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Cleaner Cooking: Exploring Tools to Measure and Understand the Long-term Adoption and Environmental Significance of Cookstoves in India

by

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Professor Ashok Gadgil, Chair
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Professor Alice Agogino

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Abstract

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About 40% of the world's population, or roughly 3 billion people, rely on solid biomass fuels like coal, wood, dung, and crop residues to cook and meet their household energy needs. This outdated energy system has severe social, health, and environmental implications. Women are disproportionately affected as they predominantly bear the burden of cooking and collecting fuelwood, which exacerbates the "time poverty" trap that restricts them from participating in economic and educational activities. Exposure to indoor solid fuel combustion, also known as household air pollution, is responsible for 3-4 million premature deaths per year and is a leading risk factor for chronic obstructive pulmonary disease, childhood pneumonia, stroke, ischemic heart disease, and lung cancer. Solid-fuel cooking contributes to 16% of global ambient air pollution, emitting CO_2 and other climate-forcing pollutants like carbon monoxide, black carbon, and methane.

To tackle the issue of solid-fuel cooking on a global scale, initiatives have been launched to introduce energy-efficient cookstoves known as "improved" or "clean" cookstoves. These cookstoves can significantly reduce fuel use, emissions, and cooking time compared to open fires or rudimentary cookstoves. They are considered a cost-effective climate mitigation strategy, with the potential to reduce emissions by 1 Gigatonne CO_2e per year if implemented globally. Nevertheless, for improved cookstoves to have any tangible health benefits, they must attain high levels of efficiency. The reduced burden on women from less fuelwood collection time and labor, as well as shorter cooking times, should not be disregarded, but households must first adopt the improved cookstoves for any benefits to be achieved.

Improved cookstoves programs have largely failed to achieve their promised advantages due

to low levels of sustained adoption. Often, cookstoves have inadequate performance in the field compared to lab settings and fail to meet users' needs. Moreover, the widespread use of unreliable methods, such as surveys, to measure the adoption and impact of the cookstoves has hindered the cookstoves sector from advancing. Surveys can be unreliable for measuring quantitative data, as there are different biases associated with interviews, and studies have shown that households tend to over-report their usage. Existing methodologies used to verify carbon emission reductions from cookstoves projects do not require usage monitoring and allow for the use of default cookstove emission factors, resulting in inaccurate estimations. Temperature dataloggers or "stove use monitors" have emerged as a reliable, objective method to measure users' actual usage and provide more granularity. Despite this, surveys are still widely used to measure usage and thus, projects may be failing to capture dis-adoption, which is still poorly understood. More research is needed to develop measurement methods that are accurate, feasible, and affordable.

The success of improved cookstoves projects depends on designing with and for users, using reliable long-term methods to measure impact and usage, and understanding the reasons for usage or lack of usage. This dissertation aims to achieve these goals by adapting a successful, cost-effective cookstove from Africa to India, identifying motivations and barriers to adoption through case studies in rural Maharashtra, where fuelwood is widely used for cooking, and improving methods for estimating the carbon significance of cookstoves projects.

Chapter 1 provides background on the health and climate effects of solid-fuel cooking, as well as current solutions and areas where more research is needed. In Chapter 2, I describe the design process of adapting a cost-effective, successful cookstove, the Berkeley-Darfur Stove (BDS) from Africa to rural Maharashtra. While some issues could not be addressed without a complete re-design, women who participated in the design process expressed interest in purchasing the modified BDS, called the Berkeley-India Stove (BIS). Chapter 3 then compares survey-reported usage and sensor-recorded cooking events (durations of use) of the BIS in two monitoring studies, in rural Maharashtra, that occurred between February 2019 and March 2021. The first was a free trial of the BIS, and the second involved households that purchased the BIS. We found that over-reporting usage was common in both studies and surveys failed to detect the long-term declining trend in usage in the second study. In Chapter 4, we analyze the sensor data of the second study. We found that about 43% of households had an overall decreasing trend in usage, average daily usage stabilized around 95 days and households used the stove intermittently, with some demonstrating intervals of nearly 3 months of no usage, on average, between periods of use. Finally, in Chapter 5, we present the results of comparing the performance and emissions in lab-based experiments of the BIS and the baseline cookstove, the mud chulha, which has existed in South Asia for millennia. We found that the BIS used 43% less fuelwood and emitted 25% less $PM_{2.5}$ compared to the mud chulha for the same cookstove task. We also present methods to use the temperature dataloggers—previously used to measure usage—for estimating the BIS' fuelwood burn rate and CO_2 emission rate.

In summary, this research presents case studies and method analyses that highlight the importance of incorporating user-centered design techniques and sensor data in cookstove interventions. Using reliable methods to measure the impact of cookstoves' projects is necessary for the development of the cookstoves sector and addressing the negative effects of solid-fuel cooking globally. Moreover, the lessons learned from these studies can also extend to technology intervention projects more broadly.

Standing before the stove
Hungry for hope
Flames, wood,
The smell of ash
The planet speaks
Not of ends, but beginnings.

- Z. Hing

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Chapter 1

Introduction

1.1 Solid-fuel Cooking: a Global Issue

For three billion people, the simple act of cooking can have detrimental health outcomes. These individuals, constituting roughly 40% of the world's population, rely on biomass to meet household energy needs and to prepare their daily meals [1]. A vast majority burn solid biomass fuels (e.g., coal, wood, dung, crop residues) using rudimentary fires or inefficient cookstoves, which has far-reaching social, health, and environmental implications, not only driving an unsustainable dependence on sources of woody biomass, but also producing extreme levels of pollutants that affect climate and human health.

This outdated energy system has the most severe impact on women. They are disproportionately affected as they predominantly bear the burden of cooking and collecting fuelwood [2]. Women may spend 3-4 hours per day cooking on traditional cookstoves [3], and anywhere from 4 to 25 hours per week collecting fuelwood [4, 5, 6]. The large amount of time and the extreme physical demands of these activities exacerbate the "time poverty" trap in which women in developing countries are often stuck [7, 8, 9]. "Time poverty" refers to when a person, particularly for women, has little or no discretionary time due to an unequal distribution of unpaid domestic work, resulting from systemic gender inequality and restrictive gender norms [8]. This trap can restrict women from otherwise participating in economic, educational, and social activities, thus resulting in potentially significant opportunity costs when it comes to tasks like fuelwood collection [10].

Solid-fuel cooking also has severe impacts on human health. The burning of solid fuels emits toxic levels of fine particulate matter ($PM_{2.5}$), which can be deadly [2]. $PM_{2.5}$ refers to particles with aerodynamic diameters less than 2.5 μm. When these particles are inhaled, they can deposit deep into the lungs, causing health problems [11]. Exposure to $PM_{2.5}$ from cooking smoke can exceed the World Health Organization's recommended air quality guidelines by a factor of 50 or more [2, 12, 13]. Exposure to indoor solid fuel combustion, also known as household air pollution (HAP) is the world's deadliest environmental health threat, responsible for 3-4 million premature deaths per year [14]. HAP exposure is a risk factor for chronic obstructive pulmonary disease, acute lower respiratory infection in children, stroke, ischemic heart disease, and lung cancer [15, 2].

In addition to negative human health impacts, the use of solid fuels to meet household energy needs also has destructive environmental effects. Globally, more than half of all harvested wood is used as fuel, and emissions from fuelwood use contribute 1.0–1.2 Gigatonnes CO_2-equivalent (CO_2e) per year [16]. Of the biomass that is used for cooking, an estimated third (27-34%) is unsustainably harvested (non-renewable biomass) [16]. About 300 million people live with acute fuelwood scarcity in Africa and South Asia [17]. HAP contributes to roughly 11% of ambient air pollution globally and 26% in South Asia [2]. Moreover, the use of solid fuels in rudimentary fires or inefficient cookstoves also involves the incomplete combustion of these fuels, which in turn, emits other climate-forcing pollutants such as carbon monoxide, methane, and black carbon. Black carbon is a short-lived greenhouse gas with large global warming impacts. Solid-fuel cooking contributes 25% of total black carbon emissions globally and as much as 60%-80% of total black carbon emissions in Asia and Africa [18]. Black carbon not only has a climate-warming impact that is 120-1800 times stronger than CO_2 per unit of mass [18], but also may reduce the albedo of sea ice and glaciers, thereby increasing their melting rate [19].

Solid fuel use for household energy needs is most prevalent in Sub-Saharan Africa and Southeast Asia [20]. In India alone, 760 million people use solid fuels, which is more than half of India's total population [12]. Approximately 500,000 premature deaths occur each year in India from exposure to indoor solid fuel combustion [12]. Notably, research in India found that measured mean daily $PM_{2.5}$ concentrations in rural solid fuel-using households were 163 $\mu g/m^3$ in the living area and 609 $\mu g/m^3$ in the kitchen area [21]. The World Health Organization air quality guidelines state that the 24-hour average exposures should not exceed 15 $\mu g/m^3$ more than 3-4 days per year [13].

1.2 Improved Cookstoves

Efforts to address this global issue of solid-fuel cooking often consist of introducing energy-efficient biomass cookstoves, termed "improved cookstoves" or "clean cookstoves", dating back to the 1970s [22]. Although there is no agreed upon definition of what makes a cookstove "improved" or "clean", the main benefits of improved cookstoves generally include reductions in total fuel use, emissions, and cooking time per cooking task compared to baseline rudimentary stoves or three-stone fires. This is achieved by improving the thermal efficiency or combustion efficiency of the cookstove. Research has shown that improved biomass cookstoves can reduce fuelwood usage and emissions by as much as 30-50% compared to baseline stoves, such as three-stone fires [23].

Improved cookstoves are considered a cost-effective climate mitigation strategy capable of offsetting 1-3 tonnes CO_2e per cookstove per year; if implemented globally, they have the potential to reduce emissions by 1 Gigatonne CO_2e per year [24]. The Clean Cooking Alliance, a non-profit organization dedicated to promoting clean cooking in developing nations, aims to achieve universal access to clean cooking by 2030 (cleancooking.org). The Sustainable Development Goal (SDG) 7 is a specific indicator for clean cooking, as it aims to ensure universal access to affordable, reliable, sustainable, and modern energy, and overall, clean cooking can also positively impact 10 of the 17 SDGs (cleancooking.org).

Although improved cookstoves can significantly reduce emissions, the relative risk to exposure function is nonlinear [15], meaning that a reduction of 30-50% in $PM_{2.5}$ exposure does not equate to a 30-50% reduction in risk to the cook. Thus, improved cookstoves must achieve high levels of improved thermal efficiency or combustion efficiency to have any tangible health benefits, in terms of reduced diseases from exposure to household air pollution.

In efforts to promote these cleaner stoves and fuels to developing countries, previous researchers hypothesized that as households gain wealth and income, they would climb a "linear energy ladder"—that as households gained wealth and moved up the energy ladder, they would not only move closer to cleaner fuels, which are more expensive, cleaner, and more efficient, but also move away from dirtier fuels [25, 26]. In practice, households tend to adopt multiple fuel-stove combinations for different tasks (aka "stove stacking") [27, 26, 28, 29, 30]. Stove stacking is a result of the complex dynamic of a household's energy use, which stems from their needs, behavior, and culture [27, 31, 32]. For example, a household's choice of fuel and stove may depend on taste, season, cooking practices, income, speed, or fuel availability [29]. If we look in our own kitchens in the United States, we most likely own more than three cooking devices for specialized tasks (toaster, microwave, stove, oven, etc.). However, research has shown that if households do not dis-adopt their polluting traditional cookstoves in developing countries, the benefits of adopting the improved cookstove are largely negated [3].

Although tangible health benefits from improved biomass cookstoves may be less achievable, the reduced burden on women from less fuelwood collection time and labor, as well as shorter cooking times, should not be overlooked. Research has shown that the availability and use of improved biomass cookstoves can lead to less time needed for cooking and fuelwood collection [33, 4, 7, 34, 35]. Notably, Jagoe et al. [7] found that improvements in quantity and quality of time were achieved without the complete dis-adoption of traditional cookstoves. The reduced drudgery and time spent cooking and collecting fuelwood leaves more time available for educational and economic opportunities. However, more research is necessary to determine how time saved from cooking and fuelwood collection is utilized. For any benefits to be achieved, though, households must first adopt the improved cookstoves.

1.3 Knowledge Gaps

Improved cookstoves offer many benefits, but for decades, efforts to achieve significant and widespread impacts have largely failed [36]. Impact is only realized if the cookstoves are regularly used. Most improved cookstove programs have been unsuccessful at reaching desired levels of sustained adoption [37, 3, 38]. In general, programs have been 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 [39]. Often, programs have failed to design cookstoves for and with the user, and they may use unreliable methods to measure impact.

Traditionally, interviews (or surveys) with cookstove users have been used to measure usage and impact. Surveys can provide critical qualitative information such as user design preferences, household information, and insights into usage [40], but they can fail to accurately measure quantitative patterns, such as usage or fuelwood savings, especially over long periods. Research has shown that such interviews can inaccurately represent actual usage because households commonly over-report their usage [41, 42, 43, 44]. Over-reporting of intervention usage via surveys has also been shown for other interventions, such as water treatment [41]. There are different biases associated with interviews, such as recall bias, courtesy bias, and the Hawthorne effect [41, 42, 45]. If program implementors rely on only surveys to measure usage, they may greatly overestimate the impact of their cookstove.

Existing methodologies [46] used to verify carbon emission reductions from cookstoves projects on the carbon offset market do not require usage monitoring which may result in inaccurate estimations [47, 48, 49]. The minimum requirement for verification in carbon offset methodologies [46, 50] is to collect survey data on cookstove usage, allowing projects to claim up to 75% of continuous usage, potentially over-reporting emissions reductions significantly.

Since the late 2000s, temperature dataloggers that are used to measure stove use, termed "Stove use monitors" (SUMs), entered the scene of cookstove impact measurement [51, 52]. These sensors provide reliable, quantitative data of users' actual usage. Additionally, sensors provide better granularity than surveys and reduce the biases associated with surveys [42, 41]. Having objective sensor data on cookstove usage can inform project implementors about the adoption or dis-adoption of their improved cookstove, allowing the stakeholders to better understand and develop tools to achieve widespread, sustained adoption.

Despite previous mixed methods studies' findings, surveys are still widely used as a method to measure cookstove usage [53, 38, 54]. Moreover, among the previous studies that have monitored usage with sensors, most are for durations shorter than 2 months [55, 56, 41, 57, 58, 42, 43, 59]. To our knowledge, only a few studies report results from continuously monitoring usage for at least 6 months [60, 45, 44] and beyond that, only three studies that continuously monitored usage for at least 1 year [61, 3, 62]. 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 [29, 61, 63]). Reasons for cookstoves dis-adoption are rarely studied and poorly understood.

Moreover, required methods to validate carbon offsets for cookstoves projects also allow project implementors to use default emission factors [46], which can lead to inaccurate estimations of emission reductions [49, 48]. The emission factors and methodologies used to calculate emission reductions can result in different calculations of total carbon credits generated from a project [64, 47, 48]. This, in turn, has significant implications for the management of carbon trade-offs. However, directly measuring pollutant emissions in the field is often technically- and cost-prohibitive [65]. There are few studies that explore the improvement of field methods for carbon offsets verification [65, 59, 44, 66]. More research is needed to develop measurement methods that are accurate, feasible, and affordable.

1.4 This Dissertation

Prior research suggests that there are three key aspects important for the success of improved cookstoves projects. We must first design for and with the user, because cooking is deeply ingrained into people's daily lives. Second, we must use reliable methods to measure impact and usage over a long-term period; sensors are more reliable than questionnaires, usage may change over time, and it is important to not over-estimate the impact of our projects by using unreliable methods. And third, we must understand the reasons for adoption or dis-adoption, because understanding behavior is as important as improving the technology. This dissertation attempts to answer four main questions:

1. How do we adapt a successful, cost-effective cookstove from one region to another? (Chapter 2),

2. How should we measure cookstoves' adoption? (Chapters 3),

3. What are trends in long-term usage and why do households dis-adopt purchased cookstoves? (Chapter 4), and

4. How can we more accurately measure CO_2 emissions and fuelwood consumption from improved cookstove use in the field? (Chapter 5).

We focus our efforts on India, in the state of Maharashtra, where two-thirds of the rural population (about 10 million households) [67, 68] use fuelwood for cooking, with 24% of collected fuelwood unsustainably harvested [16].

In Chapter 2, "Adapting a Successful, Cost-effective Cookstove from Africa to India," I describe the design process to adjust a successful, cost-effective cookstove deployed in Africa, to rural India, where women face extreme drudgery from fuelwood collection. The Berkeley-Darfur Stove (BDS) has proven successful at reducing fuelwood consumption and emissions in Darfur and Uganda [69, 70]. Throughout the design adjustment process, we recognized the importance of adjusting the cookstove design to local cooking practices, and paid special attention to stove features shown to be valued by users [71, 39, 72]. We first quantified the severity of the local fuelwood collection hardship by accompanying women on fuelwood collection trips and conducting interviews with women to gather more data on local fuelwood collection. We adjusted the cookstove design by including the users in every step of the design modification process to develop the Berkeley-India Stove (BIS)—a modified version of the BDS. We did this through an iterative process of usage trials, focus group discussion, and minor design changes.

In Chapter 3, "Comparing Survey and Sensor Methods to Measure Long-term Improved Cookstoves Use," I summarize 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 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 their monthly income (termed "post-purchase study"). We examined the accuracy of surveys to serve as a tool to measure cookstove usage over longer periods. Unlike prior works, we provided meaningful insight into the behavior of users who purchased cookstoves at a significant price relative to their monthly income. 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. This chapter has been accepted for publishing in the Journal of Development Engineering [73].

In Chapter 4, "Exploring Usage Patterns and Reasons for Dis-adoption of a Purchased Improved Cookstove," I present the analysis of longitudinal patterns of usage from the post-purchase study presented in Chapter 3. We first analyzed sensor-recorded usage for patterns in initial use, long-term use, usage stabilization, and effects on usage from special events. We also attempted to answer the question of why households dis-adopted an improved cookstove after initial periods of high use—that which was purchased with a significant portion of their monthly income and whose design was adjusted after working closely with women in the region. There are few studies in the literature that quantify long-term dis-adoption with sensors [3, 61, 62] and even fewer studies that attempt to understand factors that lead to dis-adoption of usage [74, 75], especially over a long-term period. To our knowledge, there is no study that explores the dis-adoption of a purchased, improved biomass cookstove.

In Chapter 5, "Improving the Estimates of Cookstoves' Carbon Emissions by Combining Lab and Field Data," I present the results of lab experiments comparing the performance of the BIS to the most common baseline cookstove in the area, the mud chulha ("stove"). We demonstrated the importance of using cookstove-specific emission factors for estimations of emission reductions. Additionally, we also explored methods for estimating fuelwood usage and CO_2 emissions with temperature dataloggers, or SUMs, which are typically solely used to measure cookstove usage. We explored the relationship of the cookstove temperature to fuelwood usage and CO_2 emission by conducting tests of heating and boiling water at different firepowers (a metric used to measure the power of the cookstove) on the BIS. By combining field data (cookstove usage, reported tasks, temperature time series) and lab data (cookstove emission factors, fuelwood consumption, and temperature-fuelwood/CO_2 correlations), we can make more reliable estimates for total CO_2 emissions than existing carbon offset methodologies. Moreover, the methods presented are also potentially less technically- and cost-prohibitive than measuring emissions in field.

In summary, this research presents case studies and method analyses that highlight the importance of incorporating user-centered design techniques and sensor data in cookstove interventions. The studies conducted in rural Maharashtra, India, underscore the limitations of survey-based methods in accurately measuring cookstove usage and impact, and demonstrate that even with user-centered design techniques, sustained adoption of a purchased cookstove may not be achieved. Our findings herein highlight the critical importance of incorporating sensor data to provide a more comprehensive understanding of cookstove adoption and usage patterns over time. These results have significant implications for policymakers and stakeholders in the cookstove sector, emphasizing the need for more robust data collection methods to inform decision-making and program design. Ultimately, this work aims to contribute to the development of more effective and impactful cookstove interventions that can improve health, reduce emissions, and promote sustainable development.

Chapter 2

Adapting a Successful, Cost-effective Cookstove from Africa to India

2.1 Background and Motivation

The design of improved cookstoves often fail to meet the needs of the users [39, 71]. Incorporating user-centered design principles can help to address this issue. According to Norman's "Design of Everyday Things," a product must be designed with the user's needs in mind to be successful [76]. This means considering the user's context, tasks, and goals when designing the product. The"Diffusion of Innovation Theory" also stresses the importance of considering users' perceptions of innovations, including relative advantage, compatibility, trialability, observability, and complexity [77]. In the case of improved cookstoves, design should be compatible with local cooking practices and preferences, rather than requiring users to adapt their cooking habits. Research has shown that cookstove users value a range of attributes, such as fuel savings, taste, flexibility with fuel type, reduced emissions, quick cooking, ability to cook local food, compatibility with local cooking equipment, ease of maintenance, ability to be left unattended, aesthetics, affordability, safety, the ability to heat water, and portability [71]. A common misstep in previous improved cookstove studies has been to disseminate a cookstove that was incompatible with local cooking vessels or typical meals [39]. Incorporating user feedback and conducting user testing during the design process can help ensure that improved cookstoves meet the needs of users and are more likely to be adopted.

We first assessed the needs of households in rural Maharashtra by gathering information on local fuelwood scarcity, cooking practices, and current cookstoves. In the state of Maharashtra, two-thirds of the rural population—about 10 million households—use fuelwood for cooking [67, 68]. About 24% of collected fuelwood there is unsustainably harvested [16]. There exists a need in this region for technology solutions that alleviate the burden these women face. Improved cookstoves with large fuelwood efficiencies and emissions savings have the potential to reduce the drudgery faced by these women, and reduce their large exposure to harmful biomass smoke from cooking activities.

Figure 2.1: Berkeley-Darfur Stove (BDS) disseminated in Africa.

Initiatives to disseminate both improved biomass cookstoves that are energy-efficient, and also support for transition to cleaner cooking fuels, such as liquid petroleum gas (LPG), are widespread in India [30, 39]. However, these cookstove initiatives have failed to achieve sustained adoption [37, 3]. There was a widespread campaign that distributed 400,000 "Oorja" stoves—a gasification-type biomass stove—in 2006; a study in 2013 found only 9% of respondents (n = 445), were still using the stove, citing difficulties with fuel (pellets) accessibility and supply [78]. Separately, LPG remains the cleanest cooking fuel available in the Indian market and is encouraged via a national campaign (*Ujjwala*) by the Indian government to install LPG stoves in all households [37, 39]. In research covering LPG usage in six Indian states, only 4% of households that own LPG stoves use it as their sole cooking fuel [37]. The expansion and sustained adoption of LPG stoves face major barriers in rural areas, such as affordability for refilling, price volatility, dislike for taste of staple dishes cooked with it, safety concerns, accessibility, and lack of follow-up [37]. Despite the LPG initiatives, there still exists a need for improved cookstoves using biomass with high efficiency, in rural areas.

We presumed that an adapted version of the Berkeley-Darfur Stove (BDS), shown in Figure 2.1, could be a potential solution for this region. We chose the BDS as a starting design to adapt to rural Maharashtra because of its fuel-efficiency, its success in regions of extreme fuelwood scarcity in Africa, and our familiarity with its design development at Lawrence Berkeley National Laboratory (LBNL). The BDS was invented by researchers at LBNL and University of California, Berkeley in 2005. It was initially designed for use in

Darfur during a humanitarian crisis, where women faced hardship and danger from fuelwood collection [79]. By 2016, over 40,000 BDS's were disseminated in refugee camps there [70]. To date, a total of 61,000 cookstoves have been distributed in sub-Saharan Africa and Asia, reducing global carbon emissions by 1 million tons of CO_2e (PotentialEnergy.org).

The BDS has been shown to reduce fuelwood usage by ∼35% and $PM_{2.5}$ emissions by ∼50% compared to a three-stone fire, which is the baseline stove in Darfur [23, 80, 81]. The BDS achieves these reductions by improving the thermal efficiency with a metal combustion chamber for better insulation and mixing, a raised grate for improved airflow and a tapered collar (or "pot skirt") for directing heat towards the pot [81]. Due to its large fuelwood savings, the BDS has the potential to reduce the burden and hardship of the women in rural Maharashtra where fuelwood use for cooking is widespread. Moreover, at a price of $23 and a thermal efficiency of 36%, [23], the BDS is one of the best available cookstoves in the Indian market for its performance to price ratio [23, 82].

Leveraging existing partnerships between the Gadgil Lab and local organizations in Maharashtra, we adapted the BDS design—based on user-feedback and cultural appropriateness—to Maharashtra. In this chapter, I explain the process of adapting the BDS design to local cooking practices by prioritizing user-centered design methods. We involved the users in every step of the process. We followed the user-centered design approaches used in the BDS project in Darfur [83, 79] and another successful cookstove project, the Patsari Stove Project, in Mexico [84]. They involved local researchers, community members, and women from the areas in the development, testing, and approval of the cookstoves. Our approach involved the quantification of the severity local fuelwood collection hardship, interviews with female primary cooks who owned a previously disseminated non-adapted BDS design, and an iterative design process making minor design modification to the BDS with user-input. We also studied local cooking practices and existing cooking devices' purposes in the households.

2.2 Design and Methods

Overview

All field work involving human subjects was approved by UC Berkeley's Institutional Review Board (CPHS# 2017-07-10101). We worked closely with two key partners, the Centre for Technology Alternatives for Rural Areas at the Indian Institute of Technology, Bombay (IITB CTARA), and the NGO, Light of Life Trust (LOLT) in adapting the BDS to rural Maharashtra. We began with observing three fuelwood collection trips and conducting 40 1-on-1 interviews with women in local villages before the design process in November-end and December 2018. Subsequently, we individually interviewed 36 different households who owned a non-adapted version of the BDS in early January 2019. Finally, we conducted an iterative design modification process with 30 still different households in January and February 2019. These 30 new households were in areas that had never seen the previously non-adapted BDS version before. Staff members from IITB CTARA and LOLT accompanied me on all fieldwork and provided translations for all interviews and focus group discussion into the local language of Marathi.

Fuelwood Collection Observation and Interviews

To quantify the severity of local fuelwood collection hardship we went on observation trips (n = 3) in three different villages and conducted interviews (n = 40) with women in these villages in November-end and December 2018 (see Appendix A). We identified two rural areas, Raigad District and Thane District, where IITB CTARA and LOLT had existing presences in the communities and where fuelwood scarcity and collection were reportedly major challenges for women. On the fuelwood collection trips, we measured total time the trips took, total distance walked, and the average weight and moisture content of the collected woodpiles per women—which are notably carried on their heads (see Figure 2.4). We also conducted 40 interviews with women living in local villages, with questions regarding who participates in fuelwood collection, the frequency, seasons, distance, and time.

Berkeley-Darfur Stove Interviews

We conducted 36 interviews on a version of the BDS (Figure 2.2) that was given to over 100 households for free in mid-2016 by an outside NGO (see Appendix A). The interviews were conducted in January 2019, so about 2-3 years into the interviewees' BDS ownership. This version of the BDS had the same pot-rod design (three rods) as the original BDS design, built for the round-bottom Darfuri pot. The outer, orange mesh layer was a new feature meant for protecting users from burning themselves touching the hot cookstove. This BDS design was not adapted to local cooking practices. This presented a unique opportunity for us to gather local feedback on the non-adapted BDS design. We asked households questions about BDS design features, reported advantages and difficulties, reported uses, and other baseline household attributes (cookstove ownership, household size, etc.).

Design Iteration Process

We carried out an iterative design modification process to develop the Berkeley-India Stove (BIS) based on user-feedback and cultural appropriateness, which had three main components: 1) usage trials, 2) user feedback, and 3) minor design changes. We iterated through this process twice, with two minor design changes. The minor design changes are discussed in the Berkeley-India Stove Design Iteration section below. The usage trials consisted of 5- to 10-day trial periods of 30 households. We rotated ten test cookstoves between households for these trials. For the user feedback step, we conducted 30 1-on-1 interviews and six focus group discussions, consisting of five to eight women each, after their usage trials. In our interviews and focus group discussion we asked questions on 12 stove design aspects. The households that participated in this design iteration process were from different villages than those mentioned in the Berkeley-Darfur Stove Interviews section.

Figure 2.2: Berkeley-Darfur Stove version with outer orange mesh layer and inner-grate. Originally disseminated in rural Maharashtra in 2016.

2.3 Results and Discussion

Quantification of Local Fuelwood Collection

In the fuelwood collection observation trips (n = 3), the average time of a fuelwood collection trip was 3.3 h, the average total distance walked was 3.5 km, and the average dry weight of the collected woodpiles (n = 14) was 33 kg (SD = 5.4 kg). Figure 2.3 shows the tracked path of one of the fuelwood collection trips (shown on Google Earth). Figure 2.4 shows a picture of women carrying fuelwood on their heads on the fuelwood collection trip. The average group size of the fuelwood collection trips was about 5 women.

In the one-on-one interviews, women (n = 40) reported making fuelwood collection trips like this at least once per day in the non-rainy season (October – May). Women estimated that their average time per typical trip was 6.5 h (SD = 1.1). Women described different areas where they switch to collect fuelwood for various reasons, which may explain the variations in fuelwood collection times between the observed and reported times. Moreover, it may be difficult for women to estimate an average fuelwood collection time. Given the average time and physical labor of fuelwood collection in this region, we presumed that the BDS' fuelwood savings could significantly reduce the burden on the women in these two Districts, if the design could be successfully adapted to suit their needs.

Figure 2.3: Fuelwood collection path for one observed trip on December 5, 2018. Distance to collection area was 2-2.5 km, total distance was 4.7 km, and total time was 3 h 50 min, starting at 9:40am.

Berkeley-Darfur Stove Feedback

For the households (n = 36) that we interviewed who already owned the BDS (Figure 2.2), the average number of household members was 6.3 (SD = 2.5). Among these households, about 78% of households owned LPG stoves, 53% owned three-pot mud chulhas, 47% owned two-pot mud chulhas, 6% owned kerosene stoves, 6% owned forced-draft stoves, and 3% owned electric stoves. Most households owned more than one cookstove, thus the percentages add up to more than 100%. The average years of LPG stove ownership was 3.4 years (SD = 4.9). Mud chulhas are the traditional baseline stove used by households in rural India. Some mud chulhas can hold either one, two, or three pots (i.e., similar to having multiple burners on a gas or electric stove) and are referred to as single-pot, two-pot, three-pot, respectively.

We also asked households how often they used the BDS, although we know that reported usage can be inaccurate and often over-reported [42, 41]. We further discuss survey inaccuracy in Chapter 3. We categorized households' responses into five categories: special

Figure 2.4: Picture of women carrying fuelwood on their heads on that fuelwood collection trip.

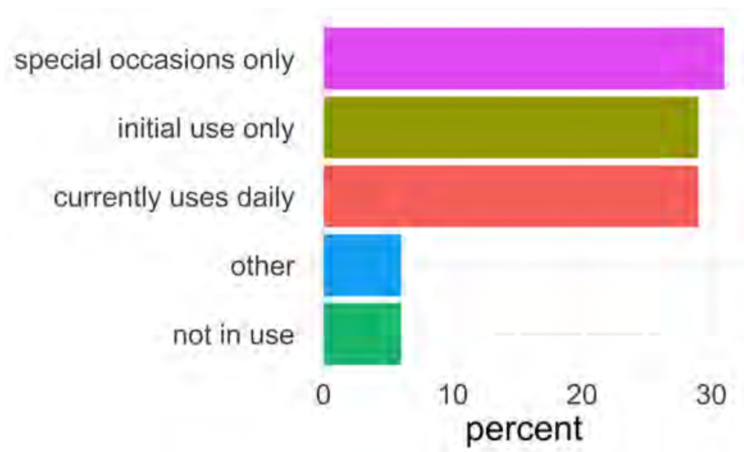

Figure 2.5: Reported frequency of BDS usage (n = 36).

occasions only, currently uses daily, initial use and then stopped, stove is not in use, and other (see Figure 2.5). About 31% of households reported using the BDS for special occasions only, 29% reported that they currently used the BDS daily, and 29% reported that they initially used the cookstove for less than two weeks and then stopped using it. We asked households what they used the BDS for, and 68% reported using it for food, 64% reported using it for bathwater heating, and 32% reported using it for tea; some households reported using it for more than one task (thus, percentages add up to more than 100%).

Table 2.1: Reported difficulties of BDS owners (n = 36).

Reported difficulties	
Fuel preparation	45%
Different sized pots don't fit	27%
No multi-pots	24%
Tawa doesn't fit	15%
Complicated to operate	9%
Stability	3%
Size	0%
Other	0%
Aesthetically displeasing	0%
Difficult to add fuel	0%

Table 2.2: Reported advantages of BDS owners (n = 36).

Reported advantages	
Saving fuel	82%
Quick cooking	26%
Less smoke	24%
Portability	18%
Other	12%
Size	3%
Saving time	0%
Aesthetic appeal	0%

In Table 2.1 and Table 2.2, the reported advantages and difficulties are listed in decreasing order. About 36% of all the households reported having no difficulties with the BDS. Among those households, 38% of them reported using it daily. The most reported difficulty of using the BDS was fuel preparation, referring to the requirement of chopping the wood into small pieces to fit inside the BDS's fuelwood opening. The next top reported difficulty was that different cooking vessels were unable to fit the BDS design. The BDS was originally designed to fit a one-sized, round-bottom Darfuri pot. However, households in rural Maharashtra owned many different-sized flat-bottom pots, depending on the cooking task. Households also reported that the BDS could not fit multiple pots at once (referred to as "no multi-pot" in the table), and it could also not fit a *tawa*—a flat plate for cooking *roti* (a type of bread), which is a staple food in the region. Among the households that owned LPG stoves, about 68% of households reported that they only used their LPG stoves for making tea to conserve fuel, since it was considered expensive and not easy to access. Households also reported that they did not prefer to make *roti* with the LPG stoves due to the difference in taste; they preferred to use the fuelwood flames from their chulhas to make it. Taste is commonly reported issue with LPG stoves [85]. Households reported that they preferred their mud chulha to make *roti* compared to the LPG stoves due to the mud chulha's fuelwood flames.

About 25% of households reported quick cooking and less smoke as advantages of the BDS. Additionally, about 18% of households reported portability as an advantage of the BDS. This was a distinguishing feature from the mud chulha, as mud chulhas are built into the a particular place of the kitchen and unmovable. About 82% of households reported saving fuel. This finding confirmed that the BDS could be of interest in the region for its fuelwood savings. We found that there were a lack of improved biomass cookstove options in the region, and that LPG stoves were minimally used.

Berkeley-India Stove Design Iteration

As mentioned in Design Iteration Process section, the BIS design iteration process consistent of three main components: 1) usage trials, 2) user feedback, and 3) minor design changes. Throughout this design adjustment process, we recognized the importance of adjusting the cookstove design to local cooking practices [39] and paid special attention to stove features (fuel savings, taste, flexibility with fuel type, reduced emissions, quick cooking, ability to cook local food, compatibility with local cooking equipment, ease of maintenance, ability to be left unattended, aesthetics, affordability, safety, the ability to heat water, and portability) shown to be valued by users [71, 72]. 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) would not significantly reduce the stoves' energy efficiency. We did not want to increase the cost of the BDS because we later planned to sell the cookstoves to households, rather than give them away for free (discussed more in Chapter 3).

Among the households (n = 30) that participated in this design iteration process, the average number of households members was 5.8 (SD = 2). About 64% of households owned LPG stoves, 30% owned three-pot mud chulhas, 33% owned two-pot mud chulhas, and 14% owned three-stone fires. The average years of LPG stove ownership was 3.4 years (SD = 4.9). We asked households about who had the purchasing power of the household, 62% said the male head of household only, 25% said both female and male head of households did regardless of who earns the money, and 13% said it depends on who makes the money. The average reported fuelwood collection trips per day was 1.7 trips per day (SD = 0.5) and time per trip was 4h per trip (SD = 1.2). The average months per year of fuelwood collection was 7.6 months (SD = 1.1), which is typically October – May, the non-rainy season.

Based on feedback from the interviews of households who already owned the BDS, presented in the Berkeley-Darfur Stove Feedback section, we first adjusted the original BDS design to accommodate different-sized flat-bottom pots. We did this by changing the pot-rod design inside the cookstove (see Figure 2.6) from three rods in a triangle, flat form in

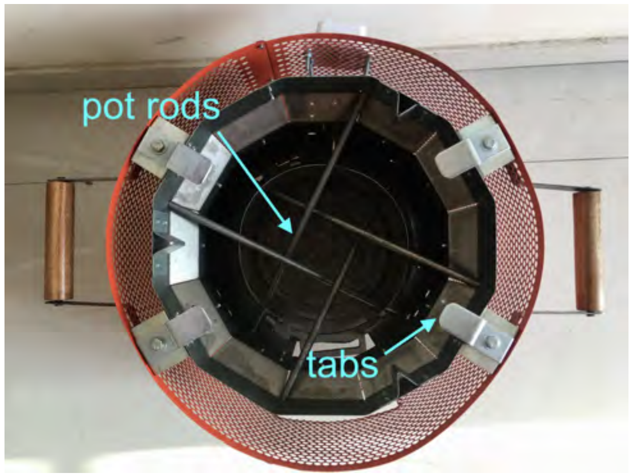

Figure 2.6: Top-view of Berkeley-India Stove (final version/version 2).

Figure 2.7: Side-view of Berkeley-India Stove (final version/version 2) in use in a household in rural Maharashtra.

the BDS to four rods in an angled, crossed form in the BIS version 1. This design allows for flat-bottom pots (as well as round-bottom pots) to sit on the rods unlike the previous BDS design. Additionally, because of the angled rods, different sizes can fit easily. A pot with a smaller diameter will sit lower (i.e., closer to the fire) than a pot with a larger diameter. We hypothesized that this design change would not have a large impact on the fuel efficiency of the BDS, since it did not change the firebox structure, although it changed the clearance (air-gap) around the pot and the stove's skirt, which would affect the efficiency to some extent. This point is later discussed in Chapter 5.

Figure 2.8: Focus group discussion; photo taken by LOLT staff member.

We conducted usage trials for of 5-10 periods with 30 households with this BIS-version 1. We measured the usage with temperature dataloggers (Geocene sensors) attached to the cookstove (Chapter 3 goes into more detail about the use of the sensors to measure usage). Figure 2.9 shows the average cooking events per day for the trial periods (cut off at 9 days) and Figure 2.10 shows the distribution of households' average cooking events per day. There were six households that never used the cookstove; these households reported running out of time to try to the cookstove during their trial period. We paid close attention to the households' feedback that used the cookstove at least once to better understand which design features were causing difficulties.

After the retrieval of the cookstoves, we also conducted one-on-one interviews and focus group discussions (groups of 5-8 women, Figure 2.8) with the women who participated in the trials. We asked households about 12 design features: weight, vessels fit, taste, stove stability, stove portability, stove height, smoke, single pot ability, fuelwood opening size, cooking time, color, and burns. The responses (n = 30) can be seen in Figure 2.11, categorized into negative (red) or positive (blue) feedback. Women had favorable feedback on the taste, stability, portability, emissions, and cooking time—known issues with other cookstove designs. Women also had favorable feedback on different pot sizes fitting with this BIS version. However, women still reported issues of stove compatibility with the *tawa*. Based on the feedback on BIS-version 1, we added tabs (see Figure 2.7) to the top of the cookstove to accommodate *tawas*, creating BIS-version 2. We considered this adjustment critical because *roti* (made with *tawas*) is a staple dish in rural Maharashtra and women wanted to be able to use the BIS for it. Moreover, households reported not being able to use their LPG stove for *roti*

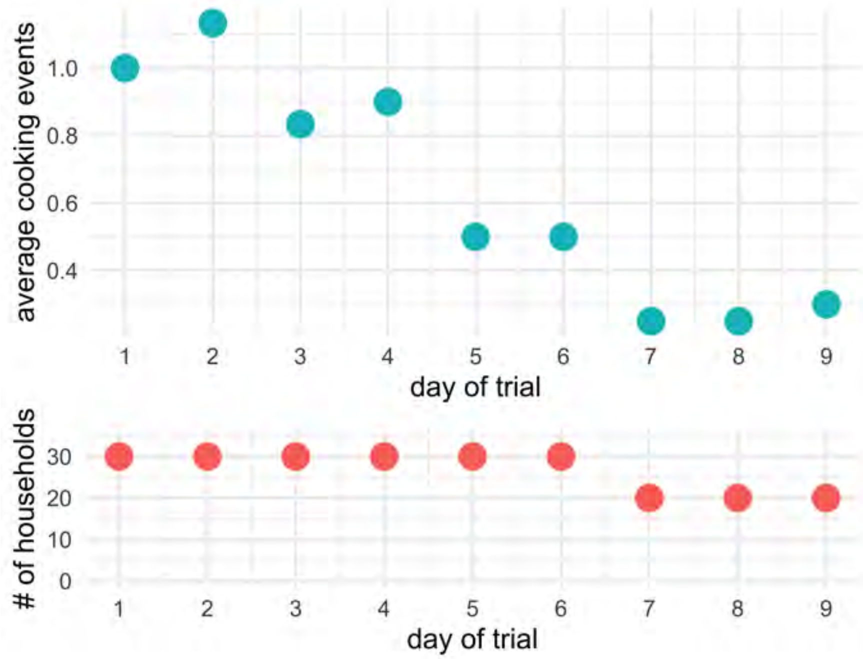

Figure 2.9: Average cooking events per day of trial (cut off at 9 days) for 30 households shown in blue (upper panel) and the number of households monitored per day shown in red (bottom panel).

either. The effects of the design changes we made to the BDS are explored in Chapter 5. The focus group discussions provided similar feedback to the one-on-one interviews, but also allowed us to show new design options to women and gather their feedback on which options to further explore.

With the BIS-version 2, we repeated the process of usage trials, interviews, and FGDs. Women gave favorable feedback on the new design adjustment of adding tabs. However, two commonly reported issues from both sets of interviews and that we were unable to address included: 1) the BIS' inability to hold more than one pot, which most mud chulhas could accommodate, and 2) the smaller fuelwood opening size (28% smaller in area), requiring women to chop their fuelwood into smaller pieces. For the former issue, we recommended the use of multiple BIS side-by-side for women that preferred a larger cooking area; making a single cookstove with a larger surface area was outside the scope of this research project as it would have required a complete redesign. To address the latter issue, we recommend an educational approach, as making the fuelwood opening larger would allow for over-loading of fuelwood, compromising the fuel-efficiency of the cookstove. The BIS-version 2 was the final BIS design. About 70% of households expressed interest in purchasing the cookstove after we made the design changes.

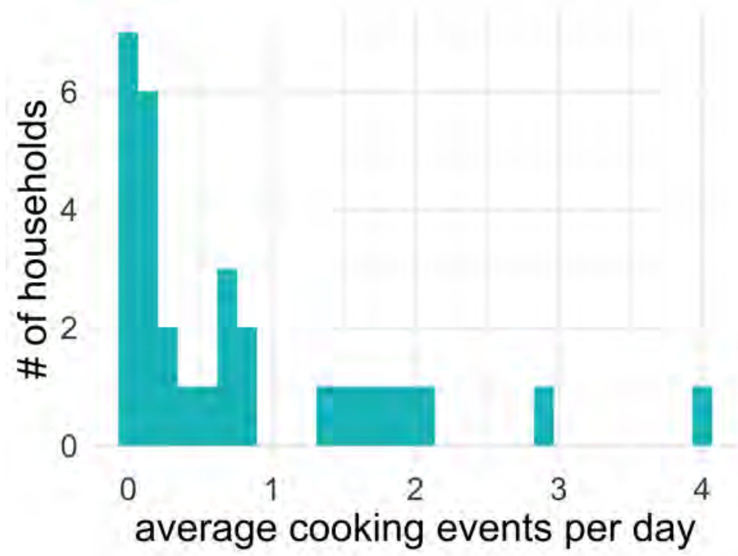

Figure 2.10: Distribution of households' average cooking events per day for their trial period.

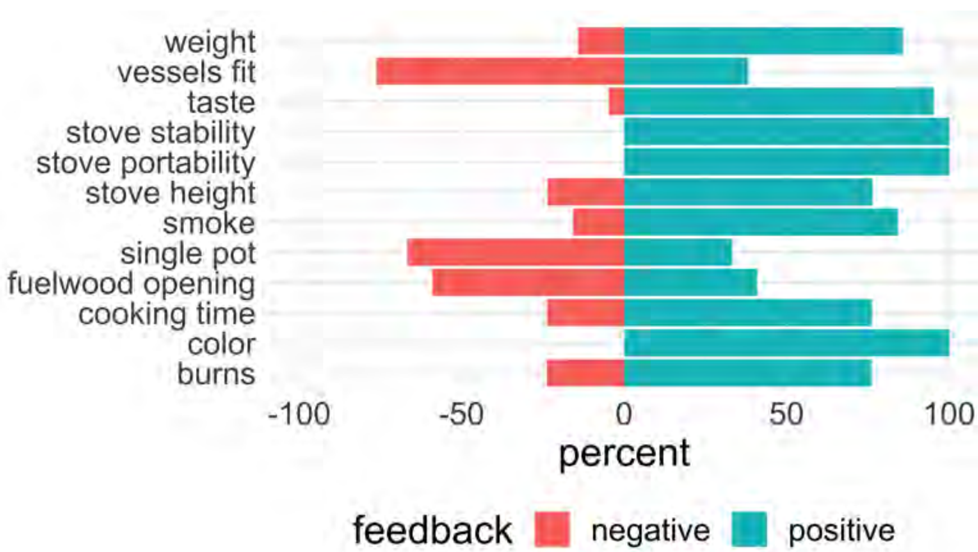

Figure 2.11: Feedback on BIS-version 1 from 1-on-1 interviews (n = 30).

2.4 Concluding Remarks

Fuelwood collection primarily falls on women in rural Maharashtra. We first quantified the severity of the local fuelwood collection hardship by interviewing women and by accompanying women on three fuelwood collection trips. We found that the average time of a fuelwood collection trip was 3-6 h, and women collect fuelwood 1-2 times per day for about 8 months per year. These findings confirmed how arduous fuelwood collection is and the potential time and labor the BDS' fuelwood savings could offer them.

We had a unique opportunity to interview households that owned a BDS design unadapted to the region and we found that the BDS was incompatible with local cooking vessels. Our subsequent design iterative process allowed us to identify that the BIS was still incompatible with *tawas* which are used to make a staple local dish, *roti*. We found this issue to be critical since *roti* is a daily dish in most households in this region, and women wanted to be able to use the BIS for roti. This design process highlighted the importance of adjusting cookstove designs to fit local cooking vessels. Failure to adjust cookstoves to a variety of local cooking vessels has been found to be a common misstep in previous improved cookstoves studies [39]. Unfortunately, we were unable to address reported issues of the fuelwood size opening to not reduce the cookstove's fuel efficiency. Moreover, we could not address the BIS's multi-pot incompatibility as this would require a complete re-design. Although, we were unable to address these issues, most women that participated in the design iterative process, expressed interest in purchasing the BIS at the end of the process. In Chapters 3 and 4, we describe pilot studies that measured the usage of the BIS.

Chapter 3

Comparing Survey and Sensor Methods to Measure Long-term Improved Cookstoves' Use

3.1 Background and Motivation

Cookstove programs commonly rely on inadequate and short-term methods to assess their impact. Although previous research has shown that using sensors as a method to measure cookstove usage eliminates the different biases associated with traditional method of surveys, where over-reporting can be common [41, 42, 43, 44, 86], surveys are still widely used to measure usage. Moreover, the current methodologies utilized to verify the carbon emission reductions achieved by cookstove projects on the carbon offset market do not mandate emissions testing or usage monitoring. As a consequence, these methodologies may produce unreliable estimations, as evidenced by previous research [47, 48, 49].

In a systematic review examining the factors that influence cookstove adoption in 32 improved cookstoves studies, none of the studies used sensors [53]. 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 [54]. Similarly, another review also examined behavior change strategies used in cookstove adoption studies, in which five out of the 18 studies used sensors [38].

Most monitoring studies that utilize sensors have been for durations of less than 2 months [55, 56, 41, 57, 58, 42, 43, 59]. There are a few studies that continuously monitored usage for at least 6 months, to our knowledge [60, 45, 44]. We know of only three studies that continuously monitored usage for at least 1 year [61, 3, 62]. Of these longer studies, Pillarisetti et al. [3] and Carrion et al. [61] 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. [62] 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. Without the use of long-term and reliable methods, studies may fail to capture dis-adoption (also called disadoption or discontinuance in some literature [29, 61, 63]).

This chapter 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"). A modified version of this chapter has previously been published in the Journal of Development Engineering [73].

Our research provides meaningful insight into the behavior of users who purchased cookstoves at a significant price relative to their monthly income. Ramanathan et al. [44] 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 that compares sensor- and survey-recorded usage [62]; 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 chapter, we define dis-adoption as the disuse of the improved cookstove, like Carrión et al. [61]. 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. These usage patterns are further explored in Chapter 4. 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.

3.2 Design and Methods

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 (see the Survey Collection section), we interviewed the female primary cook (above age 18) of each household. For stove-use monitoring (see Stove Use Monitoring section), 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 Improved Cookstove section) 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 [22]. 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 (∼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.

Improved Cookstove

The BIS, which was derived from the Berkeley-Darfur Stove (BDS), is shown in Figure 3.1 and Figure 3.2. The design adjustment process is described in Chapter 2. As previously mentioned, the BDS has been shown to reduce fuelwood usage by ∼35% and $PM_{2.5}$ emissions by ∼50% compared to a three-stone fire [23, 80, 81]. Thus, we hypothesized that women in rural Maharashtra, where fuelwood collection is widespread, would adopt the BIS to reduce the drudgery of fuelwood collection (see Figure 3.3).

Figure 3.1: Side view of BIS with Geocene sensor, the white box, attached to outer wall.

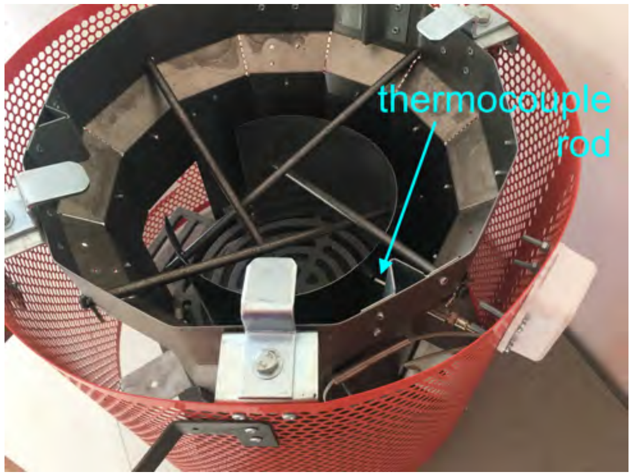

Figure 3.2: Top view of BIS showing a steel tube (shown by the yellow arrow) holding the thermocouple touching the firebox wall.

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 chapter can be found in Appendix B.

Figure 3.3: Women carrying fuelwood on their heads during a fuelwood collection trip near Raigad District, Maharashtra, March 2019.

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, there were an additional 89 households that purchased the cookstove, but we did not monitor their use owing to limitation on number of sensors. For the sake of completeness, we describe where these 89 households came from. Some of these 89 households were within the same communities that had monitored cookstoves, but some of these 89 households were in neighboring communities, which did not participate in our monitoring programs. This chapter focuses on the monitored households.

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 the Binary Question Format section).

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. [42] and Ruiz-Mercado [87]. 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. Staff members from IITB CTARA and LOLT accompanied me on all fieldwork and provided translations for all interviews into Marathi. 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.

Stove Use Monitoring

We used temperature dataloggers, Geocene Dot sensors [88], 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 3.1) 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 3.2, and recorded the temperature of the inside firebox every 5 minutes. The temperature of the cookstove firebox is a well-established proxy for usage [87]. 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, and 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 et al. [88] 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.

3.3 Results

Survey Usage Questions

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 3.1 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 3.2 and Table 3.3 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

Table 3.1: Results of sensor-recorded usage versus survey-recorded usage for binary question: "Have you used the BIS at least once within the last week? Trial data, n = 120.

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

Table 3.2: Results of sensor-recorded usage versus survey-recorded usage for binary question: "Have you used the BIS at least once within the last month?" Follow-up 1, n = 75

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

Table 3.3: Results of sensor-recorded usage versus survey-recorded usage for binary question: "Have you used the BIS at least once within the last month?" Follow-up 2, n = 69

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

than users, and 23% of households' responses did not match their sensor-recorded usage. Table 3.4 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.

Table 3.4: Results of sensor-recorded usage versus survey-recorded usage for binary question: "Have you used the BIS at least once within the last year?" Follow-up 2, n = 69

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

Quantitative Question Format

The research team asked 88 households in the free-trial study (average monitoring period: 10 d, 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 3.4 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 3.4 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: 468 d, 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 3.5 and Figure 3.6 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).

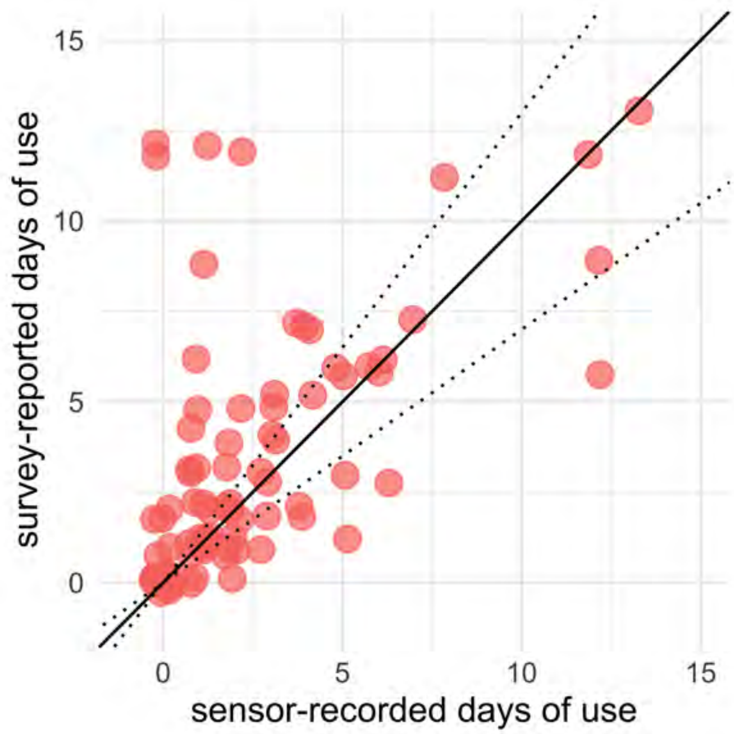

Figure 3.4: Survey-reported vs. sensor-recorded usage for households in the trial (n = 88).The solid 1:1 line represents where survey-reported usage equals sensor-recorded usage. The dotted lines are ±30% of the solid lines. Each red point represents a household. Points are"jittered" to avoid overplotting.

We ran a linear regression of survey-reported use versus sensor-recorded use for each plot (Figure 3.4, Figure 3.5, Figure 3.6). For the free-trial study in Figure 3.4, 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 3.5), 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 3.6), 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

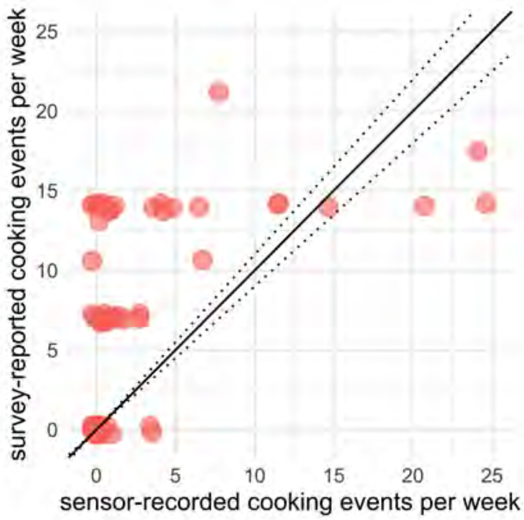

Figure 3.5: Survey-reported vs. sensor-recorded usage for households in Follow-up 1 (n = 75). The solid 1:1 line represents where survey-reported usage equals sensor-recorded usage. The dotted lines are ±10% of the solid lines. Each red point represents a household. Points are "jittered" to avoid overplotting.

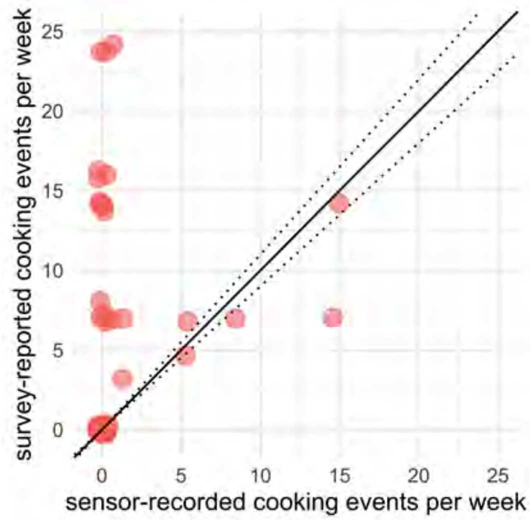

Figure 3.6: Survey-reported vs. sensor-recorded usage for households in Follow-up 2 (n = 69). The solid 1:1 line represents where survey-reported usage equals sensor-recorded usage. The dotted lines are ±10% of the solid lines. Each red point represents a household. Points are "jittered" to avoid overplotting.

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.

Long-term Decline in Sensor-recorded Usage

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 is presented in Chapter 4. The number of cooking events, averaged across all households per week after purchase, is shown in Figure 3.7 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 (Quantitative Question Format section) and plotted their response on the week after purchase that they were interviewed. The lower panel of Figure 3.7 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

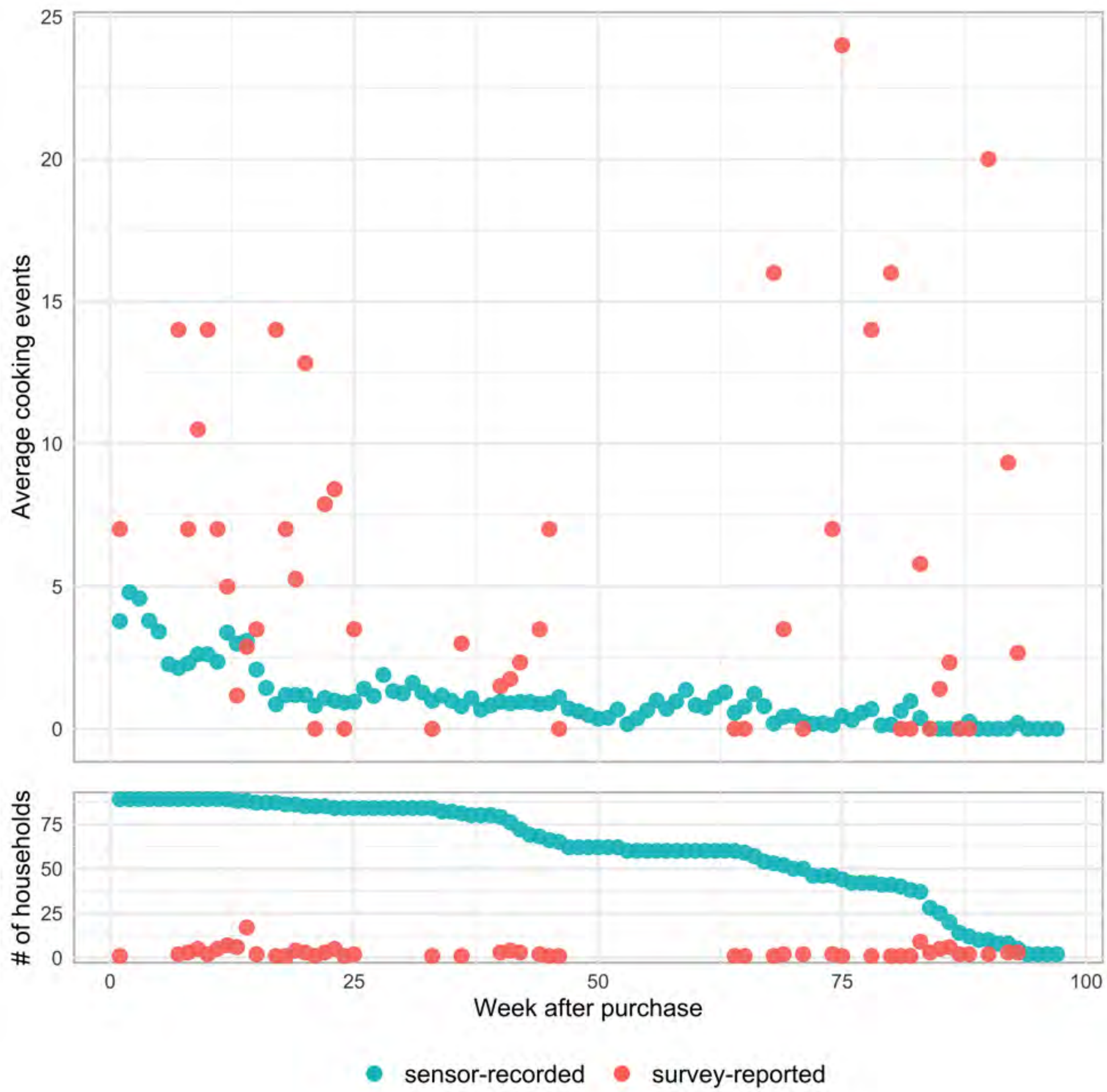

Figure 3.7: Upper panel: Average cooking events per week after purchase across all households in the post-purchase study for sensor-recorded usage (blue) and survey-reported usage (red). Lower panel: Number of households whose cookstoves were monitored on the week after purchase (blue) and number of households interviewed on that week after purchase (red).

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.

Distribution of Responses

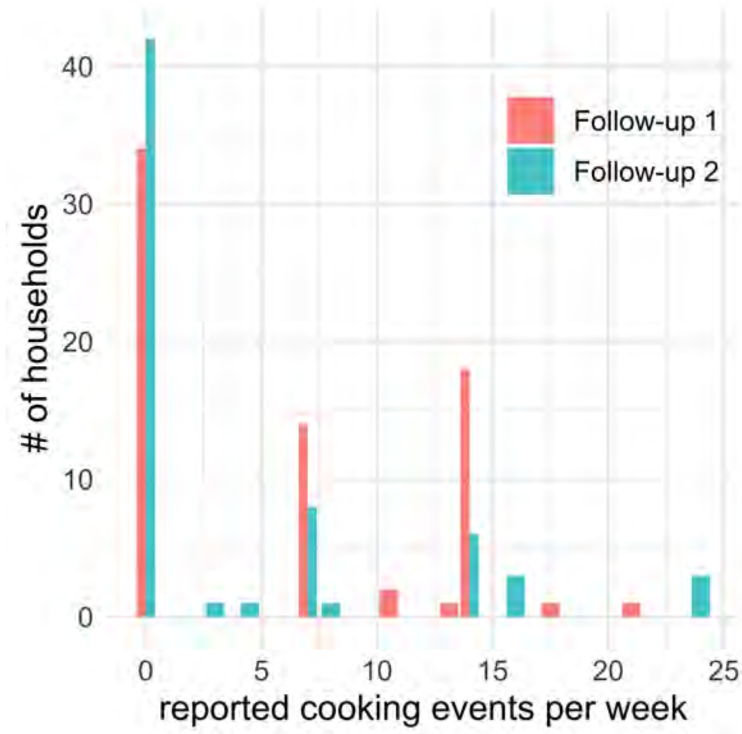

Figure 3.8: Distribution of household's responses to the question: "What is the average number of times per week that you have used the BIS in the last month?" in red for Follow-up 1 (n = 75) and blue for Follow-up 2 (n = 69).

We discovered that households were reporting nominal values of usage in the post-purchase study for the quantitative usage question (Quantitative Question Format section), 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 3.8 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.

Weekly Usage of Accurate and Inaccurate Reporters

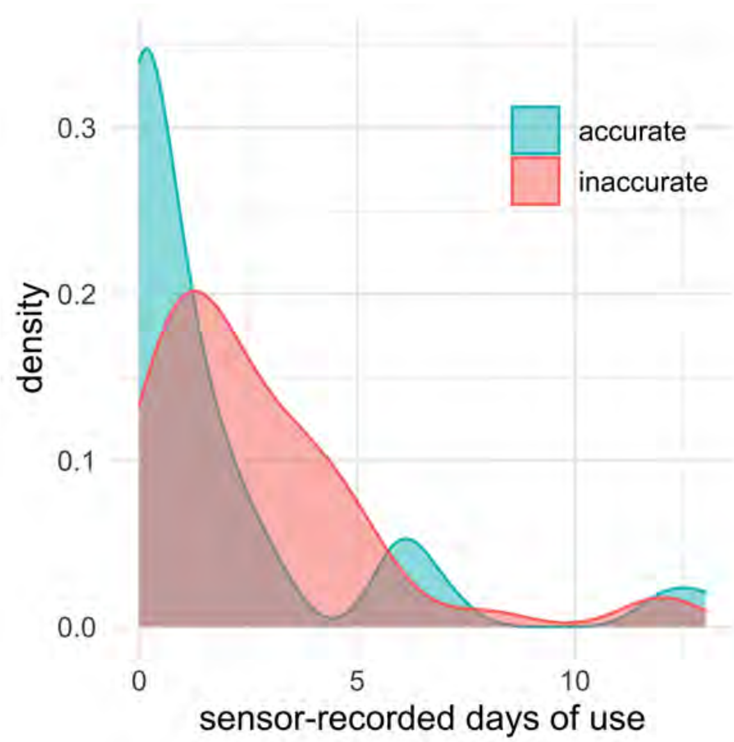

Figure 3.9: Density plots of Free Trial (n = 88) households' sensor-recorded average cooking events per week, separated by accurate (defined as survey data agreeing within ±30% of sensor data) reporters (blue) and inaccurate reporters (pink). Density plots integrate to 1; smooth curves are generated to fit the data and guide the eye better.

We compared the distributions of households' average weekly usage between the accurate and inaccurate reporters, for the free-trial study shown in Figure 3.9 and for the post-purchase study shown in Figure 3.10 (see Appendix B to see Figure 3.10 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 Quantitative Question Format section). 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.

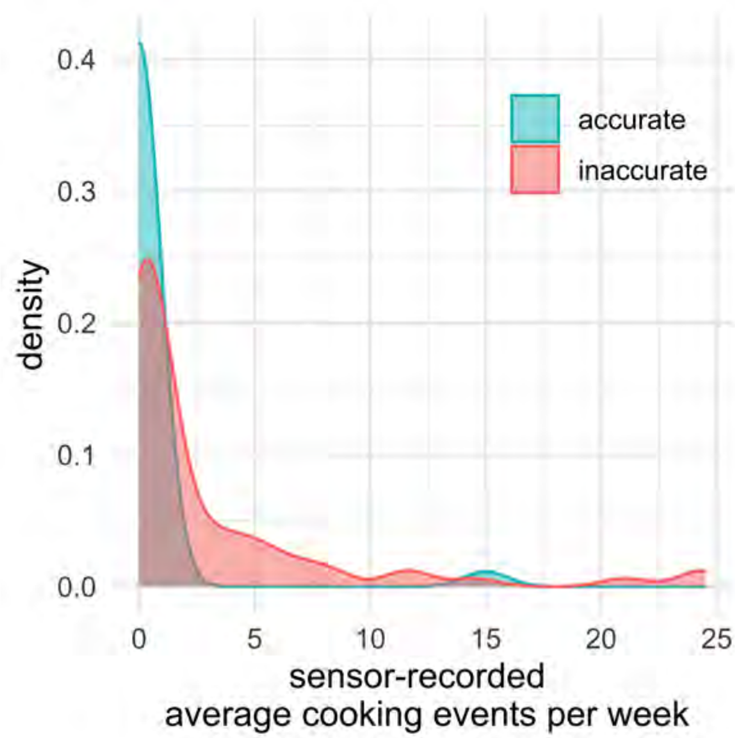

Figure 3.10: Density plots of post-purchase households' sensor-recorded average cooking events per week, separated by accurate (defined as survey data agreeing within ±10% of sensor data) reporters (blue) and inaccurate reporters (pink). Density plots integrate to 1; smooth curves are generated to fit the data and guide the eye better. Combined responses for Follow-up 1 & Follow-up 2 combined (n = 144).

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.

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%).

Household Qualitative Responses

Table 3.5: 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).

		Percent of total interviewed households that:			
Reported advantage	Follow-up survey #	Reported the advantage	Reported the advantage and reported using the stove	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)	41%	11%	9%	5%
	2 (n = 69)	14%	23%	9%	32%

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 3.5 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.

3.4 Discussion

Similar to other studies [41, 42], households over-reported improved cookstove usage. We found that over-reporting was common in both the free-trial study (average length: 10 days, SD = 4.5) and the post-purchase study (average length: 468 days, SD = 153), 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 [87, 41, 42, 62] 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. [62] 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 the findings in Piedrahita et al. [62] 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 Chapter 4, where we provide the longitudinal analysis of the sensor data, we 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 [87, 41, 62, 42, 43, 44] 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.

Chapter 4

Exploring Usage Patterns and Reasons for Dis-adoption of a Purchased Improved Cookstove

4.1 Background and Motivation

Efforts to promote improved biomass cookstoves and cleaner fuels like LPG in India have not been successful in converting most households away from the mud chulha due to barriers like affordability, accessibility, and cultural preferences [37, 39, 78]. Additionally, households often use multiple stove-fuel combinations depending on their needs and preferences, a phenomenon known as ”stove stacking” [61, 62, 27, 26, 28, 29].

Ruiz-Mercado and Masera [27] present the idea that improved cookstoves should be designed to be task-specific, as displacing the traditional cookstove with a single improved cookstove for all tasks remains impractical. Studies from Mexico, Botswana, India, Thailand, China, found have found that even when modern fuels are widely available, fuelwood is used to prepare traditional dishes [26, 25, 89, 90, 91]. Gould and Urpelainen [37] report that LPG was primarily used to prepare tea and snacks and Piedrahita et al. [62] found that the improved biomass cookstoves were reported to be superior for making some dishes but not others.

As we outline in Chapter 3, it is important that we measure cookstove usage with sensors to accurately capture dis-adoption quantitatively as well use surveys to understand specific reasons for why households dis-adopted the cookstove. Sensors provide accurate, quantitative measurement of cookstove usage [88], while surveys provide insights into reasons for adoption or dis-adoption [40, 74, 75]. This chapter summarizes the results of the post-purchase study described in Chapter 3, which occurred in the Indian state of Maharashtra between February 2019 and March 2021. We monitored 91 households' cookstove usage of the Berkeley-India Stove (BIS, see the Improved Cookstove section for description) for an average of 468 days (SD = 153). Households purchased the BIS for a subsidized price at roughly one-third of their average monthly income.

In Chapter 3, we report that surveys failed to capture the long-term dis-adoption of improved biomass cookstoves, while sensors did capture it. Here, we present an in-depth analysis in usage trends between households and attempt to develop hypotheses about why the cookstove was dis-adopted. We first present our analyses of sensor-recorded usage for patterns in initial use, long-term use, intermittent use, and effects of different events on use. We present results in support of a recommendation that researchers need to be aware of a minimum monitoring-period to capture dis-adoption. Secondly, we present our analyses of the survey data, linked to the sensor-recorded usage, to hypothesize reasons for dis-adoption. We also explore the role that stove stacking plays in dis-adoption, and whether the BIS was at all able to displace a specific cooking task of the traditional cookstove in the long-term. There are only a few studies in literature that quantify long-term dis-adoption with sensors and even fewer studies that attempt to understand factors that lead to dis-adoption, especially over a long-term period [61, 3, 62]. Carrion et al. [61] explores the dis-adoption of LPG cookstoves and Biolite cookstoves, finding that device breakage, food types, and fuel costs (and access and availability) led to cookstove dis-adoption. To the best of our knowledge, there is no study that explores the dis-adoption of a purchased, improved biomass cookstove.

4.2 Design and Methods

Study Design

Prior to any fieldwork we obtained approval for the research protocols from the Institutional Review Board of University of California, Berkeley (approval CPHS # 2017-07-10101). The fieldwork for the study was closely coordinated with and benefited from participation of the Centre for Technology Alternatives for Rural Areas at the Indian Institute of Technology, Bombay (IITB CTARA), and an Indian NGO, Light of Life Trust (LOLT). There were three phases of the fieldwork in the study: design, trial, post-purchase. More details regarding the trial phase, study design, and timeline can be found in Chapter 2 and Chapter 3. As mentioned, in the post-purchase study described here, we sold cookstoves to households because previous research has shown that giving cookstoves free of charge may influence the perceived worth of the cookstove by users [22]. Based on pre-study interviews regarding household affordability of the BIS, we decided to sell BISs to households at a 50% subsidized price (∼800 INR, 11 USD) on interest-free 3- to 6-month installment plans.

Study Site

The study took place in two rural regions of Maharashtra, India. The regions were in the Raigad and Thane Districts, which are roughly 60 km east and 90 km northeast, respectively, of Mumbai. We worked closely with LOLT and IITB CTARA to choose the villages. The village selection was based on the presence of either IITB CTARA or LOLT in reasonably accessible low-income rural communities that reported fuelwood scarcity and inadequate access to LPG fuel. The 91 study participants were spread across 20 very rural villages (17 in Raigad and 3 in Thane).

Study Participants

We monitored the BIS usage of 91 households after they purchased the cookstove. There were an additional 89 households that purchased the cookstove whose usage we were unable to monitor due to limited number of sensors. The 91 households participated in stove use monitoring and were interviewed, with all interaction complying with the IRB approval (CPHS # 2017-07-10101). We told study participants that we were "gathering data from a small temperature sensor in the new cookstove" but we did not explicitly state that we would use the sensor data to compare to survey responses.

Table 4.1: Household attributes of participating households in study (n = 91). Values inside parentheses are standard deviations.

Household attributes:	**Mean**	**Median**
# Household members	6 (± 3)	6
# Adults in household	4 (± 2)	4
Female primary cook's age	36 (± 11)	35
Male education (years)	5 (± 4)	5
Female education (years)	4 (± 3)	4
Main wage earner annual income (INR)	102,000 (± 63,000)	98,000
Annual income per capita (INR)	8,200 (± 9,300)	6,000
Percent upfront payment (%)	37 (± 29)	31
Fuelwood collection trips per day	1.5 (± 0.4)	1.5
Fuelwood weight for food for 1 day (kg)	6 (± 6)	2
Fuelwood weight for bathwater heating for 1 day (kg)	3 (± 2)	3
Total cookstoves owned before	1.8 (± 0.7)	2
LPG own time (years)	0.4 (± 1.7)	0

Household attributes including education, age, income, etc. of the households in the study (n = 91) are listed in Table 4.1. These attributes are compared between different categories of cookstove usage in the Categories of Users section. Although not noted in the table, other household statistics include: 49% of households participated in a trial and 75% of the households lived in the Raigad District.

Improved Cookstove

Households purchased the BIS, shown in Figure 4.1, with a temperature data logger ("sensor") attached. The BIS is an adapted version of the Berkeley-Darfur Stove (BDS). See

Chapter 2 for a description of the design adjustment process.

Figure 4.1: Side view of BIS in use in rural Maharashtra.

Cookstove Ownership Pre-BIS

We studied cookstove ownership before BIS ownership among households as it is common for households to own more than one cookstove and to use different cookstoves for different cooking tasks ("stove stacking"). Figure 4.2 shows the number of cookstoves owned and the combination of cookstoves owned. About 35% of households owned one, 47% owned two, 17% owned three, and 1% owned four cookstoves before owning the BIS. Of all the households, 58% owned LPG stoves, 17% owned electric stoves, 3% owned one-pot mud chulhas, 63% owned two-pot mud chulhas, 26% owned three-pot mud chulhas, and 17% owned three-stone fires. We found that the most common cookstove-ownership combination (36%) was owning two cookstoves—the two-pot mud chulha and an LPG stove.

A picture of the traditional mud chulha, the most common baseline stove, is shown in Figure 4.3. Mud chulhas may either have one-pot, two-pot, or three-pot capabilities. The mud chulha shown in Figure 4.3 can hold two pots. In rural India, three-stone fires have one-pot capacity, LPG stoves found in rural India typically have two-pot capacity, and electric stoves have one-pot capacity. Unfortunately, due to the limited number of sensors available, we were unable to measure usage of all the baseline cookstoves owned by households. We have a small sample of six households where we measured their mud chulha usage for one

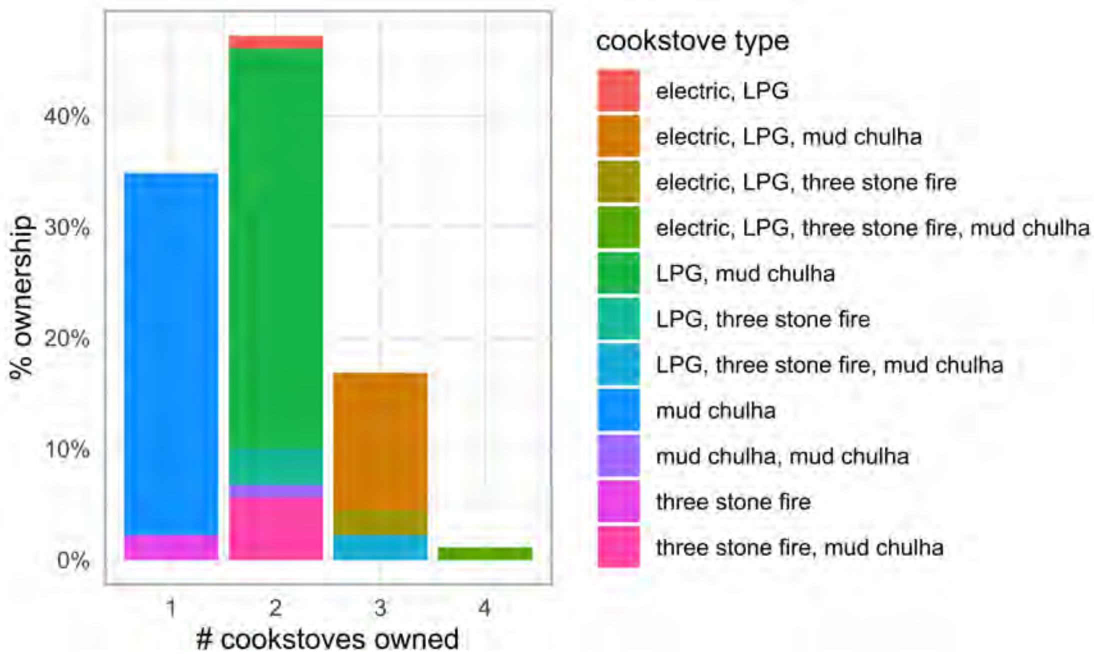

Figure 4.2: Cookstove ownership in households (n = 91) before owning the BIS. The bar plot shows the percent of households that own different combinations (color-coded) of different cookstove types, with the number of cookstoves owned indicated on the x axis. The cookstove type, "mud chulha", encompasses either one-pot, two-pot, or three-pot mud chulhas.

year while monitoring their BIS usage during the same period (see the Traditional Stove Usage section).

Survey Collection

We interviewed the female primary cooks of the 91 households roughly three times: 1) baseline survey for household attributes at the time of BIS purchase (n = 91), 2) Follow-up 1 (n = 75) at 3-5 months post-purchase, and 3) Follow-up 2 (n = 69) at about 1-year post-purchase. The interviews included questions related to household attributes (Table 4.1), usage of the BIS, and their perceived advantages and difficulties using the BIS (see the Reported Advantages and Difficulties section and Appendix B). Staff members from IITB CTARA and LOLT accompanied me on all fieldwork and provided translations for all interviews and focus group discussion into the local language of Marathi.

Figure 4.3: Baseline mud chulha stove found in Maharashtra, India. The mud chulha shown is 2-pot design.

Stove Use Monitoring

We used Geocene Dot sensors [88] to measure BIS usage. These sensors (described in Chapter 3) are Bluetooth temperature data loggers with k-type thermocouples that recorded the cookstoves' inner firebox temperature every 5 minutes. This has been shown to be a good proxy for cookstove usage [87]. Due to the COVID-19 pandemic beginning in March 2020, sensor retrieval and data collection were challenging, which resulted in different monitoring lengths for households. Monitoring began in February 2019 and ended in March 2021. The average length of monitoring was 468 days (SD = 153, median = 518). We collected 48,000 stove-days' worth of data, which is approximately 13 million data points. We were unable to retrieve ~25% of the sensors, resulting in shorter monitoring lengths for these households. Most of these households were in the Thane District.

We used the "FireFinder" algorithm, described in Wilson et al. [88] to identify periods of "cooking", based on the sensor temperature patterns. In Chapter 3, we present BIS usage in units of "cooking events", which are defined as periods of cooking with a minimum duration of 10 minutes and separated by more than 10 minutes between neighboring cooking events. In this chapter, we present BIS usage in units of "cooking minutes" to allow us to interpret changes more straightforwardly in daily usage. Using cooking events in Chapter 3 allowed us to compare reported usage more easily to sensor usage.

4.3 Results

Cookstove Usage Patterns

Categories of Users

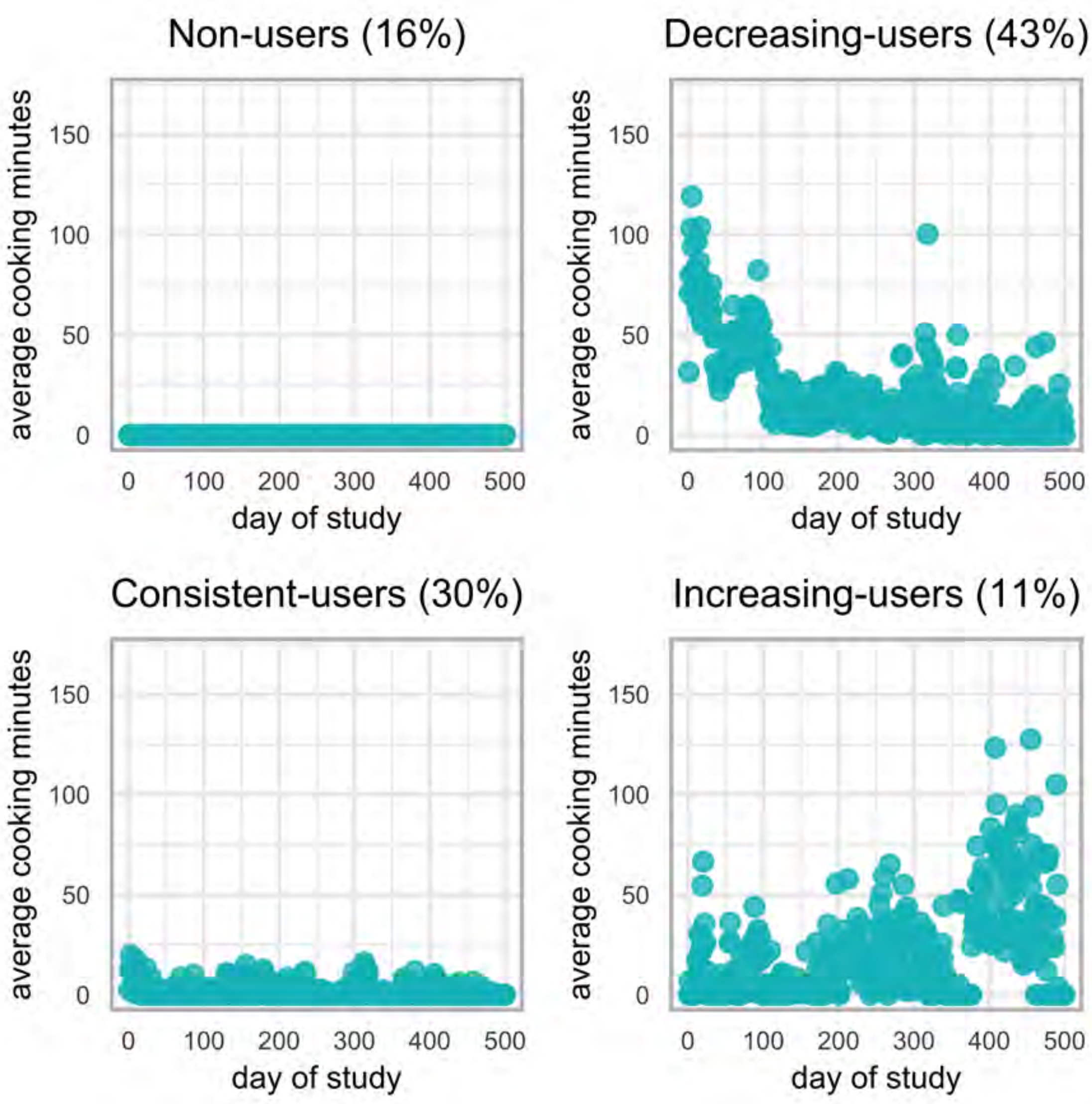

Figure 4.4: Average cooking minutes per day of study for 4 categories of users: non-users (16%, n = 15), decreasing-users (43%, n = 39), consistent-users (30%, n = 27), and increasing-users (11%, n = 10). Each plot shows daily usage averaged across all users in each category.

We determined the overall change in each household's usage by fitting a simple linear regression to its individual sensor data of average cooking minutes per day for its full monitoring period. We defined a household's usage slope to be zero if its absolute value was less than 0.01 minutes per day, which we considered to be negligible. This value is equivalent to a rate of only 3.65 minutes per year. Based on the linear regression of daily cookstove usage, we categorized the households into 4 categories based on the signs of their slopes and daily usage: 1) non-users (zero slope and zero usage), 2) decreasing-users (negative slope), 3) consistent-users (zero slope and non-zero usage), and 4) increasing-users (positive slope). Figure 4.4 shows the temporal plots of average cooking minutes per day for each category. Non-users make up 16% (n = 15), decreasing-users make up 43% (n = 39), consistent-users make up 30% (n = 27) and increasing-users make up 11% (n = 10). We compare different usage trends and household attributes between these different user-categories in the following sections.

Day of First Use

We calculated each household's first day of use after purchasing their cookstove to understand how soon households used their cookstove after purchasing. Excluding non-users, about 19% of the households used the cookstove on the day they purchased it, 48% used it within the first week and 83% used it within the first month of owning it. The average first day of use was 39 days (SD = 95) and the median was 8 days, post-purchase. About 5% of households first used it after a year. These results suggest that we needed to monitor usage at least one week to capture the beginning of the usage for half of the households.

Duration of Use

Figure 4.5 shows the household's duration of use, which was calculated by dividing a household's last day of sensor-recorded use by its total monitoring-days, versus the household's study-average cooking minutes per day. The average daily usage of all households (excluding non-users) was 14 min/day (SD = 16), and the median was 7 min/day. Households in the decreasing-user category had an average daily usage of 23 min/day, which was higher ($p < 0.001$) than consistent-users' average daily usage of 2.0 min/day. The average daily usage of the increasing-users was 12 min/day; although, not statistically different ($p = 0.1$) than the other categories.

The average duration of use of all households, excluding non-users, was 65% (SD = 35, median = 77), with the average last day of use being day 279 (SD = 186, median = 263). About 31% of households were using the BIS into the last 10% of their study-monitoring period. Increasing-users had the highest average duration of use of 95% (SD = 9), which was not statistically higher than decreasing-users' ($p = 0.07$) average duration of use of 69% (SD = 31), but was statistically higher than consistent-users' ($p < 0.001$) average duration of use of 49% (SD = 38).

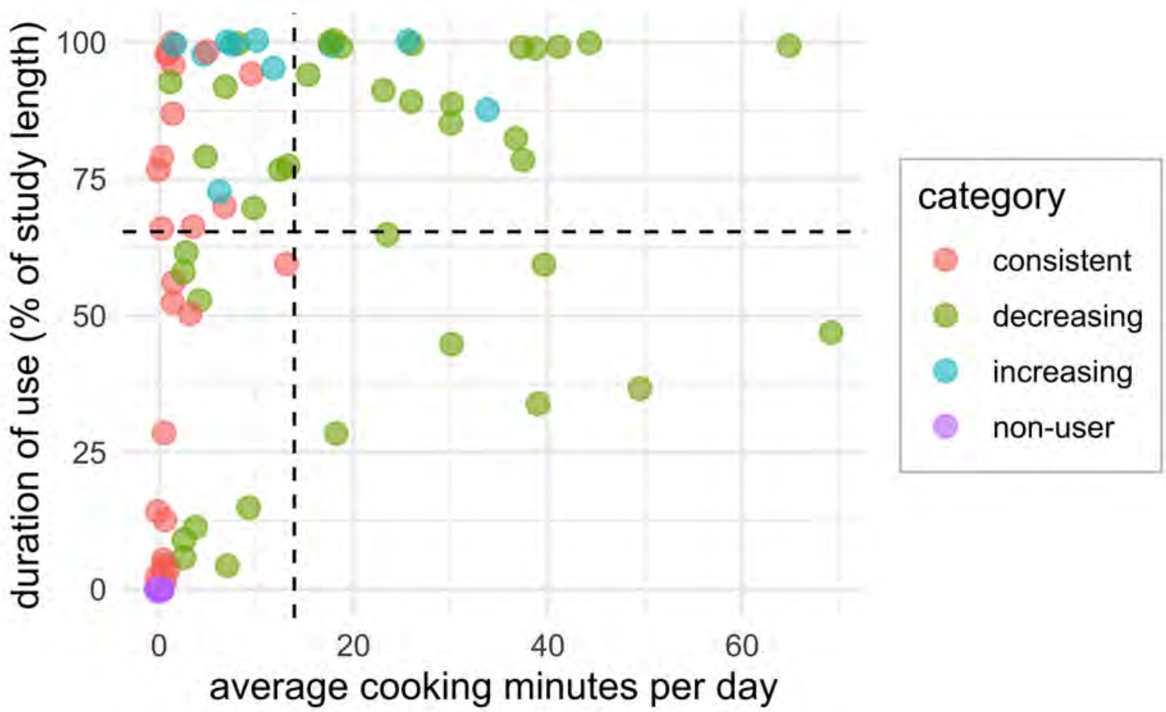

Figure 4.5: Scatter plot of households' (n = 91) duration of use (% of study length) versus their study-average cooking minutes per day. Duration of use is defined as the household's last day of sensor-recorded use divided by the household's total monitoring-days. The dashed lines represent the means of durations of use (y-axis) and average cooking minutes per day (x-axis). Note that points in all plots are "jittered" to avoid overplotting.

For "successful adoption", households would fall into the consistent category (red) and in the top-right quadrant of Figure 4.5, which would indicate high daily usage and long duration of use. There are zero consistent-users and only 3% of all households are increasing-users that fall near the top right corner of the plot, above the means. Most households with either high duration of use or high average cooking minutes per day, or both, are in the decreasing-users category.

Intermittent Usage

For each household, we calculated periods of no-use ("gaps" for short) between periods of use to answer when can a cookstove is considered completely dis-adopted. We define "gaps" as the number of days of no use between at least one day of use before and after the gap. The average longest gap of all households, excluding non-users, was 87 days (SD = 91, median = 60). On average, these longest gaps of no usage occurred about 26% (SD = 25) into households' monitoring periods. There was no statistically significant difference in the average longest gap lengths between user-categories. On average, after the maximum gaps in usage, households used the cookstoves for an additional 13 total days (SD = 24, median = 5), although not necessarily consecutive. It is possible they continued to use it beyond the end of the monitoring period. These results suggest that on average, after nearly 3 months of no usage, some households may begin to use the stove again.

Cooking Time of Day, Week, and Year

When we aggregated all household-level cooking data and grouped it by the hours of the day, there are two peaks of hourly usage at 6am and 6pm with a right tail of usage between 10am-12pm. We compared time of day use amongst different categories of users and found peaks at 6am and 6pm as well. These results confirm households' survey responses of having 2-3 meals per day in general. We found no meaningful trends in usage for the day of the week, nor statistically significant differences between weekday use amongst different categories of users.

For seasonal trends, we hypothesized that households would use the BIS more in the rainy season (May to October) compared to the dry season (November to April) to conserve fuelwood, since fuelwood collection ceases during this season. Seasonal trends in improved cookstove usage have been found in other studies [61, 87]. We found no meaningful trends between seasons, only a decreasing trend in usage over time. However, for a more complete analysis, we would need more sensor data over multiple years to analyze seasonal trends.

Long-term Trends in Usage

Figure 4.6 shows the cooking minutes per day averaged across all households in the study. Each household had a different monitoring start date due to different dates of purchasing the cookstove, so we averaged the cooking minutes by each household's respective day of study. We ended the plot when there was a minimum of 50 households left with sensor-recorded use, which extends to day 490. We found that the overall trend in aggregated data is a decreasing trend in use, which can be modeled with both segmented linear regression (R^2 = 0.67) and an exponential decay (R^2 = 0.50). The exponential decay equation is $y = 6.1 + 33exp(-0.015t)$ where y is the average cooking minutes and t is the day of the study.

We fit a segmented linear regression (using R's 'segmented' package) with two segments, shown in Figure 6 as the red line. This fit resulted in a statistically significant negative slope ($p < 0.001$) for the first segment of -0.20 average minutes per day (SE = 0.012) and -0.006 average minutes per day (SE = 0.003) for the second segment. The segmented regression fit has an R^2 of 0.67; the changepoint for these segments was day 130 (SE = 6). Essentially, the rate of change in average cooking minutes per day decreases by 97% at day 130 to a negligible rate. The first day that the absolute value of the slope remains below the negligible rate of 0.01 min/day (defined in the Categories of Users section) is day 95. Pillarisetti et al. [3]

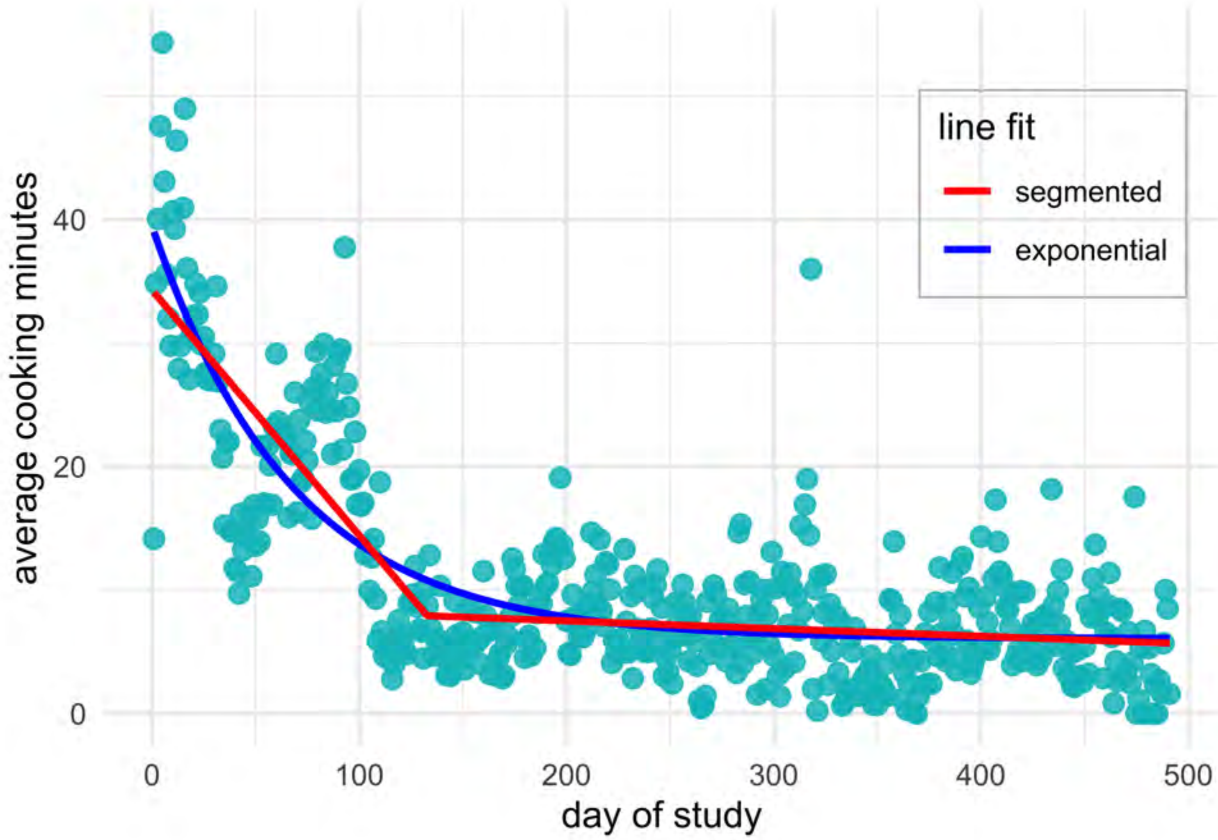

Figure 4.6: Average cooking minutes across all households per day of study, with a segmented linear regression fit (red line, $R^2 = 0.67$)and an exponential decay fit (blue line, $R^2 = 50$).

found that the improved cookstoves' sensor-recorded data had a stabilization date around day 200. They found a first segment slope of -0.28 cooking minutes per day and a second segment slope of -0.04 cooking minutes per day. However, we should note that Pillarisetti et al. [3] used a different cooking event detection algorithm than reported here.

We also fitted the individual households each with a segmented linear regression. The average changepoint for the distribution of households is 155 days (SD = 139) and the median is 94 days. About 79% of households' second slope was below the negligible rate.

Comparing Short-term versus Long-term Trends

Categorization We studied whether a household's early usage of a cookstove could predict their long-term usage patterns, and at what point we could classify a household into a specific usage category. We did this by finding the first day at which the sign (zero, negative, or positive) of the cumulative slope (change in average cooking minutes per day) remained the same as the sign of the household's study-long slope, which determined their user-category. The average day that individual household's, excluding non-users, cumulative slope sign remained the same as their study-long slope sign was 180 days (SD = 182, median = 91) and 22% of households' slope signs were changing beyond one year. These results suggest that ending monitoring before 3 months would have misclassified over half of the households' usage trends. Among decreasing-users, households' cumulative slope sign stayed the same as their study's slope sign by day 129 (SD = 150, median = 63), which was lower (statistically significant, $p = 0.016$) than increasing-users' average day 305 (SD = 155, median = 329). This indicates that on average we may be able to detect decreasing-users before we can detect increasing-users.

Stabilization We identified the day when each individual household's average daily usage stabilized or stopped changing. This was defined as the day when the slope of the remaining study days stayed less than the negligible rate of 0.01 min/day. Excluding non-users, about 95% of all households reached this stabilization day before the end of the study. On average, this day occurred at 36% of households' monitoring periods, with an average stabilization time of 75 days (SD = 109, median = 29), excluding non-users. Excluding consistent-users, who by definition have stable usage throughout the monitoring period, the average stabilization time for the rest of the households was 120 days (SD = 120, median = 86). Notably, the average stabilization time for decreasing-users was 95 days (SD = 92), which was significantly lower (p < 0.001) than that for increasing-users, which was 235 days (SD = 151). This suggests that decreasing-users' daily usage may stabilize earlier than that of increasing-users.

The average daily usage when households' usage stabilized was 9 min/day (SD = 20, median = 1). There was a statistically significant difference ($p < 0.001$) between the stabilization day of all user-categories. There was also a statistically significant ($p < 0.001$) difference between increasing-users' average usage (43 min/day, SD = 42) after stabilization and the other user-categories' average usage after stabilization (decreasing-users: 6 min/day, SD = 10; consistent-users: 2 min/day, SD = 3).

Event Effects on Usage

Effect of Interviews We investigated whether cookstove usage was affected by staff visits. Wilson et al. [42] found that staff visits increased cookstove usage for 2 weeks after the visit. Figure 4.7 (Left) shows the average cooking minutes per day before and after household interviews. We averaged usage for different durations before and after the staff visit, and then compared the pre- and post-visit averages using paired t-tests. We compared the pre-visit mean to the post-visit mean for durations from 1 day to 15 days. For example, we compared the 1-day pre-visit mean to the 1-day post-visit mean, continuing all the way up to comparing 15-day pre-visit mean to the 15-day post-visit mean. Day 0, which indicates the day of the field visit, was included in the post-visit average as all cooking events that occurred on that day occurred after field staff visited. We see an increase in usage on the

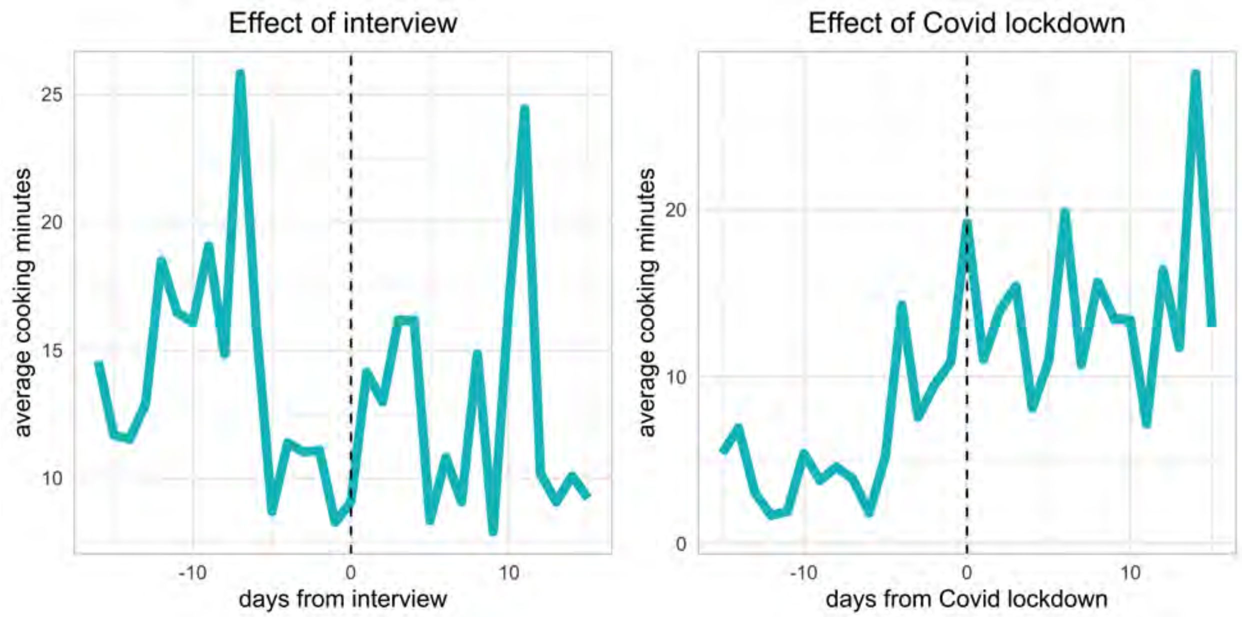

Figure 4.7: Left: Line plot of average cooking minutes per day, on 15 days from interview (before and after) (n = 69). Right: Line plot of average cooking minutes per day, on 15 days from Covid lockdown on March 24, 2020 (before and after) (n = 62).

day of the interview, because 5 households used the cookstove after field staff visited, having not used the cookstove the day before; however, we did not find a statistically significant difference ($0.3 < p < 0.8$) between any of the pre- and post-visit averages.

Effect of Covid Lockdown We also investigated whether the COVID-19 pandemic lockdown affected cookstove usage, hypothesizing that cookstove usage may increase as people were being forced to return home from major cities. In India, a national lockdown was ordered on March 24, 2020. We compared pre- and post-lockdown average usage using paired t-tests, excluding the day of the lockdown (Day 0). Figure 4.7 (Right) shows the average cookstove minutes per day before and after the COVID-19 lockdown. Like the staff visit analysis, we averaged usage for different durations, ranging from comparing 1-day pre-/post-lockdown averages up to comparing 30-day pre-/post-lockdown. We have no knowledge of whether households began returning home to their villages before or after the lockdown went into effect, but it is possible. Thus, we are unable to compare usage before exact dates of family members returning home if they differed from March 24, 2020. We found no statistically significant difference ($0.12 < p < 0.32$) in the paired t-tests between any lengths of days compared before and after the lockdown. Figure 4.7 (Right) shows usage increasing before the lockdown, continuing to increase after the lockdown, with a statistically significant ($p < 0.001$) positive slope, but at a negligible rate of 0.0032 min/day ($R^2 = 0.66$).

Holiday and Major Festivals Effects We hypothesized that usage may increase on these holidays due to family members gathering at home. We used one-way ANOVA and pair-wise t-tests to compare usage before, during, and after holidays largely celebrated in Maharashtra, including Diwali, Ganesh Chaturthi, and Navaratri, but found no statistically significant differences in use on these holidays.

Traditional Stove Usage

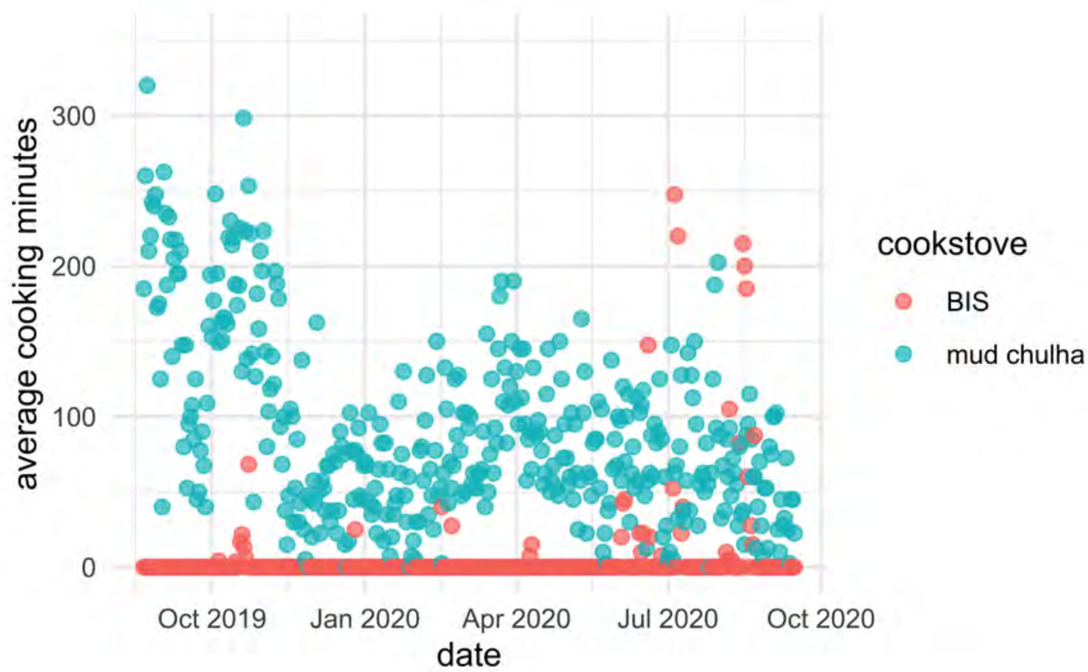

Figure 4.8: Average cooking minutes per day of six households' sensor-recorded usage on their mud chulhas and their BIS's from end of August 2019 to mid-September 2020.

In Figure 4.8, we show the average cooking minutes per day of six household's sensor-recorded usage on their mud chulhas and their BIS' from the end of August 2019 to mid-September 2020. Ideally, we would have monitored usage on all households' mud chulhas, three-stone fires, LPG cookstoves, etc., but due to limitation on sensors, we were only able to monitor mud chulha usage for six households for about one year, which limits the statistical robustness of these findings. We found that the average mud chulha usage for these six households during this 1-year period was 90 min/day (SD = 90, median = 78) and the average BIS usage was 7.4 min/day (SD = 46, median = 0). For the aggregated BIS data in Figure 4.6 (see the Long-term Trends in Usage section), the maximum average daily usage reached was 54 min/day, and the final average daily usage by day 490 was 9min/day.

Three of these six households owned only one cookstove (mud chulha) before owning the BIS, and their average daily mud chulha usage was not statistically different than that of the three other households. The other three households owned a mud chulha, and LPG stoves and had a total of either two or three stoves. Half of the households were classified as decreasing-users and the other half were classified as increasing-users for BIS usage.

Comparing Household Attributes Between User-categories

All Household Attributes

We compared household attributes listed in Table 4.1 between the different user-categories using one-way ANOVA tests and pairwise t-tests. Due to the small sample size and imbalance of households in each user-category, these results should be considered tentative and require further validation. The only statistically significant ($p = 0.040$) difference in the LPG ownership time was between the non-user category, with an average LPG ownership time of 4.0 years and the decreasing-user category, with an average LPG ownership time of 3 years. Another attribute worth noting, although with weaker statistical significance ($p = 0.062$), is the fuelwood weight of food for one day; non-users had an average fuelwood weight of 7.5 kg and decreasing-users had an average fuelwood weight of 6.0 kg.

We conducted multiple regression analyses with the household attributes in Table 4.1 as the predictor variables, including the household's region, trial participation, LPG ownership, kitchen type, and household construction type. We should note that due to the small sample size, the results from these regression analyses should be considered tentative and require further validation. Our results point to potential household attributes that are worth exploring with larger sample sizes that may contribute to increased average daily usage and longer duration of use. We conducted two multiple regression analyses—one with average daily usage and the other with duration of use as the predicted variables. For the regression analysis with the study-average daily usage in minutes per day as the predicted variable (adjusted $R^2 = 0.25$), we found that the total number of household members (positive coefficient) was statistically significant ($p < 0.01$) as well as the region (positive coefficient for Raigad District, $p < 0.05$). One variable of weak statistical significance ($p < 0.1$) was the reported purpose of stove use for bathwater heating (positive coefficient).

In addition, we conducted a regression analysis with the duration of use as the predicted variable (adjusted $R^2 = 0.26$). The variables of statistical significance ($p < 0.05$) were region (positive coefficient for Raigad District), trial participation (positive coefficient), and household construction type kutcha (positive coefficient). The word "kutcha" in Marathi signifies construction made without long-lasting materials (e.g., mud or tied-straw for walls, straw thatched roof, unfinished floor). This signifies very low level of assets. The variables of weak statistical significance ($p < 0.1$) were total cookstoves owned before (positive coefficient) and house type semi-kutcha (positive coefficient). In Marathi, the word "semi-kutcha" signifies construction made with some long-lasting materials (e.g., perhaps stones and cement was used for lower parts of the walls, but rest of the structure was straw and mud with a thatched roof). This would signify a slightly higher level of household assets.

Cookstove Ownership and Tasks

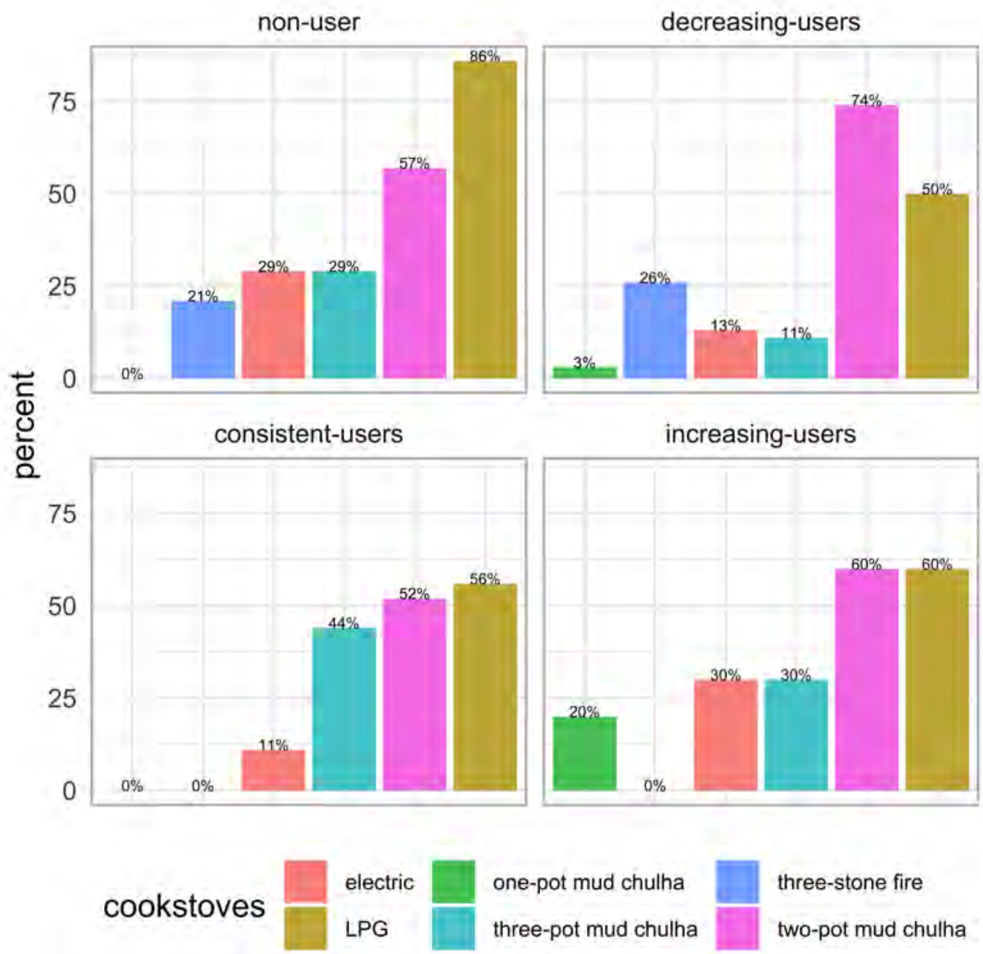

Figure 4.9: Bar plots of percent cookstove ownership of different cookstove types (electric, LPG, one-/two-/three-pot mud chulha, and three-stone fire) before owning the BIS among the different user-categories. Households may own multiple cookstoves. Values in each category are above 100% because households own more than one cookstove.

We asked households which cookstoves they used for each cooking task before owning the BIS. The single cookstove owners (35%) used their cookstove, which was either a type of mud chulha (one-pot, two-pot, or three-pot) or a three-stone fire, for all cooking tasks (food, tea, and bathwater heating). Households that owned two cookstoves but did not own an LPG cookstove (7%) used their three-stone fire for bathwater heating and their mud chulha for food and tea.

For the remaining households that owned more than one cookstove, they owned LPG stoves (58%). Of these LPG-owners, 7% reported using it for only food, 31% reported using it for only tea, and 62% reported using it for both food and tea. None of LPG-owners reported using it for bathwater heating; most of these households reported using their mud chulha or three-stone fires for bathwater and the remaining households reported using their electric stove for bathwater heating. This suggest that LPG stoves also failed to displace mud chulhas and three-stone fires for the task of bathwater heating.

As shown in Figure 4.9 we found that LPG ownership was highest among non-users (86% ownership). Two-pot mud chulha ownership (74%) and three-stone fire ownership (26%) was highest among decreasing-users, although two-pot mud chulha ownership was also high among other user-categories. Three-pot mud chulha ownership (44%) was highest among consistent-users. Notably, one-pot mud chulha ownership (20%) was highest among increasing-users; potentially suggesting that the single-pot capability of the BIS was less of a barrier to these households.

In both Follow-up surveys, field staff asked households what cooking tasks they used the BIS for. Responses fell into three categories: 1) bathwater heating, 2) food, and 3) tea. Among all households, about 93% reported using the BIS for bathwater heating, 75% reported using it for food, and 40% reported using it for tea. Percentages add up to more than 100% because households reported using the BIS for multiple tasks. We explore this in Figure 4.10, which shows the relative percentage of households reporting BIS use for either bathwater heating exclusively (red), food exclusively (green), bathwater heating and food (blue) and bathwater heating, food, and tea (purple) for each user-category, excluding non-users.

Households reported the benefits of using the BIS for bathwater heating task, as bathwater heating as a single-pot task and the BIS only allows for one pot compared to a multi-pot mud chulha. Among all households, about 25% of households reported using the BIS for bathwater heating exclusively, 27% reported using it for bathwater heating and food, 40% reported using it for all three tasks, and 8% reported using it for food exclusively.

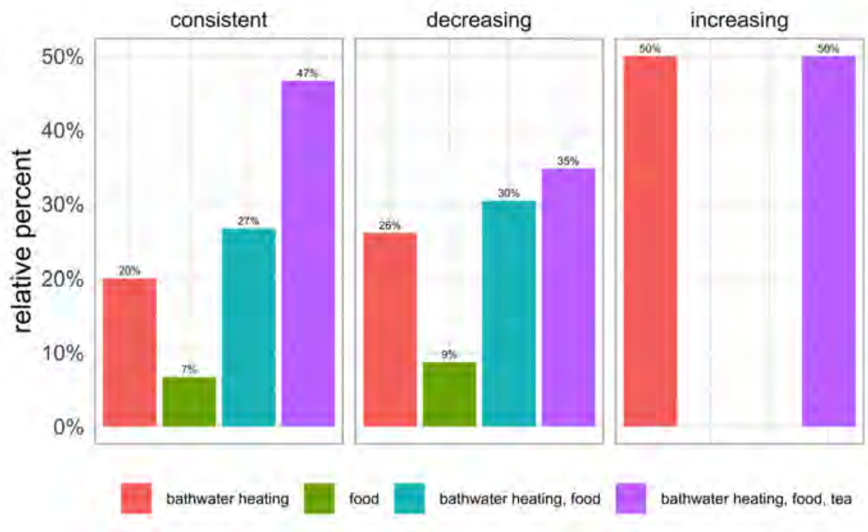

Figure 4.10: Bar plot reported tasks for BIS use: bathwater heating exclusively (red), food exclusively (green), bathwater heating and food (blue) and bathwater heating, food, and tea (purple). Responses (n = 40) are from Follow-up 2, excluding non-users. The y-axis shows the relative percentages per user-category.

Reported Advantages and Difficulties

Field staff also asked households to report perceived advantages and difficulties of using the BIS. Here, we analyze the reported advantages and difficulties among households that used the cookstove to understand potential reasons for dis-adoption (Figure 4.11 and Figure 4.12). Overall, more households in all user-categories reported more advantages in Follow-up 2 than in Follow-up 1. In Follow-up 1, saving fuel and cooking quickly were the most reported advantages in all user-categories. By Follow-up 2, saving fuel remained a reported advantage by similar percentages of households in all categories compared to Follow-up 1. Cooking quickly, less smoke, portability, saving time, size, and aesthetic appeal were reported by more households in all user-categories as advantages in Follow-up 2 than Follow-up 1. This suggests that households observed more advantages over the course of the study. Notably, the percentages of these advantages were lower for decreasing-users in Follow-up 2 compared to other user-categories.

Overall, decreasing-users reported more difficulties by Follow-up 2 compared to the other user-categories, which may be due to their higher daily usage earlier on compared to the other categories. Fuel preparation was the most reported difficulty among all user-categories in Follow-up 1. By Follow-up 2, more households reported it as a difficulty among decreasing- and consistent-users compared to increasing-users. More households reported no multi-pots and difficult to add fuel as difficulties by Follow-up 2 among decreasing- and consistent-users

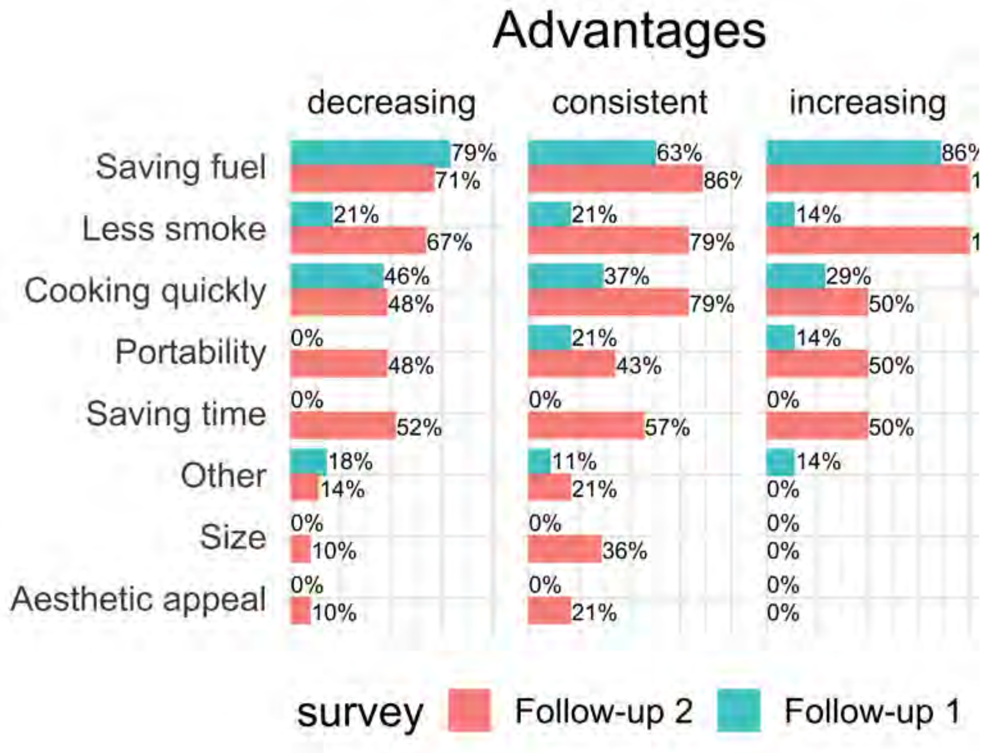

Figure 4.11: Percentages of households in each user-category reporting the listed advantages of using the BIS in Follow-up 1 (n = 75) and Follow-up 2 (n = 69).

compared to their Follow-up 1 responses. Only two difficulties—fuel preparation and no multi-pots—were reported among increasing-users in Follow-up 2.

In Follow-up 2, we also asked households that had reported they were not using the cookstove in the last one month to list the reasons they were not using it. The respondents (n = 41) to this question consisted of 46% decreasing-users, 29% non-users, 20% consistent-users, and 5% increasing-users. Table 4.2 shows the full responses broken down by user-category. The top reasons for non-users not using the cookstove were no multi-pots, no space in the kitchen, fuel preparation, and difficulty adding fuel. The top reasons for decreasing-users not using the cookstove in the last one month were no multi-pots, fuel preparation, difficulty adding fuel, and rusting or stove damage.

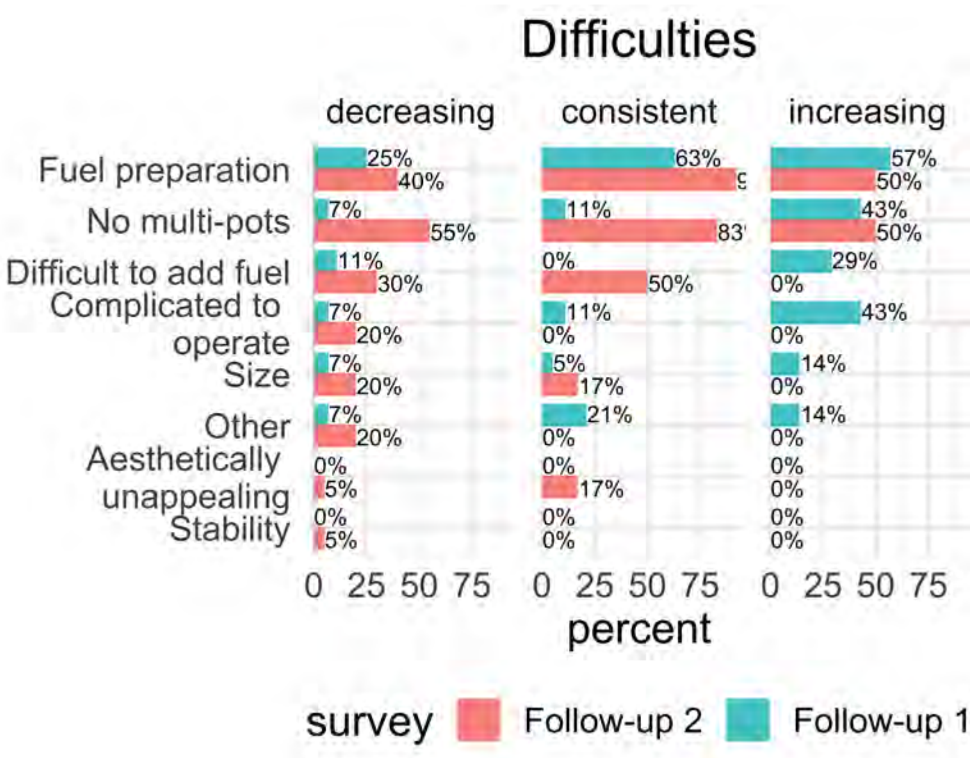

Figure 4.12: Percentages of households in each user-category reporting the listed difficulties of using the BIS in Follow-up 1 (n = 75) and Follow-up 2 (n = 69). “Difficult to add fuel” refers to the small size of the fuelwood opening of the BIS compared to their mud chulhas. “Fuel preparation” is a related difficulty, referring to the small size fuelwood opening requiring hosueholds to chop their wood to fit it in the opening. “No multi-pots” refers to the BIS’ inability to hold multiple pots at the same time (i.e. lack of multiple burners).

Table 4.2: Reported reasons for not using the BIS. Respondents (n = 41) included households that reported not using the BIS in the last month from the interview (Follow-up 2).

Reported reason:	**Relative percent of each category:** All responding households (n = 41)	Non-users (n = 12)	Decreasing-users (n = 19)	Consistent-users (n = 8)	Increasing-users (n = 2)
Size	10%	17%	5%	12%	0%
Stability	2%	0%	5%	0%	0%
Fuel preparation	39%	25%	42%	38%	100%
Aesthetically unappealing	5%	8%	5%	0%	0%
No multi-pots	34%	33%	42%	12%	50%
Difficult to add fuel	32%	25%	37%	25%	50%
Complicated to operate	5%	8%	5%	0%	0%
No space in kitchen	15%	33%	0%	25%	0%
Rusting or stove damage	7%	0%	16%	0%	0%
Prefers another stove	7%	0%	0%	0%	0%

4.4 Discussion

Although households purchased the cookstove at a price about one-third of their income on average, we found that about 43% of households had an overall decreasing trend in usage, 16% of households never used the cookstove even though they purchased it, and 30% used the cookstove at a consistent rate, but with low daily usage, and the remaining 11% of households used the cookstove at an increasing rate. For a "successful" cookstoves project, we ideally want households to have a high duration of use, high average daily usage, and overall consistent trend in usage. However, we found that nearly all of the households with high duration of use and high average daily usage had a decreasing trend in usage.

Our study aimed to inform future projects' minimum monitoring lengths by analyzing long-term usage patterns, such as the first day of usage, intermittent usage, and stabilization periods. We found that we needed to monitor usage for at least 8 days to capture just the beginning of usage for half of the households and for at least one month to capture the start day of 83% of households. Even after nearly 3 months of no usage, households may begin to use the cookstove again, indicating the difficulty of concluding complete dis-adoption. We found that for the aggregated household data, average daily usage stabilized at 95 days. However, when we looked at household's individual stabilization dates, we found an average stabilization day of 75 (SD = 109, median = 29), excluding non-users. Pillarisetti et al. [3] found that aggregate improved cookstoves usage remained at a changing rate of -0.04 min/day at 200 days.

To investigate reasons for dis-adoption, we compared household attributes among different user-categories and looked at households' survey responses. The only statistically significant variable was LPG ownership time, which was higher among non-users than decreasing-users. LPG ownership was highest among non-users compared to other user-categories. Our regression analyses revealed that having more household members and living in the Raigad District were statistically significant features, contributing to increased average daily usage. However, this does not indicate sustained, consistent usage, as we know that households with high study-average daily usage were mostly decreasing-users.

Similar to other studies, households with multiple cookstoves tended to split their cooking tasks between stoves. Bathwater heating was the most reported task on the BIS among all user-categories, potentially due to the task requiring only one pot. Nearly all (97%) households reported using their mud chulha or three-stone fire for bathwater heating before owning the BIS; no households reported using the LPG stove for bathwater heating. Ruiz-Mercado and Masera [27] suggested that improved cookstoves programs should focus on designing task-specific cookstoves. More research is needed to explore the potential of the BIS to be a task-specific cookstove, potentially for bathwater heating.

The lack of multi-pot use on the BIS was the most reported difficulty among decreasing-users, as well as consistent-users, highlighting the importance of cookstove multi-pot capability in this area of rural Maharashtra. Since decreasing-users had high average daily usage, this suggests that initially these households potentially found beneficial use in the BIS, but the reported design difficulties may have eventually led to their dis-adoption. Non-users and decreasing-users reported that no multi-pots, fuel preparation, difficulty adding fuel, rusting or stove damage, and no space in the kitchen were the top reasons for their lack of use and dis-adoption of the BIS. While our design-phase surveys revealed users' concerns of lack of multi-pot capability and smaller fuelwood opening (leading to difficulty adding fuel and fuel preparation), we had hypothesized that accommodating the other top reported concerns would increase BIS' adoption. However, these results suggest that fuel preparation, difficulty adding fuel, and the lack of multi-pot capacity were major barriers to sustained adoption and potentially led to the dis-adoption of previous users. Our pre-design surveys failed to understand the relative importance of these features as barriers to sustained use.

Saving fuel, cooking quickly, and less smoke were highly reported advantages among all user-categories in the follow-up surveys. Because we did not directly measure fuelwood saving or emissions in field, we have no way of confirming these perceived benefits. Even though households reported benefits of saving fuel, perhaps women found that there is low opportunity cost of fuelwood collection in rural Maharashtra. When there is limited economic opportunities for women, the extra labor and time of fuelwood collection does not always lead to changing cooking behaviors except in extreme fuel scarcity [39, 32].

In summary, we add to the limited research quantifying and understanding reasons for the dis-adoption of improved cookstoves. Although BIS usage started high in the beginning, usage declined over time. We suggest that future cookstoves studies monitor usage long enough to capture the potential dis-adoption of their cookstove, our findings suggest a minimum of 95 days, but likely longer due to variability in usage between households. Even when households report fuelwood savings and less smoke while cooking, as well as spend a third of their monthly income to purchase the cookstove, we still found overall dis-adoption. We observed the potential of the BIS being a task-specific cookstove, but more research is needed to explore this. We suggest that future cookstove designs target specific cooking tasks and pay special attention to understanding required, non-negotiable design features.

Chapter 5

Improving the Estimates of Cookstoves' Carbon Emissions by Combining Lab and Field Data

5.1 Background and Motivation

Inefficient cookstoves produce extreme levels of pollutants that adversely affect climate and human health. The incomplete combustion of solid fuels emits climate-forcing pollutants such as carbon monoxide (CO), methane (CH_4), and black carbon (BC). Solid-fuel cooking emits 1.0–1.2 Gigatonnes CO_2-equivalent (CO_2e) per year [16] and contributes 25% of total black carbon emissions; black carbon is a short-lived greenhouse agent with significant global warming impacts [18]. Additionally, solid-fuel cooking also emits toxic levels of particulate matter ($PM_{2.5}$) [2]. In India, measured mean daily $PM_{2.5}$ concentrations in rural solid fuel-using households were 163 μg/m^3 in the living area and 609 μg/m^3 in the kitchen area [21]. The World Health Organization air quality guidelines state that the 24-hour average exposures should not exceed 15 μg/m3 more than 3-4 days per year [13]. The impact of cooking and collecting fuelwood falls disproportionately on women, as they are predominately responsible for these activities [2].

Improved biomass cookstoves can reduce fuelwood usage and emissions by 30-50% compared to baseline stoves, such as three-stone fires [23]. Moreover, improved cookstoves are considered a cost-effective climate mitigation strategy capable of offsetting 1-3 tonnes CO_2e per cookstove per year, and if implemented globally, they have the potential to reduce emissions by 1 Gigatonne CO_2e per year [24]. The Clean Cooking Alliance, a non-profit organization dedicated to promoting clean cooking in developing nations, aims to achieve universal access to clean cooking by 2030 (www.cleancooking.org).

However, required methods to validate carbon offsets are not rigorous and allow project implementers to use default usage rates and default emission factors [46], which can lead to significantly inaccurate emission reductions [49, 48]. Moreover, using cookstove-specific emission factors is more accurate than using default emission factors [47]. In Chapter 3, we demonstrate the importance of using sensors to measure cookstove usage, rather than relying on surveys which can lead to over-reporting of usage [41, 42]. Directly measuring pollutant emissions in the field is often technically- and cost-prohibitive [65]. There are only a few studies that explore the improvement of field methods for carbon offsets verification [65, 59, 44, 66].

In the study presented in Chapter 3, we measure the adoption of the Berkeley-India Stove (BIS) (see Figure 5.2), which is an adapted design of the Berkeley-Darfur Stove (BDS). We hypothesized that the design modifications we made would not significantly affect the performance of the BIS. Previous research has shown that the BDS offers major fuelwood, time, and emissions savings compared to a three-stone fire [80, 81, 23], which presents the potential of the BDS for significant offsets in the carbon offsets market [42]. In rural Maharashtra where the BIS was sold, the baseline cookstove is typically either a three-stone fire, or more commonly, a traditional mud chulha (see Figure 5.3). The mud chulha has existed in South Asia for thousands of years [39]. While there is a quantification of the performance of the BDS and the three-stone fire [80, 81, 23], there is no comparison of the efficiency and emissions between the BIS and the mud chulha in prior literature. In this chapter, we present the results of comparing the performance (thermal efficiency, boiling time, combustion efficiency), emissions (CO, $PM_{2.5}$, CO_2, BC), and particle distributions of the BIS to the mud chulha in bringing 5 L of water to boil in two different pots, both typical of those used in the region. Since the most reported task on the BIS was bathwater heating (Chapter 4), these results can provide insight into potential field savings for the task of heating water.

There exists multiple studies that examine the performance and emissions of different versions of a single-pot traditional mud chulha (only holds one pot, and typically "U-shaped") [92, 93, 94]; however, limited research exists on multi-pot traditional mud chulhas (holds more than one pot – see Figure 5.3) [95, 96]. Moreover, these studies on multi-pot chulhas do not analyze their particle size distributions. It is important to measure the particle size distributions of cookstoves because different particle sizes have different health implications; ultrafine particles (particles less than 0.1μm in diameter) can travel deeper into the lungs where they may cause negative health effects [11].

Additionally, we also explore methods for estimating fuelwood usage and CO_2 emissions with temperature dataloggers, with the same sensors and sensor placement used in Chapter 3 and 4 to measure improved cookstove usage. We explore the relationship of the cookstove temperature to fuelwood usage and CO_2 emission by conducting tests of heating and boiling water at different firepowers—a metric used to measure the thermal power output of the cookstove (defined as the thermal energy from fuel combustion divided by test duration; see the Performance Metrics Calculations Section). We hypothesized that the steady-state temperature of the BIS would be positively correlated with the firepower of the cookstove, and thus also positively correlated with fuelwood usage and CO_2 emissions. Previous research shows that cookstove exhaust temperature is positively correlated with firepower [97, 98]. Additionally, Graham et al. [66] found that calculating the area under the cookstove's temperature time series could be used to estimate (cumulative) fuel thermal energy. However, the authors used a forced-draft improved cookstove, and they did not explore the effects of using different cooking vessels on these methods, which we do herein. This detail is important because forced draft stove will have a relatively fixed airflow rate, while airflow rate in natural draft stoves (like the BIS and the mud chulha) will vary with firepower. This granularity is also important because with the sole use of temperature sensors on cookstoves in the field, we may not know which cooking vessel is always being used, especially if households own many different kinds. Different cooking vessels may affect the performance of the cookstove.

With the results from the BIS and mud chulha performance comparison, as well as the temperature sensor correlations with fuelwood usage and CO_2 emissions, we can estimate the total CO_2 emissions and fuelwood usage from a household's BIS. Current methodologies for carbon offset verification rely on one-time measurements for fuelwood savings and default emission factor values [46]. By combining field data (cookstove usage, reported tasks, temperature time series) and lab data (cookstove emission factors, fuelwood consumption on each cookstove, and correlations between temperature and fuelwood/CO_2), we can make more reliable estimates for total CO_2 emission reductions than existing methodologies (see Figure 5.2). Moreover, the methods we present are also potentially less technically- and cost-prohibitive than measuring emissions in field. We provide a sequence of methods that can be implemented by future improved cookstoves projects that are funded on the voluntary carbon offsets market. In this chapter, we solely present these methods using the lab cookstove sensor data for validation. We do not yet use the field sensor data to make estimations as future work will involve validating these estimations with field measurements.

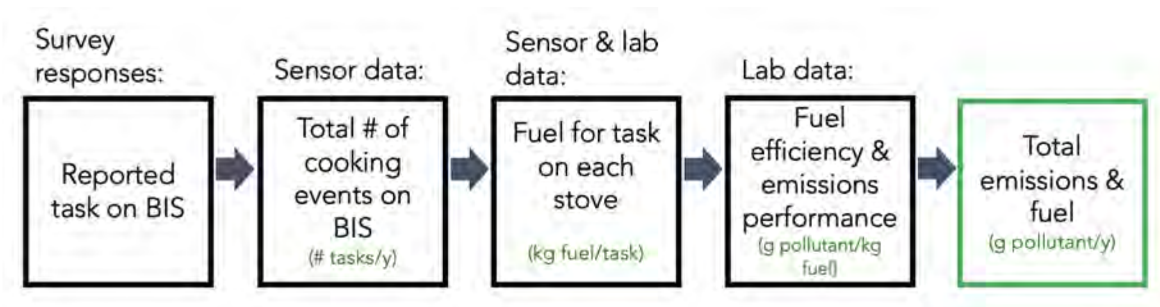

Figure 5.1: Diagram of sequence of methods and data collection to estimate total emissions and fuelwood consumption from an improved cookstove.

5.2 Design and Methods

Berkeley-India Stove (BIS)

The BIS, shown in Figure 5.2, was adapted from the BDS design for use in rural Maharashtra in 2018, and the design adjustment process is described in Chapter 2.

Figure 5.2: Berkeley-India Stove (BIS) in use at LBNL Cookstove testing facility.

Traditional Mud Chulha

The traditional mud chulha is the most common baseline stove found in the target villages in rural Maharashtra (Chapter 3). A variety of versions of the traditional mud chulha exist. They may have the ability to hold either one, two, or three pots—analogous to having multiple burners on a gas or electric stove. Additionally, the materials, shape, or size may somewhat vary between households, as they are made locally by hand, either by the female primary cookstoves themselves or purchased in a local market for ∼3-5 USD (∼200-300 INR). The mud chulha shown in Figure 5.3, is a "two-pot" mud chulha, meaning that it can hold two pots at the same time. Mud chulhas have a front fuelwood opening and an opening for each burner or pot, each with three raised "knobs" to hold the pot above the fire. In general, the front and top openings may vary by a couple inches between versions. They are made from locally found clay mud, dried grass, and water.

An artist (Jeremiah Jenkins) at Berkeley Art Studio made a mud chulha replicate based on photographs and measurements provided to him. This replicate was tested in the Stoves Lab at LBNL. The design was based on measurements of a two-pot mud chulha (see Appendix

C) that we purchased in the Raigad District of rural Maharashtra. We chose to test the two-pot mud chulha because it was the most common baseline cookstove in the BIS-adoption study, described in Chapter 3.

Figure 5.3: Two-pot mud chulha in use at LBNL Cookstove testing facility.

Experimental Set Up

All measurements were made at the cookstove testing facility at LBNL (Figure 5.4). Detailed descriptions of the testing facility and experimental setup can be found in Rapp et al. [80] and Caubel et al. [99]. We provide a summary here. Cookstoves were tested under a steel exhaust hood, shown in Figure 5.4, using the total capture method, in which pollutants are captured by the hood and transported outside through a duct system. The volumetric flow rate through the exhaust duct is ∼340 m^3/h (200 CFM). We sampled pollutants every second (Hz) in the duct using various real-time instruments. We sampled concentrations of carbon dioxide (CO_2), carbon monoxide (CO), and oxygen (O_2) using a California Analytical Instruments (CAI) 600 Series gas analyzer. BC mass concentrations were measured at 1 Hz with a Magee Scientific AE-22 Aethalometer. The particle number concentration and size distribution of particles with diameters between 5 nm to 10 μm were measured with a TSI 3330 Optical Particle Sizer (OPS) and a TSI 3091 Fast Mobility Particle Sizer (FMPS) at 1 Hz. We measured the total mass of particles with diameters less than 2.5 μm ($PM_{2.5}$) gravimetrically with 47 mm Teflon filters. We also measured ambient CO_2 with a PP Systems SBA-5 NDIR gas analyzer at 1 Hz.

We used temperature dataloggers, Geocene Dot sensors [88] to measure the temperature of the BIS' firebox at 1 Hz (described in Chapter 3). The thermocouple of the sensors touched the wall of the firebox. We also measured the temperature of the mud chulhas at 1 Hz using the sensors, however the thermocouple was placed a couple inches from the pot opening.

Figure 5.4: Testing setup of BIS under steel exhaust hood at LBNL.

Experimental Procedures

We conducted a total of 127 tests (see Table 5.1), which fall into three categories: 1) 38 tests bringing 5 L of water to boil (∼99°C), 13 on the BIS and 25 on the mud chulha; 2) 49 tests bringing 2 L of water to boil (∼99°C) on the BIS; and 3) 40 tests heating 2 L of water for 15 minutes on the BIS. All water used for testing started at room temperature. We used untreated kindling and fuelwood from a Douglas fir tree for all fires. All wood pieces were uniform in size and moisture contents were around 7-10% on a wet basis. All tests were done with the same person operating the cookstove. We conducted a minimum of 10 tests for each cookstove and cooking vessel combination within each category of tests, as previous research has shown that at least 10 tests are necessary to provide an accurate picture of a cookstove's performance [100].

In the first two categories of tests, we simulated the task of bathwater heating by bringing different amounts (5 L and 2 L) of water to a boil and conducting a modified version of the Water Boiling Test (WBT) 4.2.3 [101]. For the first category of tests (38 total), we measured the performance metrics (fuelwood, thermal efficiency, boiling time), gaseous emissions (CO_2, CO), particle emissions ($PM_{2.5}$, BC) and particle number concentrations during the task of bringing 5 L of water to a boil a high firepower of ∼5.5-6 kW, (see Table 5.2). In this

Table 5.1: Description of category of tests.

	Stove and # tests	Test type	Notes
Category 1	BIS (n = 13)	heating 5 L of water to boil (∼99°C); cold start	cooking vessel: large pot; consistent firepower
	mud chulha (n = 15)	heating 5 L of water to boil (∼99°C); cold start	cooking vessel: large pot; consistent firepower
	mud chulha (n = 10)	heating 5 L of water to boil (∼99°C); hot start	cooking vessel: large pot; consistent firepower
Category 2	BIS (n = 49)	heating 2 L of water to boil (∼99°C); cold start	cooking vessels: large pot (n = 22), and small pot (n = 27); varying firepowers
Category 3	BIS (n = 40)	heating 2 L of water for 15 min	cooking vessels: large pot (n = 20), and small pot (n = 20); varying firepowers

category of tests, 13 tests were done on the BIS and 25 tests were done on the mud chulha. The 13 tests on the BIS and 15 of the tests on the mud chulha were conducted with the stoves starting at room temperature (∼30°C), termed a "cold-start" test [101]. The other 10 tests on the mud chulha were conducted with the stove starting at a hot temperature (average = 135°C, SD = 8°C), termed a "hot-start" test [101]. We compared the performance of the mud chulha at two different temperatures because we observed that households' chulhas were hot for long periods of the day (owing to a slow cooling time for clay material – taking about 2 h to reach its starting temperature after a cooking event such as boiling water), and higher temperatures are more likely to reduce emissions.

We chose to conduct different test types of boiling water (Category 2) and heating water for 15 min (Category 3) to replicate different types of cooking tasks. Additionally, we conducted these tests on different cooking vessel sizes since the BIS can be used with different cooking vessels, and we wanted to explore how cooking vessel size affects the temperature correlations. In the second category of tests (49 total), we measured the performance (fuelwood, thermal efficiency, boiling time) and gaseous emissions (CO_2, CO) of bringing 2 L of water to boil on the BIS at varying firepowers, ranging from 3kW to 10kW. Twenty-seven of these tests were conducted with a smaller pot of 226 g mass and 20 cm diameter (referred to as "small pot" in this chapter) and the other 22 tests were done with a larger pot of 621 g mass and 27 cm diameter (referred to as "large pot" in this chapter). In the third category of tests (40 total), we measured only the performance (fuelwood, thermal efficiency, boiling time) and gaseous emissions (CO_2, CO) of heating 2 L of water for 15 minutes at varying firepowers. Twenty of the tests were done on the small pot and the other twenty tests were done on the large pot.

Performance Metrics Calculations

We used the methods presented in the Water Boiling Test 4.3.2 [101] to calculate the following performance metrics: firepower, thermal efficiency, modified combustion efficiency, and corrected time to boil. Firepower is defined as the energy from fuel divided by test duration. Thermal efficiency is defined as the ratio of energy to heat the water in the pot to the energy that is released by the burning fuel. Modified combustion efficiency is defined as the ratio of emitted CO_2 to the sum of emitted CO_2 and CO. It is considered a good proxy for combustion efficiency. We also present the temperature-corrected time to boil for comparisons between each cookstove. See Appendix C for equations for each metric. We followed the methods in the Water Boiling Test 4.3.2 [101] to calculate CO and CO_2 emission factors presented in Table 1 using the carbon balance method. $PM_{2.5}$ emission factors were calculated using the filter weights [99]. We also provide CO and CO_2 emission factors based on CO and CO_2 measurements in the duct (see Appendix C).

5.3 Results

Performance Metrics of the BIS and Mud Chulha

We report the performance metrics, such as fuelwood use, thermal efficiency, emission factors, and total mass emitted per test for the first category of tests (38 tests bringing 5 L of water to boil ~99°C) in Table 5.2. The average temperature of the cookstove at the beginning of the tests were 25.0°C (SD = 1) for the BIS, 25.6°C (SD = 3) for the cold mud chulha, and 134.5°C (SD = 10) for the hot mud chulha.

BIS Compared to the BDS

We compared the performance metrics of the BIS to those of the BDS found in previous studies [80, 81, 23]. Like our test procedure for the BIS and cold-start mud chulha, Rapp et al. [80] brought 5 L of water to boil from room temperature and at the same LBNL testing facility that we used. We should note that Preble et al. [81] and Jetter et al. [23] used different experimental set ups, and followed different test procedures than we did; Preble et al. [81] brought 2.5 L of water to boil, then simmered the water for 15 min, and Jetter et al. [23] brought 5 L of water to boil, then conducted a hot-start phase, then simmered the water for 30 mi. Additionally, all experiments for the BDS used a round-bottom Darfuri pot (~1.7-2.3 kg, aluminum).

Table 5.2: Performance metrics of the BIS (n = 13), cold-start mud chulha (MUD-C, n = 15), and hot-start mud chulha (MUD-H, n = 10), for bringing 5 L of water from room temperature to boiling. Values shown are the mean of n tests with 95% confidence intervals (assuming Student's t distribution). Values for each test are provided in the Appendix C.

	BIS (n = 13)	**MUD-C (n = 15)**	**MUD-H (n = 10)**	**BIS/ MUD-C ratio**	**BIS/ MUD-H ratio**
average firepower (kW)	5.5 ± 0.2	5.4 ± 0.3	5.8 ± 0.2	1.0	0.95
dry fuelwood mass (g/test)	374 ± 10	654 ± 48	583 ± 45	0.57	0.64
thermal efficiency (%)	28 ± 0.4	18 ± 1.4	21 ± 1	1.6	1.3
boiling time (min)	22 ± 0.8	39 ± 2	32 ± 2	0.56	0.69
fuelwood burn rate (g/min)	18 ± 0.5	17 ± 1	18 ± 0.6	1.0	1.0
modified combustion efficiency (%)	97.2 ± 0.1	97.2 ± 0.1	97.4 ± 0.2	1.0	1.0
emission factors:					
CO_2 (g/kg)	1773 ± 2	1780 ± 4	1780 ± 3	1.0	1.0
CO (g/kg)	33 ± 1	30 ± 3	30 ± 2	1.1	1.1
$PM_{2.5}$ (g/kg)	2.7 ± 0.2	2.0 ± 0.2	2.1 ± 0.2	1.4	1.3
BC (g/kg)	1.1 ± 0.2	2.2 ± 0.5	1.5 ± 0.8	0.5	0.73
total mass emitted:					
CO_2 (g/test)	663 ± 18	1164 ± 85	1038 ± 79	0.57	0.64
CO (g/test)	11.8 ± 0.8	19.2 ± 2.8	17 ± 3	0.61	0.69
$PM_{2.5}$ (g/test)	1.01 ± 0.05	1.34 ± 0.1	1.25 ± 0.1	0.75	0.81
BC (g/test)	0.40 ± 0.1	1.4 ± 0.3	0.85 ± 0.5	0.28	0.47
total mass per MJ delivered:					
CO_2 (g/MJdel)	340 ± 5	539 ± 47	457 ± 14	0.63	0.74
CO (g/MJdel)	6.1 ± 0.3	8.8 ± 1.3	7.4 ± 0.6	0.69	0.82
$PM_{2.5}$ (g/MJdel)	0.52 ± 0.03	0.61 ± 0.04	0.55 ± 0.04	0.85	0.95
BC (g/MJdel)	0.21 ± 0.04	0.66 ± 0.2	0.37 ± 0.2	0.32	0.57

We compared the emission factors we found for the BIS with those found for the BDS, rather than comparing the total mass per test, because the latter comparison should be made for the same cooking task to ensure accuracy. We found a similar CO_2 emission factor for the BIS as Preble et al. [81] found for the BDS (1,767 ± 4 g/kg), as well as Jetter et al. [23] (1,725 g/kg, SD = 193). For the CO emission factor, we found a lower value (-21%, -30%) for the BIS than Preble et al. [81] (42 ± 3 g/kg) and Rapp et al. [80] (47 ± 8 g/kg) found for the BDS, but similar to Jetter et al. (2012) [23] (34 g/kg). Similarly, for the $PM_{2.5}$ emission factor (g/kg), we found a similar value for the BIS as Preble et al. [81](3.1 ± 0.5 g/kg) but 44% lower than Rapp et al. [80] found (4.8 ± 0.5 g/kg), but 73% higher than Jetter et al. [23] found (1.56 g/kg, SD = 0.3). For the BC emission factor, we found a similar value to Preble et al. [81] (1.5 ± 0.2 g/kg). We found the same modified combustion efficiency that Jetter et al. [23] found (97.1 ± 0.4%) and similar to Rapp et al. [80] for the BDS (95.9 ± 0.7%). These results indicate that the BIS design modifications did not increase the emission factors, nor did they decrease the combustion efficiency. We observe that the different studies found varying values for some of the emission factors, likely due to different cookstove operators, but our values fall either between or near their findings.

We found a thermal efficiency of 28 ± 0.4% for the BIS compared to 34-37% for the BDS [23, 80]. We suspect that this difference is due to the difference in pots and pot-rod designs between the stoves. In the BIS tests described in this section, we use a 621 g, 27-cm diameter flat-bottom pot, which sits a couple centimeters higher and is also smaller compared to the Darfuri round-bottom pot for the BDS. The Darfuri round-bottom pot's maximum inside diameter is about 28 cm and its height is about 20 cm, with a 9.8 L capacity and ∼0.4 cm thickness [23]. There is only a ∼1-2 cm gap between the Darfuri pot walls and the BDS' pot skirt. The gap between the BIS' pot and BIS' pot skirt is ∼4-5 cm. For the BIS, the pot's smaller size and higher position, compared to the BDS, leaves a larger gap between the pot walls and the cookstove wall, allowing more heat to escape; this may reduce the thermal efficiency of the BIS. Moreover, the larger gap in the BIS leads to less flow resistance to air going up and even more excess air, and poorer heat transfer from the airstream to the pot than the stove-pot combination tested for the BDS. Our results suggest that the fit of the cooking vessel to the stove may potentially play a large role in the thermal efficiency of the cookstove. Because the BIS's pot-rod design allows for the different-sized flat-bottom pots—as women own many different-sized pots—households may experience different thermal efficiencies depending on the pot they use.

For the time to boil 5 L of water, we found that the BIS took about 22% more time than Rapp et al. [80] found for the BDS (18 ± 1 min) and Preble et al. [81] found (18 min) but about 42% less time than Jetter et al. [23] found for the BDS (38 min, SD = 2.4). Moreover, like the BDS, the BIS outperforms the three-stone fire, with 31% less time to boil, 22% higher thermal efficiency, resulting in lower total fuelwood consumption and lower total mass emissions per test [80].

BIS Compared to the Mud Chulha

In our tests, the BIS achieved a better thermal efficiency compared to both the cold and hot mud chulhas, with the hot mud chulha being more thermally efficient than the cold mud chulha. The BIS used 43% and 36% less fuelwood than the cold mud chulha and the hot

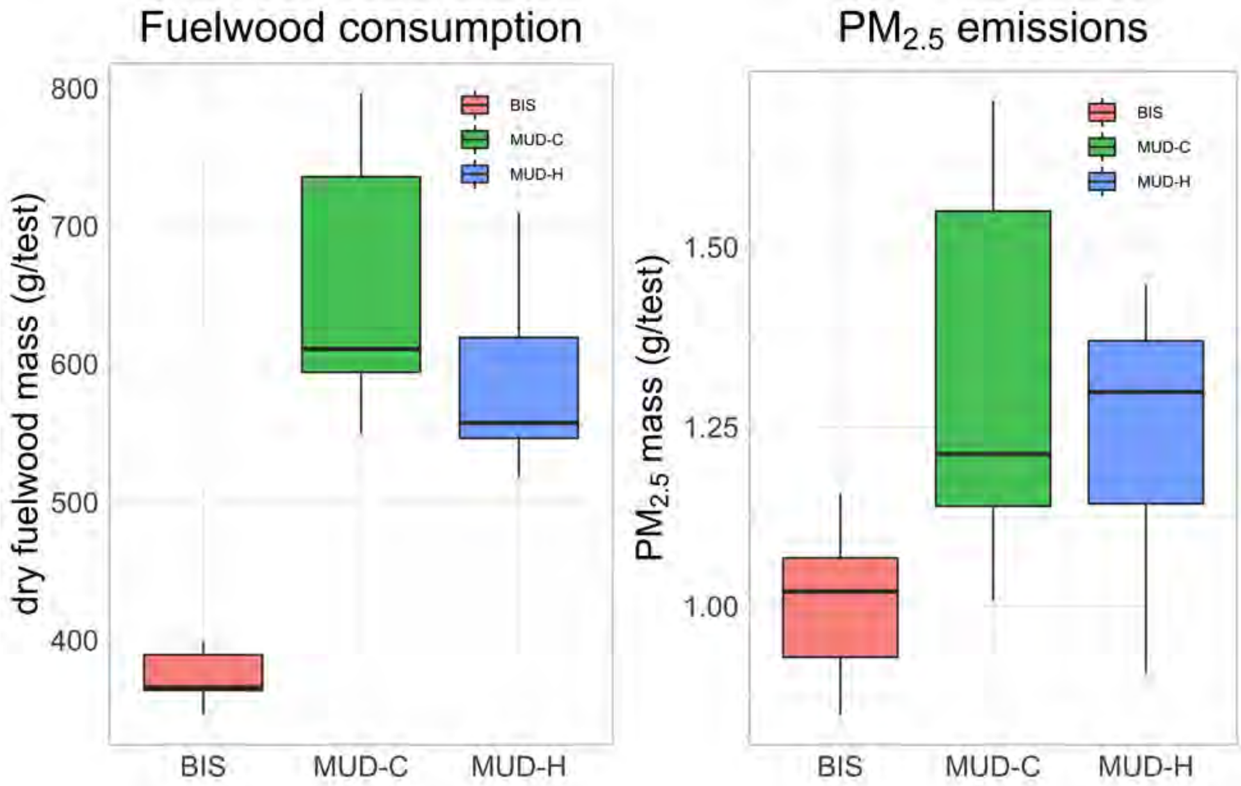

Figure 5.5: Left: fuelwood consumption in total mass (g) per test. Right: total $PM_{2.5}$ mass (g) per test, for BIS, cold mud chulha (MUD-C) and hot mud chulha (MUD-H). Note suppressed zero in y-axis on both plots.

mud chulha, respectively (shown in Figure 5.5 (Left)). We also found that the BIS' boiling time was 44% and 31% less than that of the cold mud chulha and the hot mud chulha, respectively. As expected, the hot mud chulha performs better than the cold mud chulha, since the former has a smaller cooling effect (sucks away less thermal energy) from fuelwood combustion. Compared to the BIS' air gap as an insulator, mud material is more insulating, so the stove remains hot for a while; the hot mud chulha does not quench the flame as much as the cold mud chulha. However, there is no pot skirt on the mud chulha to direct the hot air to the pot walls, and no firebox like that of the BIS to direct the fire right under the pot.

Our results indicate the lower total fuel consumption, $PM_{2.5}$ emissions, and time savings of the BIS compared to the mud chulha at both temperatures. The modified combustion efficiency of the BIS and the mud chulha tests (cold and hot) are all 97%, which is reflected in the similar emission factors between the BIS and mud chulha tests; however, the $PM_{2.5}$ emission factor is about 35% and 30% less for the cold and hot mud chulhas, respectively, compared to that of the BIS. The emission savings, in terms of total mass saved per cooking task, for the BIS compared to the mud chulha come from the improved thermal efficiency of the BIS, rather than improvements in the combustion efficiency. Due to the fuelwood savings, the BIS emitted 25% and 19% less $PM_{2.5}$ total mass per test compared to the cold and hot mud chulhas, respectively (see Figure 5.5 (Right)). Similarly, the BIS emitted less CO_2, CO, and BC, in units of total mass per test, than the cold and hot mud chulhas (see Table 5.2).

We conducted a small number of tests in the field with the BIS (n = 3) and the mud chulha (cold start, n = 3), bringing 1 L of water to boil. The results can be found in Appendix C. We found that the BIS used 64% less wood than the mud chulha used. The BIS' boiling time was 14% less than that of the mud chulha. However, more tests are needed for statistically-robust results [100].

Mud Chulha Compared to the Three-Stone Fire

We also compared the performance of the mud chulha to the performance of the three-stone fire found in the literature [80, 23], which is also used in rural Maharashtra. We should note that we did not use the same pot as these studies used for the three-stone fire. Compared to the three-stone fire (cold-start), the cold and hot mud chulhas had similar thermal efficiencies to Rapp et al. [80] of 23 ± 2% for the three-stone fire; however, Jetter et al. [23] found the three-stone fire's thermal efficiency to be 15%. The mud chulha's modified combustion efficiency, 97%, is the same as that of the three-stone fire, 97% from Jetter et al. [23] and 96.3% from Rapp et al. [80]. The cold mud chulha's boiling time (5 L of water) was longer at 39 min, compared to the three-stone fire's boiling time of 32 min [80] and 29 min [23]; however, the hot mud chulha's boiling time was 33 min. The cold and hot mud chulhas had lower CO and $PM_{2.5}$ emission factors than the three-stone fire [80].

Moreover, we compared our findings of the mud chulha to findings in the literature on two-pot mud chulhas [95, 96], although we followed different test procedures than them and have different variations (materials, size, and shape) of the mud chulhas. We found a BC emission factor (in units of g/MJ delivered to the pot) that was about 1-2 times higher compared to Garland et al. [96]. Pande [95] found a higher thermal efficiency (23.76%, SD = 0.29) than we found for both the cold and hot mud chulhas. Additionally, they found a CO emission factor (in units of g/MJ delivered to the pot) that was about double what we found for both the cold and hot mud chulhas.

Particle Distributions of the BIS and Mud Chulha

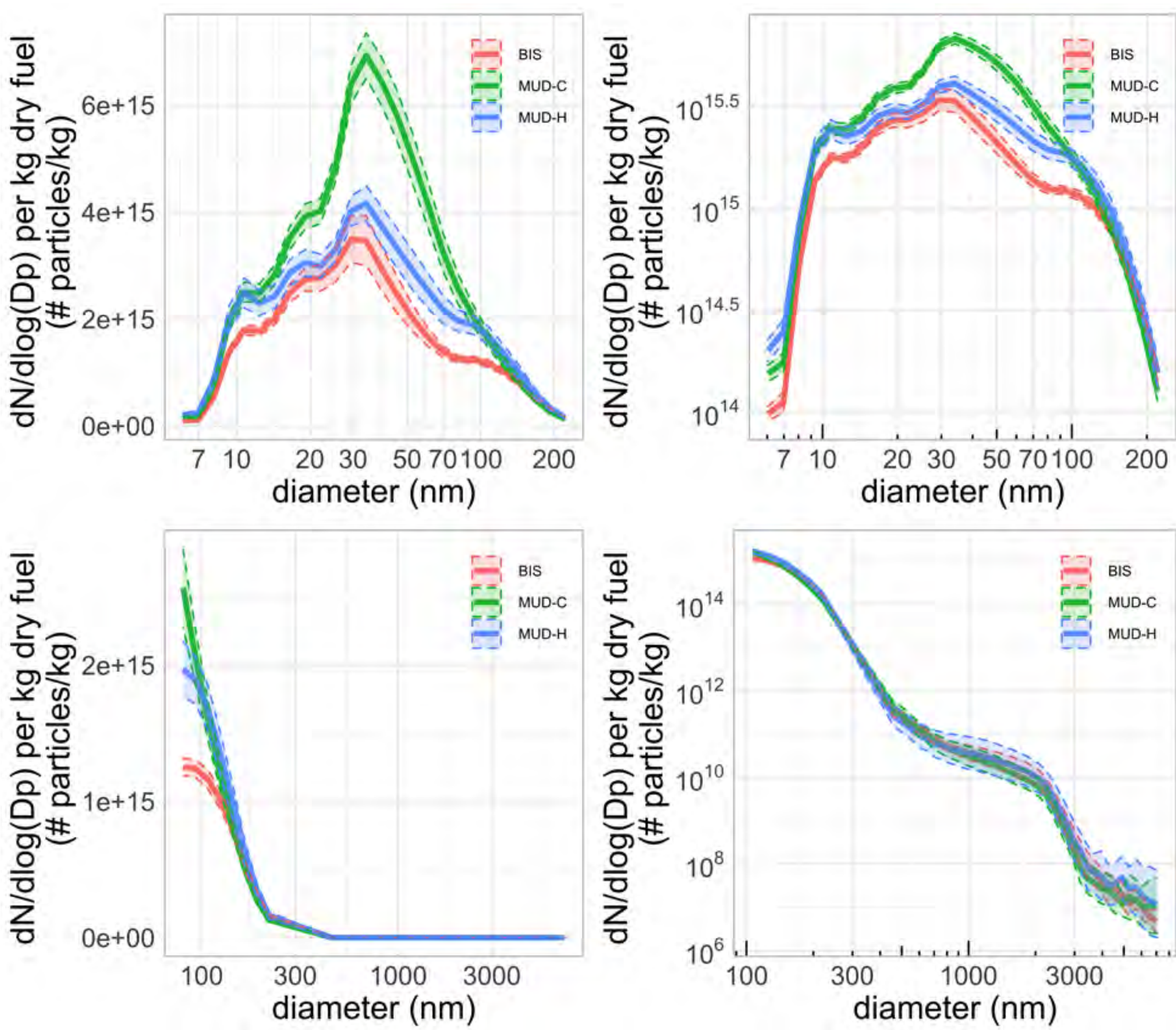

Figure 5.6: Particle size distribution for fine (diameter <2.5 mm) and ultrafine (diameter <1000 nm) particle number concentrations per kilogram of dry fuel consumed for the BIS (n = 13), cold-start mud chulha (MUD-C, n = 15),and hot-start mud chulha (MUD-H, n = 10) tests (bringing 5 L of water to boil) measured by the FMPS (top left and top right lots) and the OPS (bottom left and bottom right plots). Shaded bands represent 95% confidence bounds. Note that plots on the left are plotted on a normal-log scale and plots on the right are plotted on a log-log scale.

In Figure 5.6, we show the particle size distributions for fine particle (diameter <2.5 μ) and ultrafine particle (diameter <1000 nm) number concentrations per kilogram of dry fuel consumed for the BIS (n = 13), cold-start mud chulha (MUD-C, n = 15), and hot-start mud chulha (MUD-H, n = 10) tests (bringing 5 L of water to boil) on normal-log plots (left) and log-log plots (right). Similar to the findings in Rapp et al. [80] for the BDS, we observe a peak concentration around particle diameter, 34 nm. The cold and hot mud chulhas also have a peak concentration at 34 nm. For this peak particle size, 34 nm, the cold and hot mud chulhas generate 2.0 and 1.2 times more particles per kg of dry fuel, respectively, than the BIS. The reduced particle generation by the hot mud chulha compared to the cold mud chulha at 34 nm suggests that the hotter cookstove temperature reduces particle generation at this particle size, by allowing for better oxidation of the soot.

For particle sizes around 10 nm, both the cold and hot mud chulhas both generate 1.4 times more particles per kg of dry fuel than the BIS. This suggests that the hotter cookstove does not reduce particle generation at this smaller particle size. Similarly, at particle sizes around 100 nm, both the cold and hot mud chulhas generate 1.4 times more particles per kg of dry fuel than the BIS. This also suggests that the hotter cookstove does not reduce particle generation at this larger particle size. For particles larger than 100 nm, the BIS produces less particles per kg of dry fuel, up until particle size ~140 nm, thereafter the 95% confidence bounds overlap.

Cookstove Sensor Temperature Analysis

We used the results of the tests in the second category (49 tests bringing 2 L of water to boil (∼99°C) on the BIS at varying firepowers) and the third category (40 tests heating 2 L of water for 15 minutes on the BIS at varying firepowers), in which we measured CO_2, fuelwood use, and cookstove temperature, to determine if there were correlations between the cookstove steady state temperature and the firepower, the CO_2 emission rate, and the fuelwood burn rate. We define the cookstove's steady-state temperature as the average temperature at which the slope remains close to zero after the initial heating-up period (positive slope) and before the final cooling-down period (negative slope). For all tests, the average time to reach the steady-state temperature was 7.3 min (SD = 2.1). As we hypothesized, we found that the steady-state temperature increased with firepower. Previous studies have also found correlations between the exhaust temperature and the firepower [97, 98]. Graham et al. [66] presented a method of correlating the area under the temperature time series curve to the fuel energy, which we discuss below.

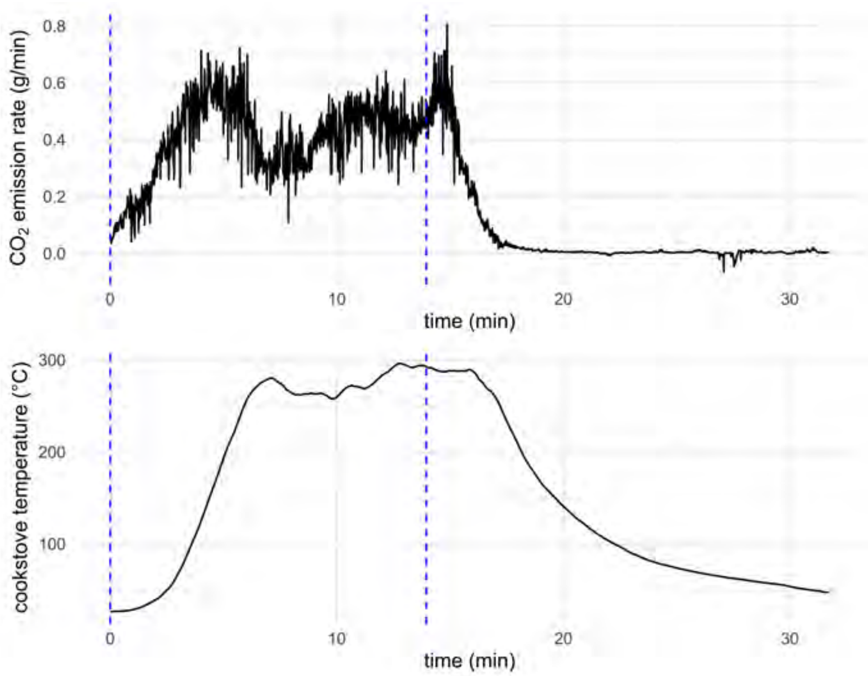

Figure 5.7: Top: Time series of the CO_2 emission rate (g/min)of the BIS at 1Hz. Bottom: Time series of BIS' firebox temperature at 1Hz. Both time series are from a BIS test of heating 2L of water from room temperature, for 15 minutes.

Figure 5.7 (Top) shows the time series of the CO_2 emission rate (g/min) and Figure 5.7 (Bottom) cookstove temperature for one test, heating 2 L of water for 15 minutes in the small pot, on the BIS. We found that the temperature cool down followed Newton's Law of

Cooling with k = 0.199 min^{-1}, $R^2 = 0.98$. The temperature time series follows the same trend (positive slope, near-zero slope, then negative slope) as the CO_2 emission rate time series, with the temperature time series lagging by a couple of minutes. See Appendix C for a time series of the mud chulha's sensor temperature.

Table 5.3: Rows 1-3: the resulting R^2 values from separate simple linear regression between fuelwood burn rate (g/min), CO_2 emission rate (g/min), and firepower (W) versus the BIS steady-state temperature ("ss-temp"). Rows 4-5: the resulting R^2 values from separate simple linear regression between dry fuelwood total mass (g/test) and CO_2 total mass (g/test) versus the area under the BIS temperature time series curve ("temp-area").

	15-min tests:			**Boiling tests:**		
	all (n = 40)	small pot (n = 20)	large pot (n = 20)	all (n = 49)	small pot (n = 27)	large pot (n = 22)
fuelwood burn rate vs. ss-temp, R^2	0.85	0.73	0.93	0.75	0.72	0.87
CO_2 rate vs. ss-temp, R^2	0.85	0.73	0.94	0.84	0.84	0.86
Firepower vs. ss-temp, R^2	0.85	0.73	0.93	0.75	0.71	0.87
Fuelwood mass vs. temp-area, R^2	0.82	0.76	0.90	0.77	0.72	0.92
CO_2 mass vs. temp-area, R^2	0.84	0.80	0.91	0.96	0.97	0.95

We conducted simple linear regressions for the cookstove steady-state temperature against different variables: firepower (W), CO_2 emission rate (g/min), and fuelwood burn rate (g/min). We conducted separate regressions for the two categories of tests (the 15-minute tests and the boiling-tests), and we also compared the regressions between the pot sizes within each category of tests. In Table 5.3, we present the resulting R^2 values from simple linear regressions between the cookstove steady-state temperature and different metrics (firepower, fuelwood burn rate, CO_2 emission rate). See Appendix C for the full equations for each regression. Because we did not vary the firepower for the mud chulha tests, we did not conduct regression analyses for the mud chulha. Moreover, previous research has shown weaker correlations between stove temperature and firepower for traditional stoves made of clay materials [97].

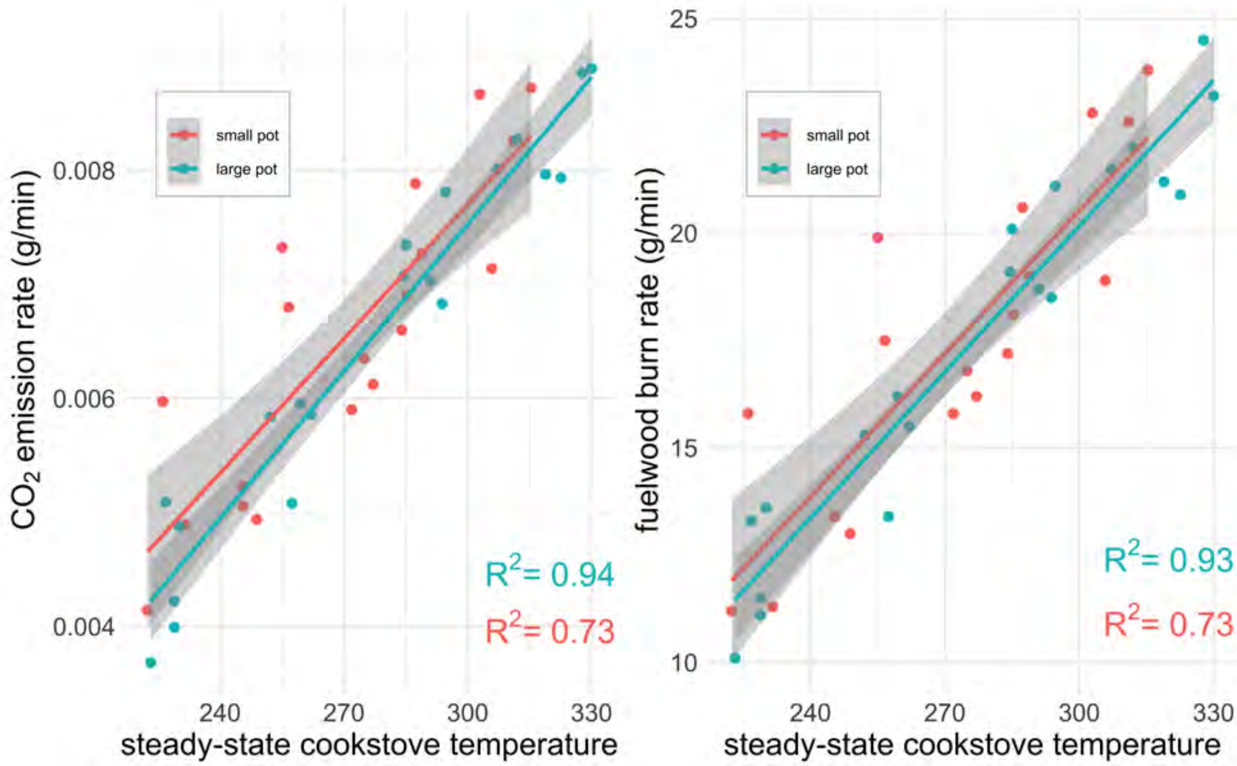

Figure 5.8: Left: CO_2 emission rate (g/min) versus steady-state cookstove temperature (°C). Right: Fuelwood burn rate (g/min) versus steady-state cookstove temperature (°C). Both plots use data from the BIS tests, heating 2 L of water for 15 minutes on the small pot (red, n = 20) and large pot (blue, n = 20). Lines represent simple linear regression fits for each pot size, with R^2 values shown in the bottom corners of the plots.

In Figure 5.8, we plot the steady-state cookstove temperature linear regressions with CO_2 emission rate (Left plot) and fuelwood burn rate (Right plot), specifically for the BIS' 15-minute tests. We found similar slopes between the small pot and large pot tests (see Appendix C), with some differences, suggesting that separate regressions may not be needed for different cooking vessels; however, the R^2 values are lower for the small pot. For all tests, we have R^2 values greater than 0.70, suggesting that steady-state cookstove temperature measurements of the cookstove can reasonably predict fuelwood use and CO_2 emissions. We found that for nearly all regressions, the R^2 values are higher for the large pot compared to the small pot, suggesting that using predictive power of these regressions may depend on cooking vessel size.

We also present the R^2 values for simple linear regressions between the area under the temperature time series curve and the metrics, fuelwood mass and CO_2 mass per test in Table 2. Graham et al. [66] found an R^2 of 0.93 for the regression of fuel energy versus area under the temperature time series curve; however, we should note that they followed a different test procedure, tested a forced-draft cookstove, and did not vary cooking vessel size. Compared to Graham et al. [66], we found lower R^2 values for fuelwood mass; however, we found higher R^2 values for the CO_2 mass for the boiling tests. We hypothesized that using the steady-state stove temperature to predict rates and the area under the temperature time series curve to predict total masses (or energies) would provide similar predictive powers since the area under the curve is essentially multiplying the steady-state cookstove temperature by the time from the beginning of the test to the start of the cool-down period.

5.4 Discussion

We began with examining the effects of the BIS design modifications on performance and emissions, compared to the original BDS design. We determined that the design modifications did not increase the emission factors, nor did they decrease the combustion efficiency. We observe that the different studies found varying values for some of the emission factors, likely due to different cookstove operators, but our values fall either between or near their findings [80, 23, 81]. However, the BIS had a lower thermal efficiency of 28% compared to 34-37% for the BDS, potentially owing to the different pot-rod design and smaller pot size compared to the Darfuri pot used on the BDS. The difference in thermal efficiencies affects the total fuelwood mass consumption and total pollutant mass emitted per cooking task. These results highlight the importance of verifying cookstove-specific emission factors and performance metrics. Moreover, these results merely confirm what has been observed by prior investigators that the combination of the cooking vessel (type and size) and the stove geometry, can affect the performance. This is important because the BIS allows for different sizes of cooking vessels, indicating that the thermal efficiency may change depending on the cooking vessel.

We found that the BIS outperformed the mud chulha, at both cold and hot starting temperatures, in terms of fuel consumption and total emissions for the same cookstove task. The thermal efficiency of the BIS was 28% compared to 18% and 21% for the cold and hot mud chulhas, respectively, resulting in 43% and 36% less fuelwood consumption for the BIS compared to the cold and hot mud chulhas, respectively. The hot mud chulha did perform better than the cold mud chulha as expected because the higher starting temperatures results in requiring less energy to heat up the mud chulha. Additionally, the BIS had similar CO_2 and CO emission factors to the cold and hot mud chulhas, but the $PM_{2.5}$ emission factor for the BIS was higher than the cold and hot mud chulhas. However, because of the increased thermal efficiency for the BIS, the BIS produced less total mass of CO_2, CO, $PM_{2.5}$, and BC compared to the mud chulha at both temperatures. The BIS also took less time to boil compared to both the cold and hot mud chulhas. These results are significant because they demonstrate the potential fuelwood, pollutant, and time savings the BIS can offer compared to the mud chulha at both temperatures.

We found a similar particle size distribution for the BIS and cold and hot mud chulhas, with peak particle generation at 34 nm, which has been found in Rapp et al. [80] for the BDS. For this peak particle size, 34 nm, the cold and hot mud chulhas generated 2.0 and 1.2 times more particles per kg of dry fuel, respectively, than the BIS. The reduced particle generation by the hot mud chulha compared to the cold mud chulha at 34 nm suggests that the hotter cookstove temperature reduces particle generation at this particle size, by allowing for better oxidation of the soot. Due to the long cooling period of the mud chulha, it is common for households to begin using the mud chulha at a hotter starting temperature.

We also found positive correlations (R^2 ranging between 0.71 to 0.94, depending on the test category) for simple linear regression analyses between the steady-state temperature of the cookstove's firebox and different metrics: fuelwood burn rate, CO_2 emission rate, and firepower. Additionally, we found positive correlations (R^2 ranging between 0.72 to 0.97, depending on the test category) for simple linear regression analyses between the area under temperature time series curve of the cookstove's firebox and different metrics: fuelwood mass and CO_2 mass. For nearly all of our tests, the correlations were stronger with the large pot size compared to the small pot size, suggesting that predictive power may depend on cooking vessel. These results agree with Graham et al. [66], which followed a different test procedure, although they found higher correlation between the area and fuel energy, $R^2 = 0.93$. However, they did not test the method for different cooking vessels and used a forced-draft cookstove.

In general, our results suggest that the temperature of the cookstove firebox—which also measures cookstove usage—may be a reasonable proxy for estimating fuelwood consumption and CO_2 emissions. These methods may potentially be used to provide more reasonable estimates than methods presented in methodology for cookstoves carbon offset projects. More research is needed to explore these methods in the field, as variables such as fuelwood type and moisture content will vary. Moreover, previous studies have found cookstoves to perform differently in field settings compared to lab-controlled settings [96]. Graham et al. [66] found that the methods performed worse in field than in laboratory settings, suggesting that estimations of CO_2 emissions from these temperature sensor methods may be less accurate when in the field. We suggest stove-specific correlations to be used, due to differences in cookstove materials and firebox variability affecting the steady-state temperatures. Moreover, more exploration is needed into the effects of cooking vessel type and size on these methods. Future work will involve validating these estimations with field measurements.

Chapter 6

Conclusion

6.1 Summary of Findings

The cookstoves sector faces notable gaps in knowledge and methodology, making it challenging to achieve sustained adoption and accurately measure impact. Common issues include unreliable survey methods, insufficient monitoring of usage, and inadequate methodologies to estimate carbon emissions. My research contributes to the improved cookstoves field by utilizing user-centered design techniques in design modification, conducting one of the longest improved cookstoves monitoring studies in the peer-reviewed published literature, investigating reasons for long-term dis-adoption of purchased cookstoves, and developing new methods for estimating cookstoves' carbon emissions in the field. Here we present the key takeaways from each chapter, based on lessons learned and methods used, in order to inform future cookstoves projects' methodologies.

In Chapter 2, we attempt to answer the question: How do we adapt a successful, cost-effective cookstove from one region to another? The key takeaways from Chapter 2 are as follows:

1. **First evaluate the need for the intervention technology in the area,**
2. **Start with a proven effective design, and**
3. **Include the user in every step.**

Before implementing any technology intervention in a specific area, it is crucial to assess its necessity and potential positive impact. We found that fuelwood collection is a major burden on women in rural Maharashtra. They may spend 3-6 h per day collecting fuelwood for about 8 months of the year. Women were interested in a fuel-efficient cookstove that would save them time and energy. We started with a proven effective cookstove design. The challenge we had was to adapt the cookstove to the region using user-centered design techniques to rural Maharashtra. Including the user in every step of the design and implementation process can lead to a more successful and sustainable technology intervention. This can help the technology meet the specific needs and preferences of the users. From our usage trials, 1-on-1 interviews, and focus group discussions with women in the region, we found that that it was critical to adjust the cookstove design to fit local cooking vessels and ensure its compatibility with staple local dishes.

In Chapter 3, we attempt to answer the question: How should we measure cookstoves' adoption? The key takeaways from Chapter 3 are as follows:

1. **Surveys exhibit different biases,**
2. **Sensors are necessary to measure quantitative metrics,**
3. **Usage should be measured over a long-term period, and**
4. **Qualitative survey data should be supported with sensor data.**

The case studies revealed several important findings regarding the accuracy of household reporting on improved cookstove usage. First, surveys alone will not provide a complete picture of cookstove usage over time. Regardless of whether households received the cookstove for free or purchased it themselves, they tended to over-report usage. Binary questions improved the accuracy of reporting, but at the cost of granularity in the data. Additionally, surveys were unable to capture the long-term decline in usage, which sensors were able to detect. Recall bias was also found, with households defaulting to nominal values when they could not remember exact usage. While surveys may provide qualitative insights, households reported advantages even when sensors recorded no usage, likely due to courtesy bias. These findings highlight the importance of using sensors to support survey responses and improve the accuracy of impact reports and design changes.

In Chapter 4, we attempt to answer the question: What are trends in long-term usage and why do households dis-adopt purchased cookstoves? The key takeaways from Chapter 4 are as follows:

1. **Initial usage varies widely,**
2. **Usage may be intermittent,**
3. **Usage should be measured long enough to capture its stabilization, and**
4. **Consistency, high daily usage, and long duration should be used as key indicators of sustained adoption.**

The study revealed several key findings regarding the long-term dis-adoption of improved cookstoves. About 43% of the households showed a decreasing trend in usage, and 16% never used the cookstove despite purchasing it. There were no households with high duration of use, high average daily usage, and an overall consistent trend in usage, indicating a lack of sustained adoption. Monitoring usage for at least 8 days was necessary to capture the beginning of usage for half of the households. Households used the stove intermittently, with some demonstrating intervals of nearly 3 months of no usage, on average, between periods of use. The average stabilization day of aggregate household data was 95 days (SD = 92), although it varied largely among individual households. Bathwater heating was the most reported task on the BIS among all user-categories, indicating the need for further exploration in designing and promoting the BIS and improved cookstoves more generally as task-specific cookstoves. We found that certain design features of the BIS may have contributed to its overall dis-adoption.

In Chapter 5, we attempt to answer the question: How can we more accurately measure CO_2 emissions and fuelwood consumption from improved cookstove use in the field? The key takeaways from Chapter 5 are as follows:

1. **Using cookstove-specific performance metrics is more accurate,**
2. **Cooking vessels affect cookstove performance, and**
3. **Temperature sensors may be a useful tool to measure CO_2 emissions and fuelwood consumption from cookstoves.**

The study compared the performance of the BIS and mud chulha cookstoves in terms of fuelwood consumption and total emissions. The results showed that the BIS outperformed the mud chulha, leading to potential savings in fuelwood, pollutants, and time. However, although the BIS did not increase CO and $PM_{2.5}$ emission factors, the modified design resulted in lower thermal efficiency compared to the original BDS design, potentially due to the differences in cooking vessel size and placement. The study found positive correlations between the steady-state temperature of the cookstove's firebox and different metrics, indicating that cookstove temperature may be a reasonable proxy for estimating CO_2 emissions and fuelwood consumption. Simple linear regression analyses were used to establish these positive correlations, although predictive power varied with different cooking vessels.

6.2 Future Work

This dissertation provides valuable insights into the long-term dis-adoption of improved cookstoves and evaluates various tools to measure the impact of cookstove interventions. The research findings suggest that while improved cookstoves have the potential to reduce emissions and fuelwood use and thus, drudgery faced by women in developing countries, challenges remain that need to be addressed in order to ensure the effectiveness and sustainability of these interventions.

One area that requires further research is the use of randomized controlled trials (RCTs) with purchased and free cookstove control groups. This approach can help to determine the most effective interventions by isolating the impact of the intervention from other factors that may influence adoption. It is also important to increase the size of study participants in monitoring studies to provide more robust results and insights into the factors or household attributes contributing to the adoption or dis-adoption of cookstoves. Additionally, the use of more sensors to measure concurrent usage of other cookstoves owned in the households could provide a more comprehensive picture of stove stacking and household energy use. In addition to exploring different intervention designs, developing new cookstove designs based on the findings of design barriers with the BIS may also improve adoption and usage rates. For example, designing a multi-pot improved biomass cookstove, which was a majorly reported design barrier of the BIS, could be a potential solution. Evaluating the adoption and usage of a multi-pot improved biomass cookstove in the region could provide valuable insights into the feasibility of this design.

Furthermore, this dissertation highlights the need to test the temperature datalogger method to measure CO_2 emissions and fuelwood consumption in the field, where more variables exist, and then compare it to lab results. This method may provide more accurate and reliable data on cookstove usage and emissions, which is essential for evaluating impact and reporting carbon offsets from cookstove projects. It is important to test the accuracy of this method with different cookstoves, such as baseline cookstoves like the three-stone fire and mud chulha, in order to ensure its reliability in various settings. Moving forward, collaboration with local communities and stakeholders to tailor cookstove interventions is essential. The future work ideas presented in this dissertation can guide further investigation to improve the effectiveness and sustainability of cookstove interventions.

6.3 Concluding Thoughts

This dissertation highlights the challenges and opportunities associated with cookstove interventions in developing countries. The research shows that designing improved cookstoves with the user is critical, but more robust data collection methods are needed to evaluate cookstoves' impact. Through monitoring studies in rural India, the limitations of survey-based methods in measuring cookstove usage and impact were highlighted. The findings underscore the need for comprehensive data collection methods to inform decision-making and program design. Moving forward, collaboration with local communities and stakeholders to tailor cookstove interventions is essential. Continued research and collaboration are necessary to address the world's deadliest environmental health threat. Moreover, this research has implications for development initiatives more broadly. In addition to offering insights into the technology-intervention adoption, my findings suggest the necessity of using reliable, long-term methods to assess impact of interventions in low-resource settings.

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Appendix A

Supporting Information for Chapter 3

A.1 Follow-up Surveys

Category 3 Villages

CMBIS Survey

Survey Code	**Date (i.e. 13/Jul/2017)**	**Time (i.e. 1:30 PM)**	**Name of enumerator administering survey**

Note: this survey is to be given only if the customer agrees to participate in the study via the Informed Consent document. Complete from start to "END OF SURVEY".

***SAY: Good morning/afternoon, my name is ________________________ (enumerator's name). I am working with Bharat Thombre and the University of California, Berkeley on this fuelwood collection project.

I would like you to know that if you feel uncomfortable at any time you may ask to skip a question or opt-out of taking the survey entirely. Do you understand?

1. Yes 2. No

Is your name (the name of the woman on the informed consent document)? (note: do not write name here)

1. Yes 2. No

Note: If the woman is not the woman on the informed consent document, find the woman who agreed to the informed consent document. If the correct woman is not available, terminate the interview.

Gender of the respondent (Do not ask: circle response)	1. Male 2. Female
What is your age in years?	Age _______
How many people live in your household?	Total Number: _________ a) Women: _________ b) Men: _________ c) Girls (under14): _________ d) Boys (under 14): _________
What is your (highest) level of education?	
What is your occupation?	
In your household, how many people on average are cooked for per day (In other words, number of people that eat from the same pot)?	Total Number: _________ a) Women: _________ b) Men: _________ c) Girls (under14): _________ d) Boys (under 14): _________
Do you cook for commercial purposes? In other words, is a significant portion of your cooking activities for people living outside of your household?	1. Yes 2. No

Category 3 Villages

Does the amount of people you cook for per day vary throughout the year?	1. Yes 2. No
If Yes, please explain how the number of people varies throughout the year.	
Please describe all cookstoves that you use in your home. (Label the primary, secondary, tertiary cookstoves).	Circle applicable codes: 1. Cool Mesh Berkeley India Stove (only for 2-week follow-up & continued follow-up surveys) 2. Clay/mud chulha 3. Three-stone fire 4. Basic metal charcoal stove 5. Basic metal wood/dung stove 6. Kerosene stove 7. LPG stove 8. Electric stove 9. Other (describe):
Please describe all fuels that you use in your home. (Label the primary, secondary, tertiary fuels).	Circle applicable codes: 1. Wood 2. Charcoal 3. Dung 4. Crop residues 5. Kerosene (not for fire lighting) 6. LPG 7. Electricity 8. Other (describe):
What is your household's primary cookstove (& fuel) used to prepare **<u>food</u>**?	Circle one: 1. Cool Mesh Berkeley India Stove ((only for 2-week follow-up & continue follow-up surveys) 2. Clay/mud chulha 3. Three-stone fire 4. Basic metal charcoal stove 5. Basic metal wood/dung stove 6. LPG stove 7. Electric stove 8. Other (describe):
What is your household's primary cookstove (& fuel) used to prepare **<u>drinks like tea</u>**?	Circle one: 1. Cool Mesh Berkeley India Stove (only for 2-week follow-up & continued follow-up surveys) 2. Clay/mud chulha 3. Three-stone fire 4. Basic metal charcoal stove 5. Basic metal wood/dung stove 6. LPG stove 7. Electric stove 8. Other (describe):

Category 3 Villages

How often do you collect fuelwood per week per season? (monsoon, winter, summer)	
Where do you go to collect fuelwood and why?	
What time of day do you go to collect fuelwood?	
How long does one fuelwood collection trip typically take?	
Who typically goes to collect fuelwood with you? Ages? Gender?	
Why do you collect fuelwood together?	
How long does one fuelwood bundle typically last?	
Do you ever purchase fuelwood? If so, at what price per kg?	
What species of wood do you collect?	
Do you enjoy or dislike collecting fuelwood?	
What would you do with your time if you did not have to collect fuelwood?	

END OF SURVEY

Category 1 Villages

CMBIS Survey

Survey Code (cookstove serial number)	**Date (i.e. 13/Jul/2017)**	**Time (i.e. 1:30 PM)**	**Name of enumerator administering survey**

Note: this survey is to be given only if the customer agrees to participate in the study via the Informed Consent document. Complete from start to "END OF SURVEY".

***SAY: Good morning/afternoon, my name is ________________________ (enumerator's name). I am working with Bharat Thombre and the University of California, Berkeley on this cookstove project.

I would like you to know that if you feel uncomfortable at any time you may ask to skip a question or opt-out of taking the survey entirely. Do you understand?
1. Yes 2. No

Is your name (the name of the woman on the informed consent document)? (note: do <u>not</u> write name here)
1. Yes 2. No

Note: If the woman is not the woman on the informed consent document, find the woman who agreed to the informed consent document. If the correct woman is not available, terminate the interview.

Gender of the respondent (Do not ask: circle response)	1. Male 2. Female
What is your age in years?	Age _______
How many people live in your household?	Total Number: _________ a) Women: _________ b) Men: _________ c) Girls (under14): _________ d) Boys (under 14): _________
What is your occupation?	
In your household, how many people on average are cooked for per day (In other words, number of people that eat from the same pot)?	Total Number: _________ a) Women: _________ b) Men: _________ c) Girls (under14): _________ d) Boys (under 14): _________
Do you cook for commercial purposes? In other words, is a significant portion of your	1. Yes 2. No

Category 1 Villages

cooking activities for people living outside of your household?	
Does the amount of people you cook for per day vary throughout the year?	1. Yes 2. No
If Yes, please explain how the number of people varies throughout the year.	
Please describe all cookstoves that you use in your home. (Label the primary, secondary, tertiary cookstoves).	*Circle:* 1. Cool Mesh Berkeley India Stove 2. Clay/mud chulha 3. Three-stone fire 4. Basic metal charcoal stove 5. Basic metal wood/dung stove 6. Kerosene stove 7. LPG stove 8. Electric stove 9. Other (describe):
Please describe all fuels that you use in your home. (Label the primary, secondary, tertiary fuels).	*Circle:* 1. Wood 2. Charcoal 3. Dung 4. Crop residues 5. Kerosene (not for fire lighting) 6. LPG 7. Electricity 8. Other (describe):
What is your household's primary cookstove (& fuel) used to prepare **food**?	*Circle:* 1. Cool Mesh Berkeley India Stove 2. Clay/mud chulha 3. Three-stone fire 4. Basic metal charcoal stove 5. Basic metal wood/dung stove 6. LPG stove 7. Electric stove 8. Other (describe):
What is your household's primary cookstove (& fuel) used to prepare **drinks like tea**?	*Circle:* 1. Cool Mesh Berkeley India Stove 2. Clay/mud chulha 3. Three-stone fire 4. Basic metal charcoal stove 5. Basic metal wood/dung stove 6. LPG stove 7. Electric stove 8. Other (describe):

Category 1 Villages

From whom did you obtain the CMBIS?	
When did you receive the CMBIS?	
Did you receive the CMBIS for free or for a nominal fee? If so, for how much?	
If a fee was paid, **<u>why</u>** did you or your HH decide to purchase the CMBIS?	
How often did you use the CMBIS? (duration and frequency)	
What was the most common fuel you burned in the CMBIS?	*Circle:* 1. Wood 2. Charcoal 3. Dung 4. Crop residues 5. Other (describe)
What do you dislike about the CMBIS, starting with the worst?	
Mark the attributes of the CMBIS that the interviewee mentioned as negative.	*Rank:* ______ Size (too big/small) circle one ______ Stability ______ Fuel preparation (breaking wood into small sticks) ______ Ugly (color, shape) ______ Complicated to operate ______ Difficult to add fuel
What do you like about the CMBIS, starting with the best?	

Category 1 Villages

Mark the attributes of the CMBIS that the interviewee mentioned as positive.	*Rank:* ______ Less smoke ______ Portability ______ Size ______ Saving fuel ______ Cooking quickly ______ Being able to show it to friends and family
Would you recommend the CMBIS to a friend or family member?	1. Yes 2. No
Do you prefer the CMBIS over your traditional (or primary) cookstove?	1. Yes 2. No

Notes/Observations about the interview and about the state of the cookstove:

END OF SURVEY

Appendix B

Supporting Information for Chapter 3 and 4

B.1 Project Timeline

Figure B.1: Timeline of the work leading up to and during the free trial monitoring study and post-purchase monitoring, and the conclusion of the studies.

B.2 Weekly Usage of Accurate and Inaccurate Reporters

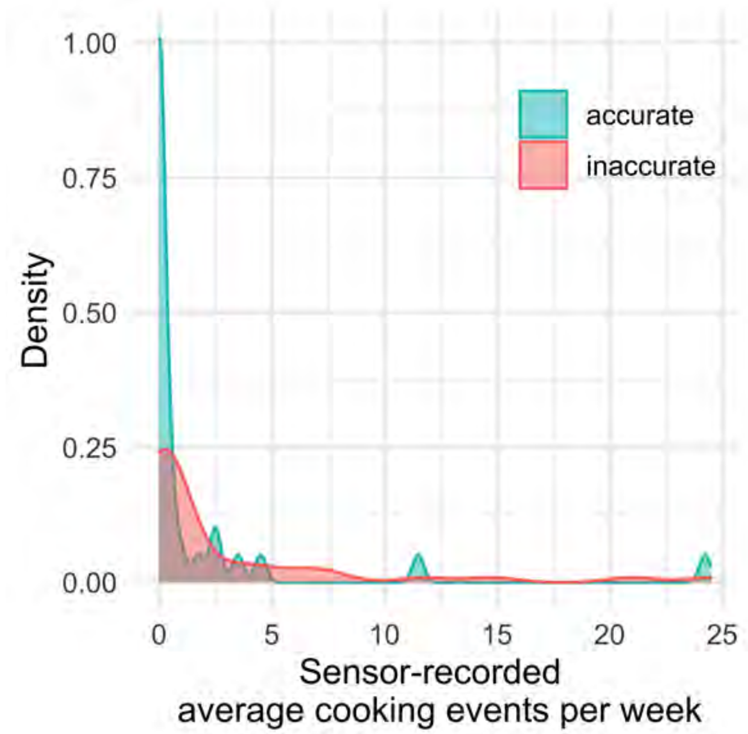

Figure B.2: Density plots of post-purchase households' sensor-recorded average cooking events per week, separated by accurate (defined as survey data agreeing within ±10% of sensor data) reporters (blue) and inaccurate reporters (pink). Density plots integrate to 1. Follow-up 1 (n=75).

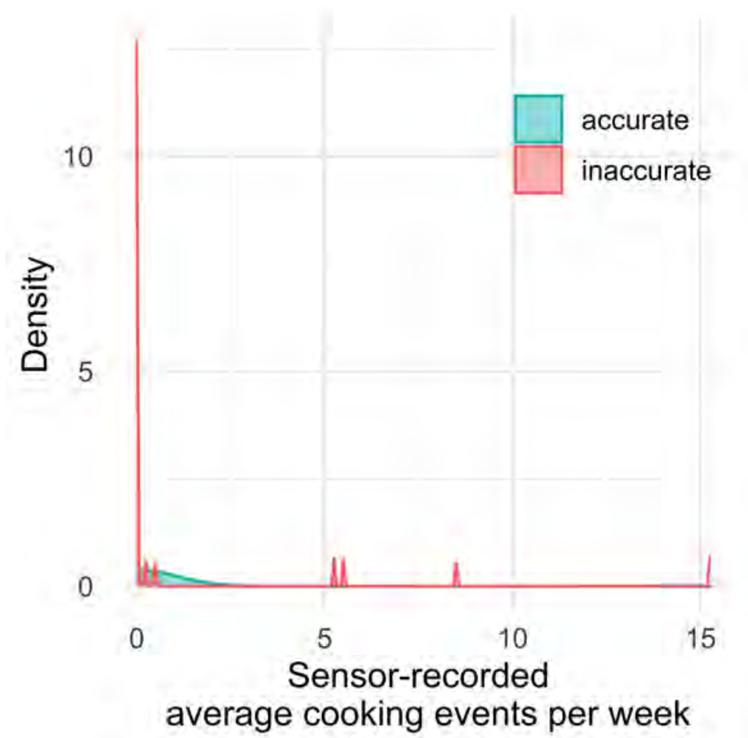

Figure B.3: Density plots of post-purchase households' sensor-recorded average cooking events per week, separated by accurate (defined as survey data agreeing within ±10% of sensor data) reporters (blue) and inaccurate reporters (pink). Density plots integrate to 1. Follow-up 2 (n=69).

B.3 Follow-up Survey

Name:

Sensor #:

Village:

Survey Code (cookstove serial number)	**Date (i.e. 13/Jul/2017)**	**Time (i.e. 1:30 PM)**	**Name of enumerator administering survey**

Note: If the woman is not the woman on the informed consent document, find the woman who agreed to the informed consent document. If the correct woman is not available, terminate the interview.

Before beginning survey, confirm that this person has purchased a Berkeley-India Stove.	☐ Yes, purchased.
Gender of the respondent (Do not ask: circle response)	1. Male 2. Female
How many people live in your household?	Total Number: _________ a) Women: _________ b) Men: _________ c) Girls (under14): _________ Boys (under 14): _________
How many years ago did your family come to this village/town?	
How many standards/years of education of the head of household?	
What is the occupation of the main wage earner in the household (if different than respondent)? Who?	1. Cultivator 2. Farm laborer 3. Other daily labor 4. Animal husbandry/dairy 5. Shop/small business/cottage industry 6. Job 7. Professional
How much cash per week does this occupation bring in? And, for how many months of the year?	

Have you used the Berkeley-India Stove at least once in the last year?	1. Yes 2. No
Have you used the Berkeley-India Stove at least once in the last 1 month?	1. Yes 2. No
What is the average number of times per week that you have used the BIS in the last month?	
In one week, how many days do you use the Berkeley-India Stove?	
How many times per day do you use the Berkeley-India Stove?	
What do you use the Berkeley-India Stove for? (i.e. food or bathwater heating?)	
If they state they **ARE** using it: What **advantages** do you have using the Berkeley-India Stove? (e.g. less smoke, portability, size, saving fuel, cooking quickly) What **difficulties** do you have using the Berkeley-India Stove? (e.g. size, stability, fuel preparation, ugly, no multi-tasking, complicated to operate, difficult to add fuel)	

<table>
<tr><td>If they state they ARE NOT using it:

Why do you not use the Berkeley-India Stove?
(e.g. size, stability, fuel preparation, ugly, no multi-tasking, complicated to operate, difficult to add fuel)

Do you plan to use the Berkeley-India Stove later? If so, when?</td><td></td></tr>
<tr><td>What cookstoves are currently in your household?

And what do you use each for?</td><td>Circle applicable codes:
1. Berkeley India Stove
2. Clay/mud chulha
3. Three-stone fire
4. Basic metal charcoal stove
5. Basic metal wood/dung stove
6. Kerosene stove
7. LPG stove
8. Electric stove
Other (describe):</td></tr>
<tr><td>Ask for wood weights (and moisture Contents, diameters) for the following items:</td><td>1. One full day:
Weight: ____________
2. Bathwater heating:
Weight: ____________
3. Common task or meal: (rice/daal)
Weight: ____________
4. Collect 3 moisture contents:
M.C.: ____________
M.C.: ____________
M.C.: ____________</td></tr>
</table>

Note where the CMBIS is kept (and where their other cookstoves are kept).	
Notes/Observations about the interview and about the state of the cookstove (please indicate whether Geocene Dot functionality could have been compromised by any obvious factors such as broken switches, melted wires, or other damage).	
Download data from sensor.	Date downloaded: ______________________
Replace batteries in sensor.	Date replaced: __________________________

Appendix C

Supporting Information for Chapter 5

C.1 Mud chulha details

Figure C.1: Top view of mud chulha.

The artist used "Black Mountain Sculpture" clay purchased form ClayPeople in Richmond, CA and studied a video (https://www.youtube.com/watch?v=1Oo_gGc8OTQ&ab_channel=JitendraVlogs) similar to the mud chulha found in rural Maharashtra to replicate the process. They incorporated dried grass and water into the material. We assumed that the emissivity and heat capacity of the material was comparable to clay and mud mixture that was used by women in the villages in rural Maharashtra.

C.2 Performance Metrics Equations

Thermal efficiency (h_c):

$$h_c = \frac{m_{H2O} C_p \Delta \mathrm{T} + \ w_{cv} \bullet \Delta \mathrm{h}_{H2O,fg}}{f_{cd} \bullet LHV}$$

m_{H2O} is the mass of water in the pot at the end of the test, C_p is the specific heat capacity of water (4.186 kJ/kg-K), ΔT is the difference in the final and initial temperature of the water in the pot, w_{cv} is the mass of the water evaporated, $\triangle h_{H20,fg}$ is the specific enthalpy of vaporization of water (2260 kJ/kg), f_{cd} is the mass of equivalent dry fuel consumed, and LHV is the lower heating value of the fuel (18766 kJ/kg for Douglas fir).

Modified combustion efficiency (MCE):

$$MCE = \frac{\Delta CO_2}{\Delta CO_2 + \ \Delta \mathrm{CO}}$$

$\triangle CO_2$ is the difference between the mean duct CO_2 concentration and the ambient CO_2 concentration (ppmv). $\triangle CO$ is the difference between the mean duct CO concentration and the ambient CO concentration (∼0 ppmv).

Corrected time-to-boil ($\triangle t_{corr}$):

$$\Delta \mathrm{t}_{corr} = \ \Delta \mathrm{t} \ \bullet \frac{75}{T_f - \ T_i}$$

$\triangle t$ is the measured time to boil, T_f is the final temperature of the water and T_i is the initial temperature of the water.

Firepower (W):

$$Firepower = \frac{f_{cd} \bullet LHV}{\Delta \mathrm{t}_{corr} \bullet 60}$$

All variables defined above.

$PM_{2.5\ total}$ mass (mg):

$$PM_{2.5_{total}} = PM_{2.5_{filter}} \times \frac{\overline{Q_{duct}}\ [CFM]}{Q_{sample}\,[CFM]}$$

$PM_{2.5,total}$ is the total mass of PM emitted during the cold start, $\overline{Q_{duct}}$ is the average duct flow rate throughout the test, Q_{sample} is the constant sample flow rate through the gravimetric filter (16.7 LPM or 0.590 CFM), and $PM_{2.5,\ filter}$ is the mass of $PM_{2.5}$ collected on the 47 mm filter, calculated as the difference in the filter's mass before and after testing (taken from Caubel [99]).

Total mass of gaseous emissions (CO or CO_2) (g):

$$\mathrm{m_{gas}[g]} = \sum_{\mathrm{t=0}}^{\mathrm{t=tf}} \frac{\mathrm{C_{gas}\,(t)\,[ppmv] \times MW\left[\frac{g}{mol}\right] \times Q_{duct}\,(t)\left[\frac{m^3}{sec}\right] \times P_{amb}\,[Pa] \times \Delta t\,[sec]}}{\mathrm{R[\frac{J}{molK}] \times (T_{duct}[^\circ C] + 273)}}$$

m_{gas} [g] is the total mass of gaseous emissions, t is the time step, t_f is the duration of the cold start test, C_{gas} is the volumetrics gas concentration, MW is the molecular weight of the gas species, Q_{duct} is the flow through the duct measured every second at the iris damper, P_{amb} is the ambient pressure (97.77 KPa at the laboratory's altitude of 300 m MSL), $\triangle t$ is the sampling period (1 second), R is the ideal gas constant (8.314 J/ (mol K)), and T_{duct} is the temperature in the duct, also logged every second (taken from Caubel [99]).

Total mass of BC (g):

$$m_{BC}\,[g] = \sum_{t=0}^{t=t_f} C_{BC}\,(t)\left[\frac{g}{m^3}\right] \times MW\left[\frac{g}{mol}\right] \times Q_{duct}\,(t)\left[\frac{m^3}{sec}\right] \times \overline{DR} \times \Delta \mathrm{t}\,[sec]$$

m_{BC}[g] is the total mass of black carbon, C_{BC} is the black carbon concentration, and $\overline{DR}$ is the mean dilution ratio through the secondary diluter over the course of the test. For each test, the secondary dilution ratio is calculated in real time as the ratio of CO_2 concentrations in the duct and diluted sampled flow (taken from Caubel [99]).

C.3 Cookstoves Testing Data

Field Testing Data

Table C.1: Testing data for field tests (n = 3) of the BIS and mud chulha (cold start), boiling 1 L of water.

	BIS (n = 3)	**MUD-C (n = 3)**	**BIS/MUD-C ratio**
Dry fuelwood mass (g/test)	103 ± 6	289 ± 80	0.36
boiling time (min)	12 ± 2	14 ± 4	0.86

BIS vs. Mud Chulha Plots

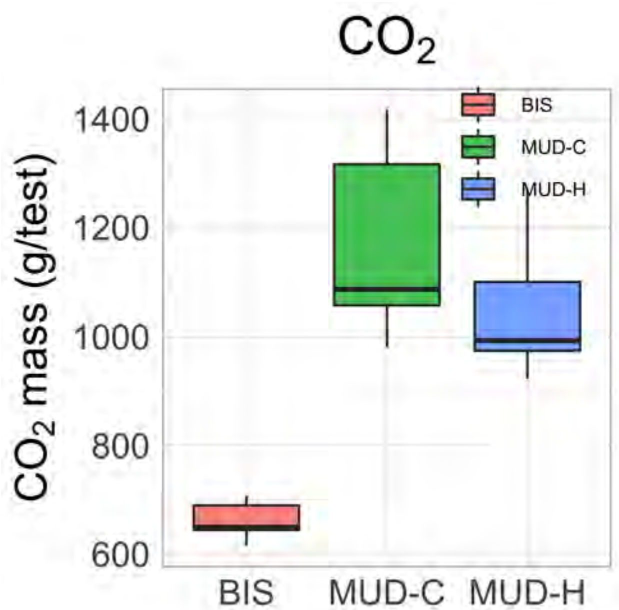

Figure C.2: Total CO_2 mass (g) per test, for BIS, cold mud chulha (MUD-C) and hot mud chulha (MUD-H). Note suppressed zero in y-axis.

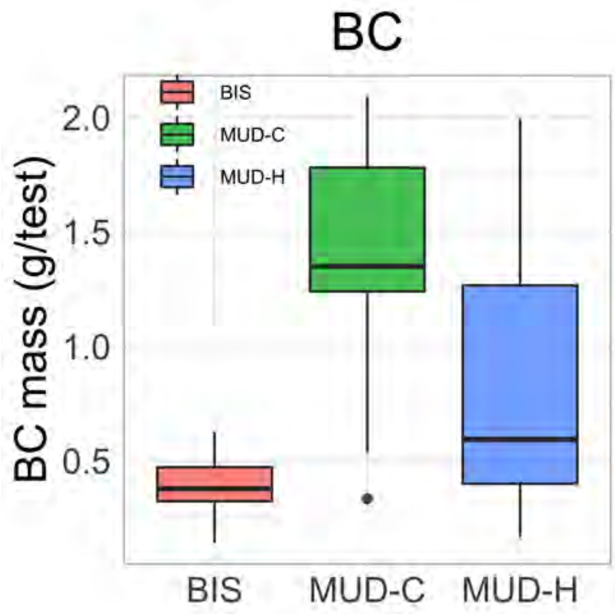

Figure C.3: Total BC mass (g) per test, for BIS, cold mud chulha (MUD-C) and hot mud chulha (MUD-H). Note suppressed zero in y-axis.

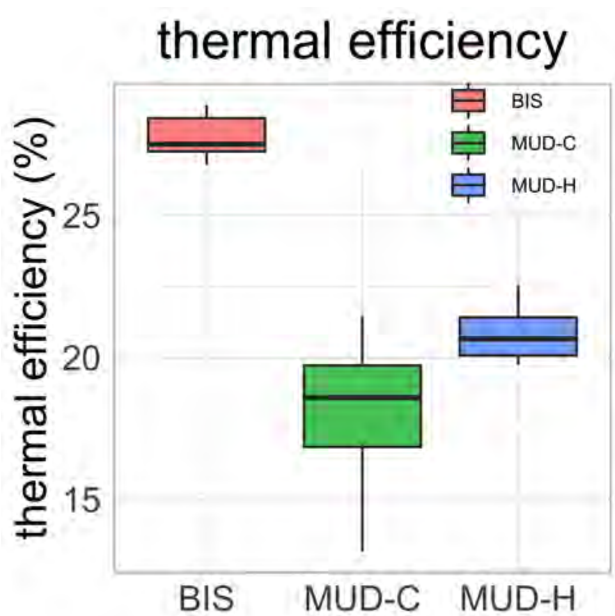

Figure C.4: Thermal efficiency per test, for BIS, cold mud chulha (MUD-C) and hot mud chulha (MUD-H). Note suppressed zero in y-axis.

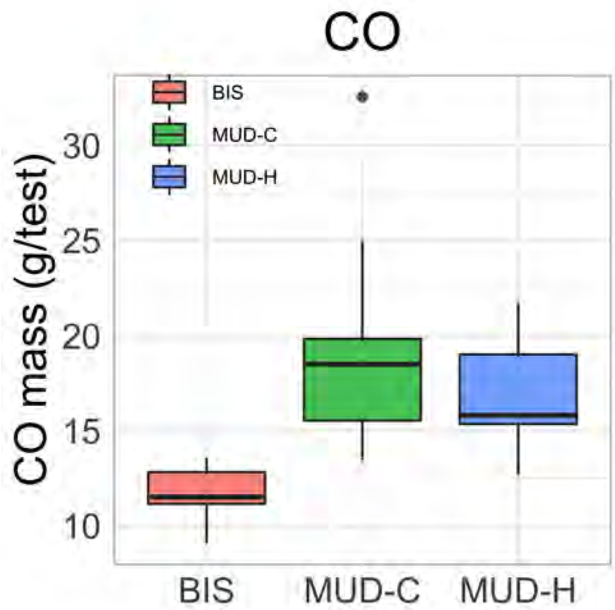

Figure C.5: Total CO mass (g) per test, for BIS, cold mud chulha (MUD-C) and hot mud chulha (MUD-H). Note suppressed zero in y-axis.

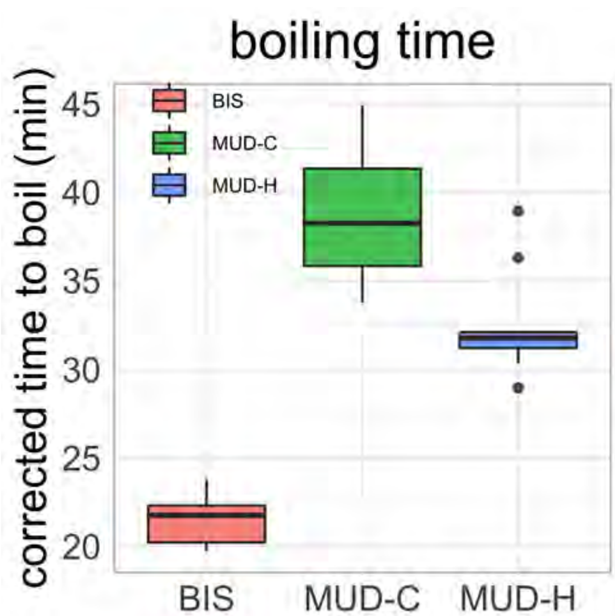

Figure C.6: Boiling time (corrected) per test, for BIS, cold mud chulha (MUD-C) and hot mud chulha (MUD-H). Note suppressed zero in y-axis.

BIS Testing Data

Table C.2: Performance metrics for individual BIS tests, boiling 5 L of water.

BIS Test #	Firepower (W)	Equivalent dry fuelwood (g)	Thermal efficiency (%)	Corrected time to boil (min)
1	5800	363	28.6	19.7
2	5902	389	27.4	20.2
3	5945	364	27.2	20.2
4	5602	346	28.9	20.0
5	5578	360	28.3	20.9
6	5157	361	28.4	22.7
7	5627	382	27.3	21.4
8	5285	364	28.6	22.3
9	5182	397	27.3	23.6
10	5386	382	28.0	21.8
11	5536	399	26.8	22.0
12	5504	366	27.5	22.1
13	5193	392	27.1	23.8
Mean (95% CI)	5515 ± 161	374 ± 10	27.8 ± 0.4	21.6 ± 0.8

Table C.3: Performance metrics for individual BIS tests, boiling 5 L of water.

BIS Test #	**Modified combustion efficiency (%)**	**Fuelwood burn rate (g/min)**	**Exhaust carbon concentration (ppm)**
1	97.2	18.5	2876
2	97.1	18.9	2927
3	97.3	19.0	2892
4	97.6	17.9	2752
5	97.2	17.8	2720
6	97.2	16.5	2527
7	96.8	18.0	2727
8	97.2	16.9	2564
9	97.0	16.6	2526
10	97.2	17.2	2706
11	97.1	17.7	2709
12	97.4	17.6	2688
13	97.0	16.6	2537
Mean (95% CI)	97.2 ± 0.1	17.6 ± 0.5	2704 ± 83

Table C.4: Emissions for individual BIS tests, boiling 5 L of water.

BIS Test #	**CO_2 total mass (g) (duct)**	**CO total mass (g) (duct)**	**$PM_{2.5}$ total mass (g)**	**BC total mass (g)**
1	494	9.49	0.91	0.37
2	531	10.46	0.85	0.45
3	490	8.89	0.93	0.60
4	469	7.57	0.92	0.38
5	478	8.96	1.01	0.41
6	483	9.49	1.16	0.62
7	500	11.00	1.02	0.30
8	478	9.56	1.05	0.47
9	517	10.74	1.07	0.32
10	516	9.92	1.00	0.26
11	522	10.24	1.07	0.37
12	480	8.78	1.10	0.52
13	501	10.63	1.06	0.14
Mean (95% CI)	497 ± 12	9.67 ± 0.6	1.01 ± 0.05	0.40 ± 0.08

Table C.5: Emissions for individual BIS tests, boiling 5 L of water.

BIS Test #	**Cooking energy CO_2 emissions (g/MJ_{del}) (duct)**	**Cooking energy CO emissions (g/MJ_{del}) (duct)**	**Cooking energy $PM_{2.5}$ emissions (g/MJ_{del})**	**Cooking energy BC emissions (g/MJ_{del})**
1	253	4.86	0.47	0.19
2	265	5.22	0.42	0.23
3	263	4.77	0.50	0.32
4	250	4.04	0.49	0.20
5	250	4.69	0.53	0.21
6	251	4.93	0.60	0.32
7	255	5.61	0.52	0.16
8	244	4.88	0.54	0.24
9	254	5.29	0.53	0.16
10	257	4.95	0.50	0.13
11	260	5.11	0.53	0.18
12	254	4.65	0.58	0.28
13	252	5.33	0.53	0.07
Mean (95% CI)	255 ± 3	4.95 ± 0.2	0.52 ± 0.03	0.21 ± 0.04

Table C.6: Emissions for individual BIS tests, boiling 5 L of water.

BIS Test #	**CO_2 total mass (g) (WBT)**	**CO total mass (g) (WBT)**	**Cooking energy CO_2 emissions (g/MJ$_{del}$) (WBT)**	**Cooking energy CO emissions (g/MJ$_{del}$) (WBT)**
1	644	11.3	330	5.77
2	690	12.7	344	6.34
3	647	11.1	347	5.94
4	615	9.1	328	4.85
5	638	11.2	334	5.83
6	640	11.4	332	5.90
7	675	13.6	344	6.91
8	645	11.5	330	5.88
9	703	13.3	346	6.56
10	677	12.1	338	6.02
11	707	12.8	353	6.39
12	649	10.9	344	5.76
13	693	13.2	348	6.64
Mean (95% CI)	663 ± 18	11.9 ± 18	340 ± 5	6.1 ± 0.3

Mud Chulha - Cold Start Testing Data

Table C.7: Performance metrics for individual mud chulha cold start tests, boiling 5 L of water.

MUD-C Test #	Firepower (W)	Equivalent dry fuelwood (g)	Thermal efficiency (%)	Corrected time to boil (min)
1	6667	773	15.7	37.9
2	5726	736	14.8	40.9
3	4656	632	13.2	43.6
4	5442	623	18.3	34.7
5	5119	736	19.0	44.9
6	5536	579	18.4	33.8
7	4981	598	18.9	38.2
8	5118	611	19.6	37.6
9	5073	582	19.9	36.3
10	5491	604	18.6	35.4
11	4712	550	21.5	39.0
12	5125	590	19.8	33.8
13	6528	796	13.7	38.7
14	5636	796	18.0	44.8
15	4690	604	20.4	41.8
Mean (95% CI)	5367 ± 334	654 ± 48	18 ± 1.4	38.8 ± 2.1

Table C.8: Performance metrics for individual mud chulha cold start tests, boiling 5 L of water.

MUD-C Test #	**Modified combustion efficiency (%)**	**Fuelwood burn rate (g/min)**	**Exhaust carbon concentration (ppm)**
1	96.4	21.3	2679
2	98.2	18.3	2434
3	97.3	14.9	2307
4	97.3	17.9	2565
5	97.5	16.4	2549
6	97.9	17.7	2659
7	97.6	15.9	2444
8	97.3	16.4	2594
9	97.6	16.2	2509
10	97.4	17.6	2686
11	97.6	15.1	2558
12	97.1	16.4	2455
13	97.3	20.9	2640
14	97.3	18.0	2582
15	97.2	15.0	2428
Mean (95% CI)	97.4 ± 2.2	17.2 ± 1.1	2539 ± 60

Table C.9: Emissions for individual mud chulha cold start tests, boiling 5 L of water.

MUD-C Test #	**CO_2 total mass (g) (duct)**	**CO total mass (g) (duct)**	**$PM_{2.5}$ total mass (g)**	**BC total mass (g)**
1	832	20.8	1.67	1.03
2	847	10.5	1.21	1.80
3	839	15.6	1.01	2.09
4	792	14.9	1.37	1.34
5	986	17.0	1.70	1.92
6	750	10.6	1.12	1.42
7	784	12.7	1.21	1.76
8	828	15.4	1.43	1.73
9	771	12.9	1.11	1.26
10	783	13.5	1.21	1.35
11	792	13.0	1.16	1.32
12	746	15.7	1.11	1.22
13	834	15.4	1.46	0.33
14	924	17.9	1.64	0.54
15	788	15.4	1.65	2.03
Mean (95% CI)	820 ± 36	14.8 ± 1.5	1.34 ± 0.13	1.41 ± 0.28

Table C.10: Emissions for individual mud chulha cold start tests, boiling 5 L of water.

MUD-C Test #	**Cooking energy CO_2 emissions (g/MJ_{del}) (duct)**	**Cooking energy CO emissions (g/MJ_{del}) (duct)**	**Cooking energy $PM_{2.5}$ emissions (g/MJ_{del})**	**Cooking energy BC emissions (g/MJ_{del})**
1	365	9.13	0.73	0.45
2	415	5.14	0.59	0.88
3	538	9.98	0.64	1.34
4	371	6.99	0.64	0.63
5	376	6.49	0.65	0.73
6	376	5.31	0.56	0.71
7	370	5.99	0.57	0.83
8	368	6.85	0.64	0.77
9	354	5.92	0.51	0.58
10	372	6.41	0.57	0.64
11	358	5.88	0.52	0.60
12	339	7.15	0.50	0.56
13	411	7.57	0.72	0.16
14	344	6.64	0.61	0.20
15	341	6.66	0.72	0.88
Mean (95% CI)	380 ± 27	6.81 ± 0.7	0.61 ± 0.04	0.66 ± 0.16

Table C.11: Emissions for individual mud chulha cold start tests, boiling 5 L of water.

MUD-C Test #	**CO_2 total mass (g) (WBT)**	**CO total mass (g) (WBT)**	**Cooking energy CO_2 emissions (g/MJ_{del}) (WBT)**	**Cooking energy CO emissions (g/MJ_{del}) (WBT)**
1	1362	32.6	597	14.25
2	1321	15.2	647	7.42
3	1123	19.1	719	12.21
4	1107	18.5	518	8.64
5	1312	20.6	500	7.83
6	1035	13.5	519	6.75
7	1067	15.7	503	7.38
8	1086	18.3	483	8.14
9	1040	15.4	477	7.07
10	1075	17.3	510	8.18
11	981	14.3	443	6.43
12	1047	19.1	476	8.69
13	1416	24.8	694	12.13
14	1417	25.0	527	9.28
15	1074	18.5	465	7.99
Mean (95% CI)	1164 ± 85	19.2 ± 2.8	539 ± 47	8.83 ± 1.2

Mud Chulha - Hot Start Data

Table C.12: Performance metrics for individual mud chulha hot start tests, boiling 5 L of water.

MUD-H Test #	Firepower (W)	Equivalent dry fuelwood (g)	Thermal efficiency (%)	Corrected time to boil (min)
1	5653	652	21.0	38.9
2	5510	543	20.5	32.1
3	5486	519	21.7	31.4
4	5501	518	22.6	29.0
5	5785	556	20.8	30.4
6	5779	559	20.5	31.5
7	5715	555	21.5	31.1
8	6192	631	19.8	32.1
9	6143	710	19.8	36.3
10	5782	584	19.9	32.1
Mean (95% CI)	5755 ± 177	583 ± 45	21 ± 0.01	32.5 ± 2.1

Table C.13: Performance metrics for individual mud chulha hot start tests, boiling 5 L of water.

MUD-H Test #	Modified combustion efficiency (%)	Fuelwood burn rate (g/min)	Exhaust carbon concentration (ppm)
1	97.1	18.1	2971
2	97.6	17.6	2748
3	97.3	17.5	2938
4	97.8	17.6	2885
5	97.4	18.5	2904
6	97.5	18.5	3029
7	97.5	18.3	3027
8	97.2	19.8	3106
9	97.6	19.6	3325
10	97.2	18.5	2991
Mean (95% CI)	97.4 ± 0.2	18.4 ± 0.57	2992 ± 109

Table C.14: Emissions for individual mud chulha hot start tests, boiling 5 L of water.

MUD-H Test #	**CO_2 total mass (g) (duct)**	**CO total mass (g) (duct)**	**$PM_{2.5}$ total mass (g)**	**BC total mass (g)**
1	866	17.29	1.41	1.99
2	720	11.54	1.13	0.17
3	732	13.19	0.91	1.41
4	720	10.66	1.15	1.76
5	736	13.15	1.38	0.48
6	767	13.06	1.14	0.27
7	771	12.67	1.34	0.54
8	797	15.21	1.26	0.37
9	976	15.25	1.45	0.84
10	761	14.24	1.34	0.65
Mean (95% CI)	785 ± 57	13.6 ± 1.4	1.25 ± 0.12	0.85 ± 0.46

Table C.15: Emissions for individual mud chulha hot start tests, boiling 5 L of water.

MUD-H Test #	**Cooking energy CO_2 emissions (g/MJ_{del}) (duct)**	**Cooking energy CO emissions (g/MJ_{del}) (duct)**	**Cooking energy $PM_{2.5}$ emissions (g/MJ_{del})**	**Cooking energy BC emissions (g/MJ_{del})**
1	336	6.71	0.55	0.77
2	345	5.52	0.54	0.08
3	346	6.25	0.43	0.67
4	328	4.86	0.52	0.80
5	339	6.05	0.63	0.22
6	356	6.06	0.53	0.12
7	344	5.64	0.60	0.24
8	340	6.49	0.54	0.16
9	371	5.80	0.55	0.32
10	348	6.52	0.62	0.30
Mean (95% CI)	345 ± 8.4	5.99 ± 0.4	0.55 ± 0.04	0.37 ± 0.2

Table C.16: Emissions for individual mud chulha hot start tests, boiling 5 L of water.

MUD-H Test #	**CO_2 total mass (g) (WBT)**	**CO total mass (g) (WBT)**	**Cooking energy CO_2 emissions (g/MJ_{del}) (WBT)**	**Cooking energy CO emissions (g/MJ_{del}) (WBT)**
1	1158	21.7	449	8.41
2	969	14.7	464	7.03
3	923	15.6	437	7.41
4	926	12.7	422	5.78
5	990	16.0	456	7.34
6	996	15.7	462	7.28
7	990	15.3	441	6.80
8	1121	20.3	478	8.65
9	1268	19.2	482	7.30
10	1037	18.4	475	8.39
Mean (95% CI)	1038 ± 79	17.0 ± 2.0	457 ± 14	7.44 ± 0.62

C.4 Cookstove Sensor Temperature Data

Mud Chulha Sensor Temperature

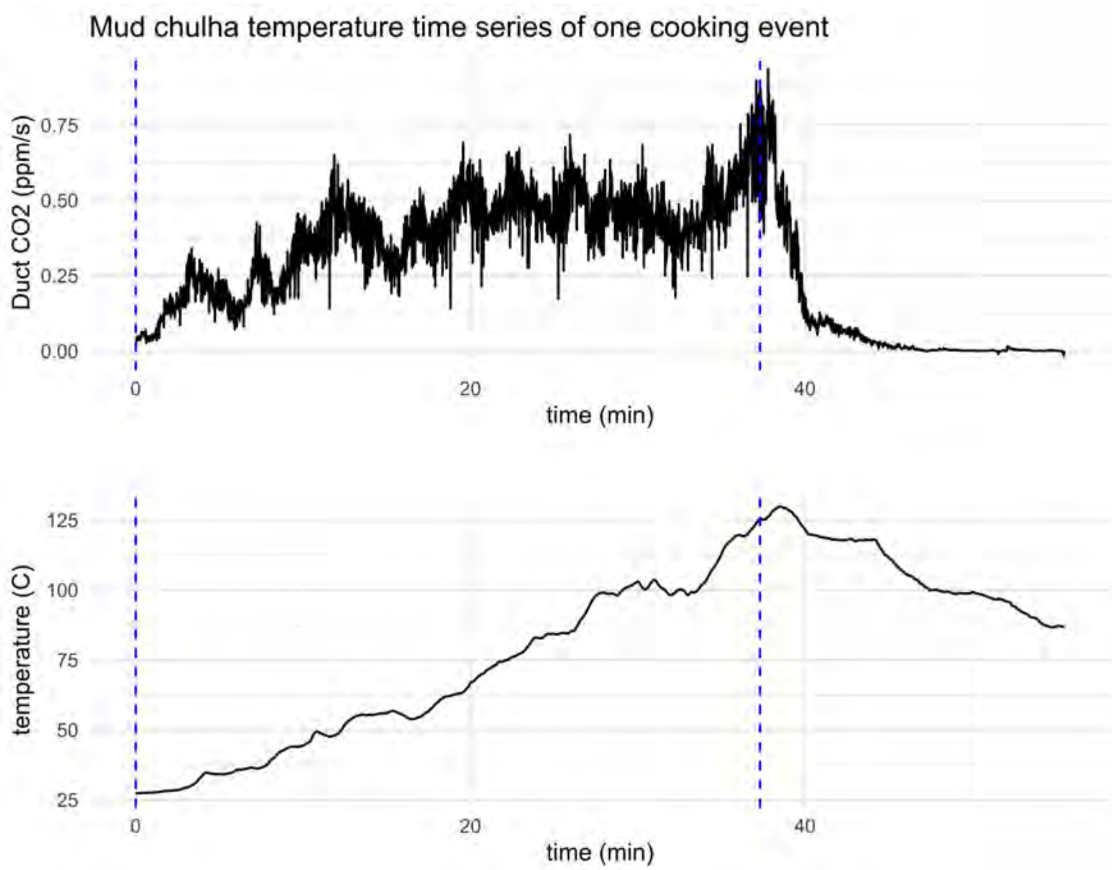

Figure C.7: Top: Time series of the CO_2 emission rate (g/min)of the mud chulha at 1 Hz. Bottom: Time series of mud chulha temperature at 1 Hz. Both time series are from a mud chulha test of heating boiling 5 L of water from room temperature.

Correlation Equations

Table C.17: Equations for correlations between BIS' sensor temperature and different metrics on different-sized cooking vessels.

Metric:	**15-min tests: all (n = 40)**	**small pot (n = 20)**	**large pot (n = 20)**
Burn rate vs. ss-temp	y = 0.11x - 13.2, R^2 = 0.85	y = 0.11x - 12.8, R^2 = 0.73	y = 0.11x -13.8, R^2 = 0.93
CO_2 rate (g/min) vs. ss-temp	y = 4.12e-05x - 4.75e-03, R^2 = 0.85	y = 3.9e-05x - 4.1e-03, R^2 = 0.73	y = 4.3e-05x - 5.4e-03, R^2 = 0.94
Firepower (W) vs. ss-temp	y = 34.9x - 4116, R^2 = 0.85	y = 34.7x - 3994, R^2 = 0.73	y = 35.4x - 4302, R^2 = 0.93
Fuelwood mass (g) vs. temp-area	y = 1.6e-3x - 126, R^2 = 0.82	y = 1.7e-3x - 147, R^2 = 0.76	y = 1.6e-3x - 134, R^2 = 0.90
CO_2 mass (g) vs. temp-area	y = 2.1e-3x - 164, R^2 = 0.84	y = 2.2e-3x - 175, R^2 = 0.80	y = 2.2e-3x - 191, R^2 = 0.91

Table C.18: Equations for correlations between BIS' sensor temperature and different metrics on different-sized cooking vessels.

Metric:	**Boiling tests: all (n=49)**	**small pot (n=27)**	**large pot (n=22)**
Burn rate vs. ss-temp	y = 0.15x - 24.2, R^2 = 0.75	y = 0.20x - 38.9, R^2 = 0.72	y = 0.10x -13.3, R^2 = 0.87
CO_2 rate (g/min) vs. ss-temp	y = 4.3e-05x – 6e-03, R^2 = 0.84	y = 4.9e-05x – 7.7e-03, R^2 = 0.84	y = 3.9-05x – 4.7e-03, R^2 = 0.86
Firepower (W) vs. ss-temp	y=45.7x-7565, R^2 =0.75	y=48x-7200, R^2 =0.71	y=33x-4212, R^2 =0.87
Fuelwood mass (g) vs. temp-area	y = 6.2e-4x + 96, R^2 = 0.77	y = 4.9e-4x + 153, R^2 = 0.72	y = 7.1e-4x + 53, R^2 = 0.92
CO_2 mass (g) vs. temp-area	y = 9.1e-4x + 91, R^2 = 0.96	y = 8.6e-4x + 112, R^2 = 0.97	y = 1e-3x + 64, R^2 = 0.95