, lights, charging hardware, pots, pans, and wood were all given as incentives for women to participate. The research team elected to disseminate lights to approximate charging loads expected in communities with long-term USB charging capability. Antodaya, the NGO, suggested that in Kalahandi, like in much of India, families opt to purchase battery-operated LED lights once they gain access to small amount of electricity from the grid, residential

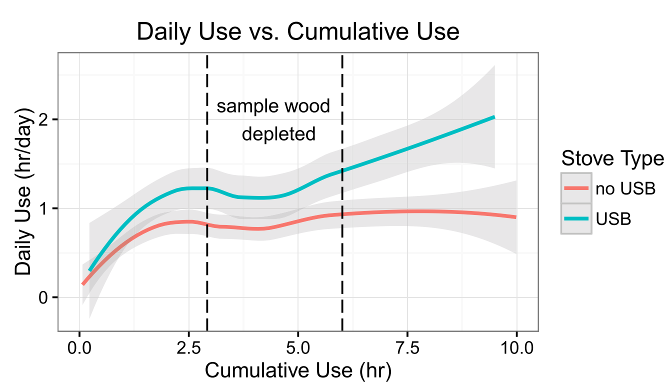

Fig. 4. Average daily cooking per user as a function of cumulative hours of cookstove use. The region between the dashed lines represents ± 1 standard deviation from the cumulative cooking time at which we expect full sample fuel depletion. Shaded regions represent standard error about the mean. For both non-USB and USB stoves, there was significantly more cumulative use to plot, but the x-axis is limited to highlight the effects of sample wood depletion.

Table 2
Use and perceptions about Shakti Chulhi compared to primary cookstoves at baseline and followup. For the best/worst feature questions, participants were asked a free-response question about the Shakti Chulhi's best and worst features. Participants were also asked if Shakti Chulhi is superior or inferior for cooking six different staple foods. Percentages are the percentage of respondents agreeing with or reporting the category and metric listed. Sample size n = 72 for baseline and followup with n = 36 in both USB and no USB groups.

category	metric	baseline			followup		
		USB	no USB	total	USB	no USB	total
main food stove	Shakti Chulhi	0%	0%	0%	17%	22%	19%
main food stove	Chulha	100%	100%	100%	86%	81%	83%
main tea stove	Shakti Chulhi	0%	0%	0%	97%	100%	99%
main tea stove	Chulha	100%	100%	100%	3%	11%	7%
top 3 worst feature	size	92%	83%	88%	64%	67%	65%
top 3 worst feature	fuel loading	56%	72%	64%	92%	92%	92%
top 3 worst feature	fuel prep	14%	14%	14%	11%	11%	11%
top 3 worst feature	volume/food lim.	31%	47%	39%	58%	47%	53%
top 3 worst feature	no USB	0%	36%	18%	0%	31%	15%
top 3 best feature	fast cooking	67%	89%	78%	75%	83%	79%
top 3 best feature	less smoke	75%	94%	85%	81%	94%	88%
top 3 best feature	less fuel	47%	78%	63%	58%	78%	68%
top 3 best feature	USB	75%	3%	39%	78%	0%	39%
top 3 best feature	portability	0%	8%	4%	0%	0%	0%
top 3 best feature	fan	8%	17%	13%	11%	22%	17%
superior for	tea	100%	100%	100%	100%	100%	100%
superior for	rice	19%	14%	17%	6%	0%	3%
superior for	dal	36%	17%	26%	31%	11%	21%
superior for	curry	69%	64%	67%	69%	72%	71%
superior for	upma	100%	100%	100%	97%	94%	96%
superior for	khichdi	94%	67%	81%	72%	78%	75%

photovoltaic, or other distribution sources. By providing LED lights, we sought to simulate the expected long-term steady-state charging burden faced by the cookstove. Additionally, we provided free charging cables. Some households do not own charging cables and instead rely on the cables provided at neighbors' or business' charging points. All participants were also provided wall outlet-to-USB charging adapters to ensure an even field in terms of the capacity for an individual to seek grid power for charging. A 2 kg bundle of chopped wood was provided as a bridge fuel to accustom women to the benefits of the cookstove without the burden of breaking their own wood into small pieces; we included this fuel with the intention of measuring if there was a marked decrease in Shakti Chulhi usage after pre-prepared fuel supplies ran out. Finally, at the recommendation of our NGO partner, we included a pot and pan (kadai) as a tangible lasting benefit to study participants who may not realize any long-term benefit from lights and cables after the study was complete and the cookstove was returned.

All research was performed under University of California, Berkeley's Institutional Review Board approval of Protocol 2014-09-6691.

3. Results

3.1. Sensors

Using ASUMs, we observed 772 cooking events with 493 and 279 events from USB a non-USB cookstoves, respectively. This was aggregated over 34 USB households observed for 417 household-days, and 30 non-USB households observed for 475 household days. Attrition

Table 3
Baseline and followup ratings of aspects of Shakti Chulhi. Rating were performed on a 1–7 scale (using a scale from 1-to-7 1-Rupee coins) with 1 being bad/undesirable and 7 being good/desirable. Sample size n = 72 for baseline and followup with n = 36 in both USB and no USB groups.

metric	baseline						followup					
	USB		no USB		total		USB		no USB		total	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
overall	5.1	1.2	5.3	0.8	5.2	1.0	4.8	1.2	4.8	1.0	4.8	1.1
size	3.8	1.6	4.3	1.7	4.0	1.7	3.8	1.8	4.0	1.6	3.9	1.7
stability	3.9	1.2	4.3	1.3	4.1	1.2	4.5	0.9	4.8	1.0	4.6	1.0
fuel prep.	3.9	1.4	4.4	1.4	4.2	1.4	4.2	1.4	4.5	1.1	4.3	1.2
appearance	5.8	1.2	5.9	1.3	5.8	1.2	5.8	1.2	6.0	1.0	5.9	1.1
complexity	4.3	1.4	4.9	1.2	4.6	1.3	4.6	1.0	4.7	1.1	4.7	1.1
fuel addition	3.2	1.7	4.4	1.5	3.8	1.7	2.9	1.2	3.0	1.0	2.9	1.1
smoke	6.1	0.8	6.5	0.8	6.3	0.8	5.8	0.9	6.0	1.0	5.9	0.9
USB for family	6.2	0.9	–	–	6.2	0.8	6.1	0.8	–	–	6.1	0.8
USB for others	5.2	1.0	–	–	5.2	1.0	4.5	0.8	–	–	4.5	0.8
fan	5.8	0.8	6.0	0.8	5.9	0.8	5.4	0.7	5.6	0.8	5.5	0.7
fuel use	5.6	0.9	5.9	1.1	5.8	1.0	5.5	0.8	5.6	0.8	5.5	0.8
cooking speed	5.5	0.9	5.4	1.3	5.4	1.1	5.2	0.9	5.4	1.0	5.3	0.9
showing others	4.4	0.9	4.7	1.0	4.5	0.9	4.3	0.6	4.5	0.9	4.4	0.8

Table 4
Satisfaction and primary use case for Shakti Chulhi at followup. Sample size n = 72 for followup with n = 36 in both USB and no USB groups.

category	metric	USB	no USB	total
satisfaction	would recommend Shakti C.	89%	78%	83%
person who likes Shakti Chulhi most	you (the cook)	72%	53%	63%
person who likes Shakti Chulhi most	husband	11%	25%	18%
person who likes Shakti Chulhi most	children	8%	19%	14%
person who likes Shakti Chulhi most	other family	11%	3%	7%
primary use case	make a part of a larger meal	47%	56%	51%
primary use case	make snacks or tea	47%	44%	46%
primary use case	make full meals	6%	0%	3%

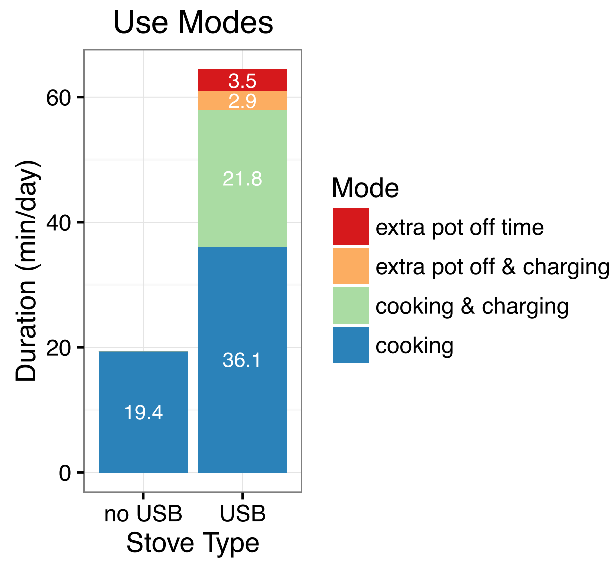

Fig. 5. Average daily durations of adoption modes for USB and non-USB cookstoves. The non-USB stove could only be adopted in a "cooking" mode, while the USB-enabled stove could be adopted for cooking, cooking and charging, or charging only. The charging only behavior is represented as the sum of simultaneous measured pot-off and charging time as well as additional marginal pot-off time. Not all USB-group "cooking" is done with an available ready-to-charge USB port. We estimate 29% of all daily cooking, or about 18.5 min of the "cooking" mode are performed with an unavailable USB port.

of ASUM sensor data from the sample of 72 total households was due to loss of data from several corrupted/empty micro SD cards (we found one particular SD card that contained MP3 files of Bollywood musical hits, giving a hint about the cause of other missing data) and physical damage of cookstoves due to thermal or impact-induced damage.

USB cookstoves were used significantly more per day than non-USB stoves ($p = 0.002$, independent t-test) with USB and non-USB having average daily use of 63.4 min [SD = 77.2 min] and 19.1 min [SD = 16.7 min], respectively. Use of the non-USB stoves was assumed to be entirely of in the "cooking" adoption mode while adoption of the USB stoves was broken into four modes: cooking, cooking & charging, pot off & charging, and extra pot-off time.

To calculate the amount of time spent charging without simultaneous cooking, we analyzed both charging and pot status. No matter what, there is some proportion of time that we expect for the pot to be off the stove, including while charging a mobile phone. For example, whether charging or not, users need to tend the fire and stir the pot. Additionally, there is some time that the pot is on the stove that may not be useful cooking. For example, users might leave an empty pot on the stove or use a water-filled pot as a thermal load while utilizing the USB port. However, for the purpose of this study, we assume there is no bias in non-cooking pot-on behavior between the USB and non-USB groups.

We found that USB cookstoves were operated without a pot for significantly longer proportions of use events ($p < 0.001$, independent t-test). Cookstoves with USB were operated without a pot for 65.4% [SD = 28.1%] of the duration of each event compared with 54.8% [SD = 24.7%] for cookstoves without USB. A summary of cooking duration mode statistics can be seen in Table 6. Using non-USB cookstoves as a control, we attribute the extra 10.6% of pot-off time in USB stove use to the presence of the USB port. This accounts for an average marginal increase of 6.7 min per day of extra non-cooking use for USB stoves. This additional 6.7 min of daily stove use for charging purposes only can be broken down into two sources: more-than expected pot-off charging time (3.3 min/day), and more than expected pot-off non-charging time (3.4 min/day). A breakdown of average daily use broken down by adoption mode is shown in Fig. 5.

In addition to greater daily average use, USB cookstoves were used for significantly longer per use event than non-USB cookstoves ($p < 0.001$, independent t-test): USB cookstoves were used an average of 58.7 min [SD = 49.6 min] per event while non-USB cookstoves were used for 27.0 min [SD = 19.4 min]. For stoves with USB, the USB port was used for charging for 23.0 min [SD = 38.8 min] of each use event and for a daily average of 25.3 min [SD = 55.1 min] per day. This amount of daily charging would be enough to charge up a typical 10 kJ mobile phone battery by about 30%. These data are presented graphically in Fig. 3 and tabulated in Table 6. Fig. 6 illustrates adoption mode as a function of the proportion of the event that has been completed.

In the laboratory, wood burning rates in Shakti Chulhi were an average of 8.5 g min^{-1} (SD 3.0 g min^{-1}) for 20 replicates of a standardized 35-min 2-L water boiling task. Assuming an aggregate lower heating value of 17,500 $kJkg^{-1}$, Shakti Chulhi burns with an event-average firepower of 2.5 kW. At an average fuel depletion rate of 8.5 g min^{-1} (SD 3.0 g min^{-1}) during use events, we expected most customers to fully deplete their sample fuel supply between 2.9 h and 6.0 h of cumulative cookstove use (calculated using ± 1 standard deviation of the mean fuel wood burning rate). Fig. 4 plots use rate in average use hours per day as a function of cumulative use. Fig. 4 suggests that depletion of the complimentary 2 kg "sample wood" did not impact daily use of the cookstove. In other words, users switched from using the prepared wood provided by the research team to preparing their own wood without any meaningful change in daily use of the cookstove.

3.2. Surveys

Baseline and followup surveys of participants also revealed several interesting insights. Table 2 shows users' perceptions of Shakti Chulhi at baseline and followup. After owning Shakti Chulhi for two weeks, 99% of participants reported using Shakti Chulhi as their primary cookstove for making tea while only 19% reported Shakti Chulhi was the primary cookstove for making food. At both baseline and followup, the small size of Shakti Chulhi and the process of loading it with fuel were consistently rated as some of the cookstove's three worst features in surveys. Fuel loading (by lifting the pot and depositing small pieces of

Table 5
Baseline and followup assessment of willingness to pay. Participants were asked to state whether or not they would be willing to purchase Shakti Chulhi or rent Shakti Chulhi on a weekly basis. Shakti Chulhi was not for sale as part of the study. The question was posed as a hypothetical under the condition that Shakti Chulhi was for sale at a local market. Sample size n = 72 for baseline and followup with n = 36 in both USB and no USB groups.

metric	baseline						followup					
	USB		no USB		total		USB		no USB		total	
	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
willing to buy	67%	–	67%	–	67%	–	69%	–	64%	–	67%	–
willing to rent	47%	–	47%	–	47%	–	50%	–	44%	–	47%	–
buy bid (INR)	360	190	342	140	351	165	329	114	303	132	317	122
rental bid (INR)	27	17	25	20	26	18	27	20	32	22	29	21

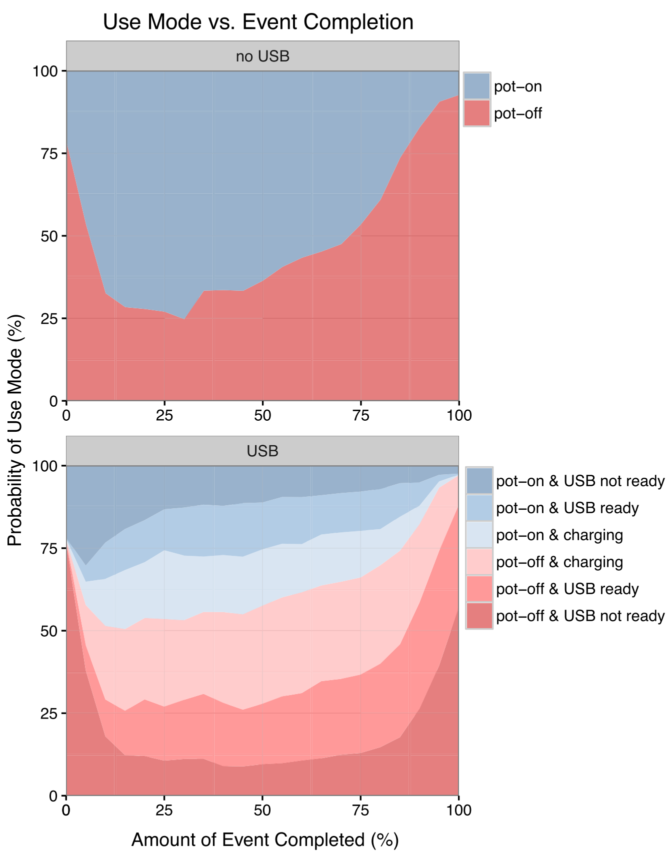

Fig. 6. Use modes vs. proportion of event completed. Blue shades indicate times and probabilities that the pot is on the stove while reds indicate when the pot is off the stove. “USB not ready” indicates a status where the USB port has yet to become available because the cookstove is not hot enough to power the outboard USB port. USB “ready” indicates the USB port is active and available to charge a load, but no load is being charged.

wood) was perceived as a much worse feature at followup than at baseline: at baseline just 64% of respondents expected fuel loading to be one of the cookstove's three worst features, but at followup 92% rated fuel loading as one of the worst features. We anticipated that fuel preparation (breaking/chopping large sticks into small sticks) would be perceived poorly, but only 14% thought of it as a major drawback at baseline, and even fewer people, 11%, saw it is a major drawback at followup. The features viewed as the most attractive were Shakti Chulhi's lower consumption of fuel, less smoke, less fuel, and, where applicable, availability of USB. At both baseline and followup, almost all participants viewed Shakti Chulhi's ability to cook tea and light-thermal-load snacks (like upma) as superior to their traditional chulha. High-thermal-load foods like rice and dal scored significantly lower.

Table 3 summarizes ratings on a 1-to-7 scale of Shakti Chulhi's features. Participants ranked features using a scale of up to seven 1-Rupee coins (numerical ranking was not culturally understood). Shakti's Chulhi's overall ranking decreased from 5.2 to 4.8 over the course of the 2-week trial. The stability ratings for Shakti Chulhi increased from baseline to followup (4.1–4.6), while fuel addition ratings decreased substantially (3.8–2.9).

Table 4 enumerates satisfaction with Shakti Chulhi and primary use cases. For the USB group, 89% of participants would recommend Shakti Chulhi while just 78% of the non-USB group would do the same. Both groups report that, of all family members, the primary cook enjoyed Shakti Chulhi the most. Because men in the household typically control the cellphone, we anticipated that men might enjoy USB-enabled Shakti Chulhi more than primary cooks. However, 25% of husbands in the non-USB group were reported to have enjoy Shakti Chulhi the most while just 11% of husbands in the USB group enjoyed Shakti Chulhi most. Among both groups, the overwhelming use cases for Shakti Chulhi were to make tea, snacks, or parts of meals.

At baseline and followup, we asked questions about whether participants would purchase or rent Shakti Chulhi, and if so for how much. To reduce the tendency to low-ball as a bartering technique, enumerators ensured participants that Shakti Chulhi was not, and would not, be for sale. The question was posed hypothetically under the assumption that Shakti Chulhi would be available for sale at a local market. As shown in Table 5, at baseline, 67% of both USB and non-USB participants claimed willingness to purchase Shakti Chulhi for INR 360 ($5.25 USD) for the USB group and INR 342 ($4.98 USD) for the non-USB group. By followup, willingness to pay had decreased slightly as shown in Table 5. Fewer participants were willing to rent, just 47%, but willingness to pay for rental was substantially higher on an annualized basis than purchasing outright. At the followup, the average participant was willing to rent Shakti Chulhi for INR 29 ($0.42 USD) per week. This is equivalent to just over INR 1508 ($21.97 USD) per year, or about 4.8 times the average purchase price reported at followup.

As shown in past studies (Wilson et al., 2016), sensor- and survey-based measures of cookstove adoption show very poor correlation. Fig. 7 illustrates a comparison between daily use of Shakti Chulhi measured by sensors and surveys. We analyzed survey data about self-reported adoption in multiple ways. We analyzed responses to direct inquiries about daily Shakti Chulhi use as well as extrapolating data from estimates of weekly and daily meals cooked on Shakti Chulhi multiplied by estimates of average meal duration. Although we found the product of weekly meal estimates multiplied by average meal duration to be correlated most strongly with sensor data, surveys and sensors are still very poorly correlated with $R^2 = 0.0002$. Table 6 shows that, in surveys, the non-USB group actually reported *greater* adoption (48.0 min per day) than the USB group (57.3 min per day).

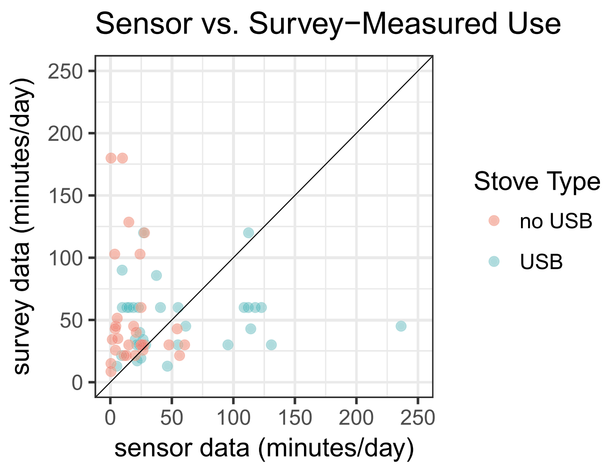

Fig. 7. Daily use of Shakti Chulhi measured using sensors and surveys demonstrates poor correlation. Black line indicates 1:1 agreement between survey-measured and sensor-measured daily use of Shakti Chulhi.

Table 6
Summary of stove use for USB and non-USB cookstoves as measured by sensors and surveys.

instrument	metric	unit	USB			no USB		
			mean	SD	n	mean	SD	n
survey	mean total use per day	min	48.0	26.7	36	57.3	47.6	36
survey	mean event duration	min	53.1	26.2	36	71.0	53.2	36
sensor	mean total use per day	min	63.9	77.2	34	19.1	16.7	30
sensor	mean event duration	min	58.7	49.6	493	27.0	19.4	279
sensor	prop. of event w/o pot	%	65.4	28.1	493	54.8	24.7	279
sensor	charging per day	min	25.3	55.1	34	–	–	–
sensor	charge duration per use	min	23.0	38.8	493	–	–	–

4. Discussion

The presence of USB on Shakti Chulhi dramatically increased adoption of the cookstove. The increased adoption of USB-equipped Shakti Chulhis was due primarily to increased adoption of the cookstove as a cooking tool as illustrated in Fig. 5. This increased adoption of the cookstove as a cooking tool (cooking + cooking & charging modes) was roughly 3.5 times that of the non-USB stove. This increased adoption came at a relatively modest price of 11% of total use time being used for activities not linked to cooking. This dramatically-increased adoption of USB-enabled Shakti Chulhi was not proportionally reflected in survey responses about willingness to pay or overall satisfaction with Shakti Chulhi, and this lack of utility of survey instruments to assess impact underlies the value of the sensor-based data collected in this study.

In surveys, women reported that Shakti Chulhi was a useful tool for cooking chai (tea), upma, and other smaller thermal loads. 89% of USB stove owners and 78% of non-USB owners said they would recommend Shakti Chulhi to a friend or family member. However, as expected, women reported that Shakti Chulhi was a poor tool for cooking large thermal loads such as rice and dal. Women's primary complaints about the cookstove, in order, were the hassle of lifting the pot to deposit small pieces of fuel, its small size, and the difficulty of cooking large thermal loads, especially rice. We were surprised to find the fuel preparation (cutting and breaking sticks into smaller pieces) was not rated as a significant drawback in surveys. Sensor data validated this survey finding because ASUMs showed consistent Shakti Chulhi use even after donated fuel was depleted.

As with past studies, we have reaffirmed the unreliability of survey data and the need for sensors to accurately measure behavior. Using surveys alone, this study would not have discovered the significant boost in adoption among the USB group. In fact, survey data suggested that the USB group used Shakti Chulhi *less* than the non-USB group. Sensors were the instrument that derived all useful adoption insights from this study, and this study reaffirms sensors' indispensable role in quantifying the performance, adoption, and impact of cookstoves.

Other than charging, women reported that Shakti Chulhi's primary benefits were, in order, reduced smoke, cooking speed (understood by field staff to primarily mean speed in total meal preparation time which was reduced by Shakti Chulhi's short warm-up time), and reduced fuel consumption. At followup, both the USB and non-USB groups reported a low willingness to pay for outright purchase of Shakti Chulhi. Both groups reported willingness to pay of just over 300 Rupees (5 USD) for the cookstove, which is much lower than the cookstove's $120 USD retail price in the USA. We were surprised that the USB group was only willing to pay about 10% more for their cookstoves than the non-USB group. The marginal increase in willingness to pay among the USB group represented less than 2 weeks worth of 3rd party charging fees. About half of participants were willing to rent the cookstove, and to rent the cookstove at a weekly rate equivalent to about $22 USD per year–still far short of US retail price, but a potentially viable business revenue stream depending on transaction cost and if the cookstove can be made to last several years.

We were curious about how users charge loads within use events. For example, we wanted to explore whether users charge evenly throughout a use event, or do they just keep the fire going a bit longer at the end of an event to charge a load? Fig. 6 has insights about this behavior by looking at adoption mode as a function of the duration of the cooking event completed. This figure illustrates that USB stoves have increased pot-off behavior throughout the duration of the event when compared with non-USB stoves (red shades), and there does not seem to be any meaningful bias of the charging behavior favoring the end of cooking events (the two lightest blue and red color bands in the middle of the bottom chart). Our analysis strongly suggests that charging behavior is dispersed throughout cooking events and not biased at the end of events.

Fig. 4 explores whether users stop using the USB and/or non-USB cookstoves when sample fuel was depleted. Although daily use plateaued for both non-USB and USB stoves in the time period where we expected sample fuel to run out, adoption was sustained after sample wood ran out and even increased in the case of the USB stoves. This behavior indicates that users transitioned to preparing their own fuel without significant impacts on adoption. However, we do see some temporary reductions in the rate of increased adoption that may be catalyzed by sample fuel wood running out; we suggest that a sample fuel source may assist adoption by helping users realize cookstove benefits before facing the "plateau" of preparing their own fuel.

The question of whether Shakti Chulhi or its marginal use as a charging-only tool has net positive impacts on health is beyond the scope of this study. However, we lay out a framework for further analysis. To estimate improved cookstoves' impact on health, we will need to analyze the extent to which improved cookstoves displace dirtier traditional cookstoves. Assuming just one traditional stove, the total emissions released to the indoor environment before and after the cookstove intervention are given by Equations (1) and (2) where E represents total emissions in the indoor environment while $\dot{E}$ and t represent average event-wise emission rate and time per day spent using each cookstove, respectively.

$$E_0 = \dot{E}_{trad} t_{trad_0} \tag{1}$$

$$E_f = \dot{E}_{trad} t_{trad_f} + \dot{E}_{new} t_{new_f} \quad (2)$$

Setting E_0 and E_f equal to each other represents the break-even point between emission exposure in the baseline and intervention scenarios. Solving for t_{new_f}, we find Equation (3). Equation (3) illustrates that the total time that the new cookstove can be used before break-even is reached is a function of how much cleaner the new cookstove is compared to the old cookstove $\left(\frac{\dot{E}_{trad}}{\dot{E}_{new}}\right)$ and the displacement of the old cookstove by the new cookstove $(t_{trad_0} - t_{trad_f})$. Further work with instrumentation of all cookstoves in the household is needed to fully analyze these two factors and their impacts on exposure.

$$t_{new_f} = \frac{\dot{E}_{trad}}{\dot{E}_{new}}\left(t_{trad_0} - t_{trad_f}\right) \quad (3)$$

This study has analyzed, for the first time, adoption modes of TEG- and USB port-enabled cookstoves. We have demonstrated that presence of a USB charging port dramatically increased adoption of the cookstove, and this increased adoption is primarily in the desirable “cooking” or “cooking & charging” adoption modes rather than the emissions exposure-increasing “charging only” mode. Charging-only behavior was limited to 11% of total use among the USB group, and this behavior was spread evenly throughout cooking events with no compelling evidence of end-of-event charging-only episodes. All meaningful insights about cookstove use were derived from sensor data because survey data about adoption was shown to be unreliable.

For this community, we believe the Shakti Chulhi cookstove design represents a worst-case scenario for estimating charging-only behavior because the cookstove does not meet most of the community's cooking needs. In a context where fuel is more plentiful and cheap (in terms of collection time or purchase price), there may be even more charging-only behavior as the fuel resource is less constrained.

We were surprised that Shakti Chulhi demonstrated the utility and desirability of a small auxiliary cookstove for performing light cooking tasks, even when that cookstove required prepared fuel. Depletion of the sample fuel wood resource did not have a significant impact on use. Users responded positively to the cookstove, especially in regards to its ability to cook small thermal loads.

This study points to the utility of TEG cookstoves, especially those outfitted with USB ports. This study has demonstrated that USB ports may serve as a catalyst for adoption of more advanced cookstoves that would otherwise not be adopted. This important lever to influence adoption behavior may be an increasingly important tool towards the goal of ending the crisis of cooking.

Conflict of interest

In 2018, author Wilson became the CEO of Geocene Inc., a company which creates commercial cookstove adoption sensors and software. However, the ASUM sensors and software used in this study were created in 2014 and predate Geocene Inc. Sensors and software used in this study are not produced, sold, or promoted in any way by Geocene Inc.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.deveng.2018.08.001.

References

Access to Electricity (Percent of Population). . http://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?end = 2014&name_des c = true&start = 1990&view = chart.
Bond, T.C., Venkataraman, C., Masera, O., 2004. Energy Sustain. Develop. 8.
Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N.G., Mehta, S., Pruss-Ustun, A., Lahiff, M., Rehfuess, E.A., Mishra, V., Smith, K.R., 2013. Environ. Health Perspect. 121.
Champier, D., Bedecarrats, J., Rivaletto, M., Strub, F., 2010. Energy 35, 935–942.
Chaurey, A., Kandpal, T.C., 2009. Energy Pol. 37, 4910–4918.
Forouzanfar, M.H., et al., 2015. Lancet 386, 2287–2323.
Gao, H.B., Huang, G.H., Li, H.J., Qu, Z.G., Zhang, Y.J., 2016. Appl. Therm. Eng. 96, 297–310.
Horman, C., Lee, M., Wagner, M., 2013. Thermoelectric Cookstove (Ph.D. thesis). Santa Clara University.
Jetter, J.J., Zhao, Y., Smith, K.R., Khan, B., Yelverton, T., DeCarlo, P., Hays, M.D., 2012. Environ. Sci. Technol. 46, 10827–10834.
Johnson, M.A., Chiang, R.A., 2015. Environ. Health Perspect. 1–32.
Just, B., Rogak, S., Kandlikar, M., 2013. Environ. Sci. Technol. 3506–3512.
Lam, N.L., Chen, Y., Weyant, C., Venkataraman, C., Sadavarte, P., Johnson, M.A., Smith, K.R., Brem, B.T., Arineitwe, J., Ellis, J.E., Bond, T.C., 2012. Environ. Sci. Technol. 46, 13531–13538.
Lewis, J.J., Pattanayak, S.K., 2012. Environ. Health Perspect. 120, 637.
Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., 2013. Lancet 380, 2224–2260.
MacCarty, N., Still, D., Ogle, D., 2010. Energy Sustain. Develop. 14, 161–171.
Mal, R., Prasad, R., Vijay, V.K., 2014. Int. Proceed. Chem.
Mal, R., Prasad, R., Vijay, V.K., Verma, A.R., 2015. Procedia Comput. Sci.
O'Hanley, H., 2009. Performance of a Stove Mounted Thermoelectric Generator.
Pillarisetti, A., Vaswani, M., Jack, D., 2014. Environ. Sci. Technol.
Priya, S., Inman, D.J. (Eds.), 2009. Energy Harvesting Technologies. Springer.
Rai, S., 2016. India Just Crossed 1 Billion Mobile Subscribers Milestone and the Excitement's Just Beginning. https://www.forbes.com/sites/saritharai/2016/01/06/india-just-crossed-1 -billion-mobile-subscribers-milestone-and-the-excitements-just-beginning/#6ff1 fc607db0.
Rapp, V.H., Caubel, J.J., Wilson, D.L., Gadgil, A.J., 2016. Environ. Sci. Technol. 50, 8368–8374.
Ruiz-Mercado, I., Lam, N.L., Canuz, E., 2008. Boiling Point.
Ruiz-Mercado, I., Masera, O., Zamora, H., Smith, K.R., 2011. Energy Pol. 39, 7557–7566.
Ruiz-Mercado, I., Canuz, E., Smith, K.R., 2012. Biomass Bioenergy 47, 459–468.
Ruiz-Mercado, I., Canuz, E., Walker, J.L., Smith, K.R., 2013. Biomass Bioenergy 57, 136–148.
Smith, K.R., Sagar, A., 2014. Energy Pol. 75, 410–414.
Smith, K.R., Bruce, N.G., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., Dherani, M., Hosgood, H.D., Mehta, S., Pope, D., Rehfuess, E., 2014. Annu. Rev. Publ. Health 35, 185–206.
The World Bank, 2011. Household Cookstoves, Environment, Health, and Climate Change.
Thomas, E.A., Barstow, C.K., Rosa, G.A., 2013. Environ. Sci. Technol.
Thomas, E.A., Tellez-Sanchez, S., Wick, C., Kirby, M., Zambrano, L., Abadie Rosa, G., Clasen, T.F., Nagel, C., 2016. Environ. Sci. Technol. 50, 3773–3780.
Wilson, D.L., Coyle, J., Kirk, A., Rosa, J., Abbas, O., Adam, M.I., Gadgil, A.J., 2016. Environ. Sci. Technol. 50, 8393–8399.