AN ABSTRACT OF THE THESIS OF

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Title: Design and Testing of the FUEL Monitoring System: Integrating Engineering and Ethnographic Methods in Global Development Efforts.

Abstract approved:

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Clean cooking technologies and fuels have been cited as a viable way to slow climate change and reduce the health and environmental impacts associated with traditional cooking devices used by 40% of the world. While engineers in the Design for Development sector have created hundreds of stove designs that perform well in laboratory settings, quantifying their impact in real-world households has been a greater challenge. Both technical performance and user adoption are context-specific metrics that need to be monitored directly in households for practitioners to understand actual impact and secure results-based financing or reevaluate less successful projects.

While sensor-based monitoring has become increasingly common in the clean cooking sector to capture long-term, relatively objective data, one glaring performance metric not yet captured by these methods is fuel use, which is linked to deforestation, time expended towards firewood collection or purchase, and emissions. This gap motivated the development of the Fuel, Usage, and Emissions Logger (FUEL), a wireless logging load cell that monitors fuel weight data over time. These data can be aggregated to determine long-term fuel use and savings when compared to a baseline stove through a developed algorithm, and used in equations to determine emissions, carbon credits, and averted Disability Adjusted Life Years (aDALYs).

The purpose of this research was to develop, evaluate, and validate the FUEL system in terms of usability, technical feasibility, and accuracy. Assessment methods included an interdisciplinary combination of sensor-based monitoring and ethnographic techniques, such as semi-structured surveys, informal interviews, and participant observation. A preliminary evaluation was conducted in Honduras with four households in May 2017, and later scaled in Uganda in August 2017 and July 2018 to 85 and 44 households, respectively, to log for 30-45 days. Following this, fuel consumption as measured by FUEL was compared to that of the Kitchen Performance Test, the current accepted manual method to measure fuel consumption, to validate measurements. Validation was conducted in Uganda and Burkina Faso for four days each between July and August 2018, in 20 and 10 households, respectively. A combination of wood, LPG, and charcoal stoves were monitored, and the majority of households in the Burkina Faso study were stacking at least two of the three fuel types.

Preliminary results point to user acceptance of the FUEL system in the context of the study villages in northern Uganda. Analysis indicated that the FUEL is a viable method to report key metrics of interest, including per-capita measures of fuel use per day or longer, cooking events and duration, and extrapolated average firepower and climate impacts. Results also inform frameworks for how to integrate sensor-based and ethnographic methods in Design for Development settings to assess technology usability. The two comparison studies to validate the FUEL showed that FUEL data closely match those of the Kitchen Performance Test on an aggregate level, captured several sources of potential error with both methods, and indicated that FUEL can be a cost-effective option over longer monitoring durations.

These cross-cultural studies have provided evidence of the efficacy and usability of the FUEL system and pave the way for future work in the area of global fuel consumption measurements. Broadly, this system can be used for monitoring a wide variety of stoves and fuel types, and for additional applications such as agricultural products or crop residues to understand impacts of agricultural practices. It is hoped that the FUEL system can serve as a useful and usable tool to more objectively monitor real-world fuel use, and ultimately support increased accountability, transparency, and impact of the development sector.

Design and Testing of the FUEL Monitoring System: Integrating Engineering and Ethnographic Methods in Global Development Efforts

by
Jennifer L. Ventrella

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jennifer L. Ventrella, Author

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CONTRIBUTION OF AUTHORS

Dr. Shaozeng Zhang assisted with the editing of Chapter 2.

Olivier LeFebvre and Thomas Thivillon assisted in the design of the Burkina Faso study to compare the FUEL and KPT, and Olivir LeFebvre assisted with the editing of Chapter 4.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Development of technologies that address basic human needs such as food, clean water, and energy remains a critical need of our time. Billions of dollars are spent annually on technologies for humanitarian aid and development, yet the verification of their usability and long-term impacts is often a significant challenge for designers and regulators (Thomas, 2017). For projects that successfully meet user needs, effective monitoring can help these projects be replicated and secure additional results-based financing. On the other hand, barriers to accurately measuring technology efficacy means that a remarkable number of products may never fully serve their purpose, and without feedback, ineffective projects will continue. Transparent program evaluation can help practitioners to more effectively allocate time, money, and resources, and ultimately, address global economic and social inequalities. Although methods to measure performance exist, the international development sector is calling for less expensive, more accurate, and more timely monitoring tools to strengthen its accountability and impact.

One such example of a development sector technology in need of better monitoring is that of improved biomass cookstoves, which were designed to reduce the health and environmental impacts of traditional cooking devices. Currently, almost 40% of people worldwide continue to rely on inefficient traditional open fires to meet their energy needs, which comes at the cost of 4 million premature deaths each year from smoke inhalation and up to 8% of anthropogenic climate change (Lim, 2012; Masera et. al, 2015). The problem of energy access disproportionately affects lower income families who do not have the financial or infrastructural access to cleaner energy sources. Since 2010, 116 million cookstoves have been distributed around the world to combat reliance on traditional fuels and stoves, with 81 million considered clean or efficient, but millions more are needed (Clean Cooking Alliance, 2017). Clean cookstove project developers and regulators have identified two key problems associated with creating a thriving market for efficient cookstoves and fulfilling their collective mission of improving health, livelihoods, and protecting the environment. These are 1) understanding user adoption and technical performance of clean cookstoves and 2) financing their dissemination. However, because clean cookstove project developers and regulators struggle to effectively quantify the health and environmental impacts of these devices, impact and access to results-based financing are reduced.

Project stakeholders must have data to prove that technologies are being adopted at rates sufficient to provide the desired health and environmental outcomes. In addition, informed decisions about what stoves and programs work best cannot be made if there is not adequate data on performance and usability. Currently, these highly context-specific evaluations require significant technical skill and training for data acquisition and processing or rely solely on more biased and time-consuming survey data. They also do not quantify the range of variables, including usage, fuel consumption, and emissions, needed to fully evaluate the efficacy of a project. To address these challenges, development of monitoring and evaluation (M&E) technologies that reduce cost and time and can acquire key quantitative adoption and performance data are needed.

1.2 FUEL, USAGE, AND EMISSIONS LOGGER

To address this challenge, OSU researchers in engineering and anthropology partnered with electronics manufacturers Waltech Systems and Climate Solutions Consulting, as well as two international cookstove non-profit organizations in Central America and Uganda to develop and test the Fuel, Usage, and Emissions Logger (FUEL), a sensor system to measure cookstove and fuel usage. Inspired by the sector's need to quantify in-field fuel savings, FUEL was designed to quantify cookstove usage and fuel consumption using an integrated temperature sensor and load cell. The temperature sensor attaches to the cookstove and monitors cooking activity, while the load cell supports a household's fuel supply to monitor fuel usage over time. With its ultra-low power draw, the system can autonomously operate for at least three months per charge to capture variations in usage over time. The FUEL sensor transmits data wirelessly to a local launch device, and functions as an IoT device. For analysis, automated data analytics translate time-stamped temperature and weight data to cookstove usage, fuel consumption, and emissions.

1.3 MIXED-METHOD APPROACH

The FUEL system would not have been conceived or developed without engaging rapid ethnographic methods that are commonly practiced in the field of anthropology. Adapted from traditional ethnography, which is the study of people and their culture, rapid ethnographic methods are generally conducted on a shorter time scale and in less depth than their historical counterpart, but are thought to be better suited to the timeframe and goals of engineers, designers, and entrepreneurs. Integrating ethnography with the design process improves the chance of identifying and meeting design, user, and customer requirements to adequately address a need, and are increasingly being deployed to inform the ideation and development of new ideas, products, and services (Bernard, 2006; Wai & Siu, 2003). A mixed-method approach that combines qualitative and quantitative data can be used to triangulate data and reduce bias (Creswell & Creswell, 2018). Mixed methods analysis has seen increasing success in informing industrial design processes, however, researchers are calling for more contextual examples of how these processes can be applied in the development sector.

1.4 DEVELOPMENT & TESTING

This thesis traces the development and testing of a sensor system that would be usable for both stove practitioners and the people operating the system in their homes, using mixed methods design methodologies and frameworks. It explores a range of data on stove performance analyzed from empirical testing in Honduras and Uganda. Lastly, it compares the FUEL system with the current standard method for measuring fuel consumption, the Kitchen Performance Test (KPT). The thesis is a compilation of three journal article manuscripts. Chapter 2, the first article currently under revision for *Design Studies,* describes the integration of ethnographic methods and the design process to develop and test the performance and usability of the FUEL system in a multi-stakeholder context. Testing and evaluation were conducted in rural villages in Guatemala, Honduras, and Uganda with cooks who rely primarily on wood stoves. Chapter 3, the second article currently under revision for *Energy for Sustainable Development,* details the installation, testing, and analysis of 68 FUEL systems in northern Uganda, and reports desired metrics of stove performance, including usage patterns, fuel consumption, and resulting global warming commitment. Chapter 4, the third article in preparation for submission to *Development Engineering*, describes the comparison of the FUEL and KPT using wood, charcoal and LPG fuels in two communities in Burkina Faso and Uganda in terms of measurement accuracy, cost, and deployment effort, to assess if FUEL is a viable alternative.

1.5 RESEARCHER POSITIONALITY

In reflection of my positionality as a researcher, I bring several biases to this work. Although I am a woman relatively similar in age to many of the Honduran and Ugandan women who participated in our studies, we come from different cultures, do not share a common language, and my position as a paid academic researcher creates a power differential. To reduce these biases, we worked with local translators who fostered an environment of comfortable rapport with the women participating in the studies. We held community meetings where we showed participants how the FUEL system worked to level the understanding of and comfort with the technology. While in each village, I remained conscious of following customary greetings and mannerisms, and wearing inoffensive clothing. Nevertheless, my use of a cell phone to take notes or use as a flashlight, or laptop to check data in households represented wealth disparity and may have created feelings of inequality or discomfort for participants. Another bias was my role as a developer and simultaneous evaluator of the FUEL system and personal interest in its success. However, as a researcher in both anthropology and engineering I have been trained to think critically, reflexively, and objectively, which has helped to limit this conflict of interest.

CHAPTER 2

ENERGY, ETHNOGRAPHY, AND EMPIRICISM: DESIGN OF A SENSOR-BASED CLEAN ENERGY IMPACT MONITORING SYSTEM USING RAPID ETHNOGRAPHIC TECHNIQUES

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In revision for *Design Studies*

ABSTRACT

Stakeholders in the Design for Development sector, particularly clean cookstoves and fuels, have called for better monitoring tools to evaluate and promote impacts of new products in a way that is affordable, accessible, and appropriate for the communities they serve. This paper presents the design, development, and testing of the sensor-based Fuel, Usage, and Emissions Logger (FUEL) to quantify cookstove impacts. A mixed-method, rapid ethnographic approach that allows practitioners to conduct ethnographic studies under limited time and resource constraints was used. Methods of evaluation included participant observation, semi-structured interviews, surveys, and sensor-based monitoring, with the goals of evaluating technical feasibility, system usability, and market value. Results showed that triangulation of ethnographic and sensor-based data improved our certainty of survey results, and increased algorithm accuracy by contextualizing outliers in the data. Ethnographic data also allowed us to recognize and address negative, context-specific perceptions of the sensor, and point to the value of incorporating visual or sensory cues into development technologies. Theoretical discussions include incorporation of product modularity, pro-innovation bias, and ethical considerations in Design for Development contexts. Broadly, this study encourages the design community to incorporate sensor-based data with rapid ethnographic methods in design for development.

2.1 INTRODUCTION

Design for Development (DfD) is a growing field that focuses on designing technologies and services targeted towards low-resource contexts (Donaldson, 2009). Reflected by the United Nations' Sustainable Development Goals set in 2015, the overarching objective is to increase quality of life and community resilience by fulfilling basic human needs (United Nations, 2015; VanderSteen, 2008; Wood and Mattson, 2016). Although ambitious targets for meeting these needs have been set, it is not always clear if technologies and services designed for development goals achieve their intended impact, often due to a lack of accountability and robust monitoring tools (Mazzurco and Jesiek, 2014). Examples of DfD projects include products for clean water, household energy services, and medical devices that help prevent or treat curable diseases. Technologies developed to meet these needs should be cost-effective and reflective of user preference while delivering high technical quality (Moses and MacCarty, 2019; Wai and Siu, 2003). However, because there is often considerable distance between the designer and end-user, which refers to not just geographical, but also socio-economic and cultural distance, it can be challenging to design technologies and services for these contexts that sufficiently address user needs (Thomas, 2017). Inability to address these knowledge gaps can result in reduced impact and a drain on resources.

One example of a common development project is the implementation of improved cookstoves designed to meet the needs of the 2.8 billion people who currently rely on traditional biomass (e.g. wood, charcoal, dung, agricultural waste) to meet their household energy needs (Bonjour et al., 2013). Generally, traditional stoves or open fires have inefficient heat transfer and combustion, resulting in high rates of pollutants that contribute to climate change and lower respiratory illness, and unsustainable fuel harvesting that can contribute to forest degradation (Lim, 2012; Masera et al., 2015). Despite thousands of improved stove models, adoption rates have been lower than expected, and in-field performance often lacks standardized, holistic verification. Often, improved stoves are tested in a laboratory setting and designed for ideal combustion and heat transfer efficiencies. However, it is typically much more challenging to evaluate stove performance and adoption under real-world conditions, which have been found to vary significantly depending on the local context. Therefore, stove designs often have lower adoption and impact than predicted or preferred (Mobarak, Dwivedi, Bailis, Hildemann, & Miller, 2012a). Due to the gap between theoretical and actual outcomes, the sector has called for more accurate and cost-effective monitoring tools to better quantify and address in-situ cookstove performance and adoption (Masera et al., 2015).

The overarching goal of this research was to investigate new ways to better understand and measure the impacts of clean cookstove programs. To meet this need, we ultimately conceptualized, designed, prototyped, and tested a sensor system called the Fuel, Usage and Emissions Logger (FUEL), to monitor household fuel and stove usage patterns. Specific objectives were to clearly define a relevant and high-impact problem in the stove sector, develop a solution, and evaluate for technical feasibility, usability, and market potential. To investigate, a rapid ethnographic, mixed-method approach that combined both qualitative and quantitative methods was used with participant observation, interviews, surveys, and focus groups. Because providing clean and usable stoves is a global issue, this research was conducted in several location-specific phases, including Central America and Eastern Uganda, as well as interviews with stakeholders across the globe, with the goal of creating a robust, usable solution to a prevailing problem in the cookstove sector.

2.2 BACKGROUND

2.2.1 Motivation for Impact Monitoring of Development Projects

Growth in the DfD sector has in turn provoked demand for measuring its impact. Outside of development, qualitative and quantitative impact monitoring have been used to regulate and measure performance in both the private and public industrial sectors for decades. However, due in part to its relatively recent (post WWII) beginnings, decentralized market (Prahalad, Di Benedetto, and Nakata, 2012), and a lack of financing or incentive for product quality and usability regulation, DfD is still considerably far from reaching the same standards or potential as its industrial counterpart (Prahalad et al., 2012; Rapley, 2007). For these reasons, better tools and standards are needed for effective impact evaluation in the DfD sector.

2.2.2 Monitoring in the Clean Cooking and Fuels Sector

The improved cookstove sector is one example of a development project that is currently in need of more robust impact monitoring tools and standards (Masera et al., 2015). Currently, around 40% of the global population relies on fuels such as wood or charcoal to meet their energy needs (Bonjour et al., 2013). These fuels are often used in traditional open fires or other inefficient stoves, which has been linked to 3.9 million deaths annually from lower respiratory illnesses, approximately 8% of anthropogenic climate change, forest degradation, gender inequality, and opportunity costs (Masera et al., 2015). To mitigate the harmful health and environmental impacts of this common practice, engineers and designers have developed improved cookstove models that increase heath transfer and combustion efficiencies.

Despite these efforts, studies have found low adoption rates amongst improved cookstove beneficiaries, suggesting that the potential health and environmental benefits are not always realized (Hanna, Duflo, and Greenstone, 2012). One example is a case study that examined improved cookstove usage in rural Bangladesh and found that there was low demand among women cooks (Mobarak et al., 2012). The authors examined the factors for low adoption using qualitative surveys and found that women did not perceive indoor air pollution as a significant health issue and therefore did not prioritize improved cookstoves. Additional factors limiting stove uptake was the design of the combustion chamber, which did not accommodate larger fuel and required women to chop fuelwood into small pieces, and a stove design that was not well adapted to local cooking equipment. Although the project had the potential to improve health, the stove was not well-adopted and resulted in lower overall impact because the designers focused on technical performance and did not consider local contextual data to inform their design. Impact monitoring can help identify these issues earlier on in the design process, and therefore, rapid, actionable data are a significant need for cookstove practitioners.

To increase impact in the sector, stakeholders including researchers, non-government organizations (NGOs), funding organizations, and climate financing institutions (e.g. Gold Standard) have called for rapid, cost-effective and accurate quantification of cookstove usage, fuel consumption, air pollution, and time allocation to measure stove impacts in user households, and not just in highly controlled and unrealistic laboratory settings. With the recent rise of information and communications technology (ICT), sensor-based monitoring has been regarded as a valuable tool to provide objective, long-term measurements for these types of indicators (Lozier et al., 2016; Ruiz-Mercado et al., 2013; Thomas et al., 2013; Wilson et al., 2015). Some examples in the development sector include sensors to measure handwashing behavior, water filter use, and pit latrine use (Clasen et al., 2012; Islam et al., 2010; Thomas

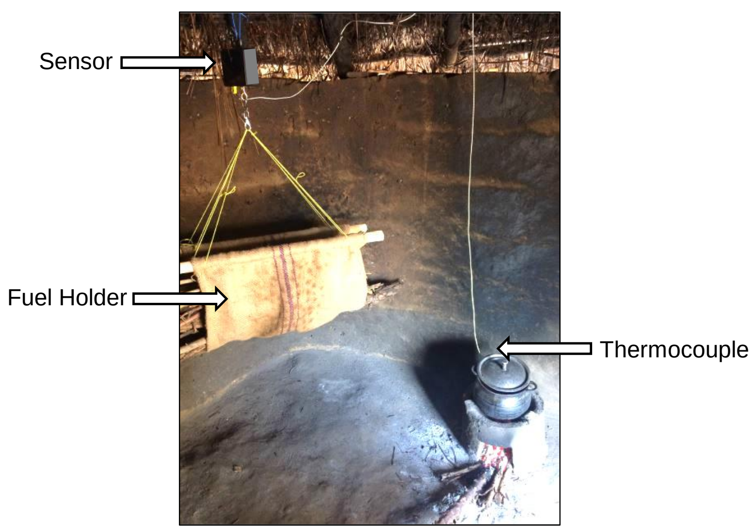

Figure 2.1 FUEL System (Ventrella, 2018)

et al., 2013). To monitor cookstoves, sensors that autonomously measure cookstove temperature as a proxy for usage and adoption are used, as are indoor air pollution monitors (Pillarisetti et al., 2017; Ruiz-Mercado, Canuz, and Smith, 2012). However, there has been no sensor-based technology to directly measure fuel consumption, which is a key indicator of stove performance. This unaddressed need was the motivation to develop the Fuel, Usage and Emissions Logger (FUEL), a sensor system that quantifies impacts of clean stoves on human health and the environment in terms of cooking duration, fuel, and emissions (Figure 2.1).

To measure fuel and cookstove usage in households, the FUEL system uses a logging load cell that records the weight of the fuel stored in the fuel holder, and temperature sensor. The temperature sensor is attached directly to the stove to capture cooking activity. To capture fuel use over time, the stove user is instructed to store his or her fuel supply in the holder and remove as needed for cooking. Raw fuel weight data can then be integrated to understand fuel use over time and used in calculations to estimate emissions and health impacts.

2.2.3 The Contextual Gap: When Designs Fall Short

Professor of Design History Victor Margolin claimed that we need "modes of thought that recognize design as a practice within culture" (2002). Successful design for diverse stakeholders requires a deeper understanding of their cultural practices, capabilities, and constraints (Wasson et al., 2018). When these user differentiators are not adequately identified or addressed, designs are prone to higher chance of failure. In the DfD sector, limited knowledge or understanding of the people and context for which the product is intended can result in the design of ineffective technologies. An analysis of eight development projects found four main modes of failure, including 1) failure to assess needs, 2) failure to understand the culture, 3) failure to assess assets, and 4) failure to apply knowledge (Mazzurco and Jesiek, 2014). A separate but complementary literature review outlined advantages to involving users in product or service development in DfD settings, including: 1) increased adoption, 2) more flexibility and robustness in use, 3) reduction in the number of design iterations and therefore expended cost and time, and 4) identification of requirements that are not obvious, but critical (Mink, Diehl, and Kandachar, 2018). Past studies have shown that rapid ethnographic methods can be a useful approach to involve users more directly in the design process, better understand the context, and alleviate failure modes (Chatti et al., 2017; Durix, Carlsson Rex, and Mendizabal, 2016; Mazzurco and Jesiek, 2014; Stanistreet et al., 2015).

2.2.4 Rapid Ethnographic Methods

To avoid these potential failures and apply best practices, ethnographic techniques can be integrated into the design process. Stemming primarily from the field of anthropology, ethnography is the study of people and their culture, and anthropologists rely on ethnographic methods to understand these domains. Traditional ethnography aims to generate in-depth, long-term, theory-based details on many facets of a chosen topic, and therefore in its original form is often not well-suited for product design that is subject to time and resource constraints (Ball and Ormerod, 2000). Historically, this has created some tension between anthropology and design fields, as designer-defined ethnography that relied on short research periods and high-level analyses did not fit under anthropologists' definition of pure ethnography (Ball and Ormerod, 2000). Therefore, the concept of rapid ethnography was created as an adaption of and deviation from traditional ethnography for the specific purpose of product design (Hughes, King, Rodden, & Andersen, 1995).

While still relying on the use of traditional ethnographic methods, rapid ethnography is characterized by an initial, substantial narrowing of research scope, data triangulation, and collaborative, computerized data collection and analysis (Millen, 2000). Once collected, data can be systematically interpreted using thematic coding (Attride-Stirling, 2001). Benefits to using rapid ethnographic techniques as opposed to conducting a traditional ethnography include time and cost savings, making them a good fit for DfD projects with strict timeline and budget constraints (Bernard, 2006; Coleman et al., 2007; Daae and Boks, 2015; Isaacs, 2013). Similar research has also incorporated rapid ethnographic methods into DfD, citing their ability to obtain valuable user insights in a time frame and budget conducive to DfD projects (Burleson et al., 2019; Mink et al., 2018; Moses, Pakravan, and MacCarty, 2019; Moses and MacCarty, 2019). In addition, using rapid ethnographic methods can improve the ability to sufficiently identify and address needs in design, particularly for people from a different culture or background than the designer (Bernard, 2006; Tayal, 2013; Wai and Siu, 2003). A non-exhaustive overview of widely used ethnographic methods and their intended purposes and limitations is shown in Table 2.1 (Bernard, 2006; Daae and Boks, 2015; Dicks, 2002; Meis Friedrichsen and Dana, 2003; Sovacool, Axsen, and Sorrell, 2018).

Table 2-1 Ethnographic Methods (adapted from Daae and Boks, 2015; Sovacool, Axsen, and Sorrell 2018; Dicks, 2002, Meis Friedrichsen and Dana, 2003; Bernard, 2006)

Method	**Purpose**	**Limitations**
Background interviews, surveys	Collecting data related to needs and expectations of users; evaluation of design alternatives, prototypes, final design	Subject to interviewer and social desirability bias
Focus groups	Small groups of various stakeholders (5-8 people) to discuss issues and requirements	Subject to interviewer bias, group responses may be different from individual
Participant observation, focal follow	Collecting information concerning the environment and culture in which the design will be used	Can be time intensive, immersion difficult when outside the culture of study, subject to misinterpretation
Usability testing	Collecting quantified data related to measurable usability criteria	Sample and testing environment may not be representative of real-life scenario and population
Card sorting	Collecting information related to how a user perceives product functionality	Subject to interviewer bias
Diary studies	Users document their lives, through e.g. photos or written work to provide personal record of experiences	Subject to bias in self-reporting

While rapid ethnographic techniques can be of value to researchers, they are not without their limitations. A major limitation of these techniques is the issue of rigor, which can be defined in terms of representativeness, accuracy, and validity (Shah, 2018): in shortening the ethnographic process, researchers will gain a less in-depth understanding than if they conducted a traditional ethnography (Isaacs, 2013). Representativeness can suffer from small sample sizes that may not be indicative of a larger population, and from an inability to capture changes over time due to the short time-scale of rapid methods. Accuracy can also be a problem when there is little time for iteration. Finally, validity comes into question based on the inherent biases of the researchers and their often differing worldviews and perspectives (Shah, 2018).

To overcome some of the weaknesses associated with rapid ethnographic techniques, triangulation of multiple data sources or methods, especially a combination of qualitative and quantitative data and often referred to as a mixed-method approach, can be of use (Bernard, 2006). Quantitative methods can aid the researcher in collecting more objective, statistically significant data that has higher generalizability to a larger sample as compared to qualitative methods. They are also good at evaluating trends and correlations. However, quantitative methods do not always provide the context-specific "why" of observed trends in numerical results. Qualitative methods allow for deeper understanding of local context that can in turn inform quantitative data. Therefore, combining both allows researchers to corroborate and validate findings to help account for bias and compensate for the weaknesses of the other (Ball and Ormerod, 2000; Creswell and Creswell, 2018; Sovacool et al., 2018). Ultimately, if a practitioner is faced with time and budget constraints and/or has a narrowed research question in mind, rapid ethnographic techniques can help articulate a given problem, refocus project direction, and provoke brainstorming for addressing a known problem with a timeframe more realistic for practicing researchers, engineers, and designers (Isaacs, 2013).

2.2.5 Ethnographic Methods in the Design Process and Lean Startup

Rapid ethnographic methods have been increasingly recognized for their role in informing both the design process and entrepreneurial startup methodology. Recognition of design failures as a byproduct of insufficient understanding of the user prompted the seminal work of anthropologist Lucy Suchman and her colleagues, whose ethnographically-informed design work at the Xerox Palo Alto Center in the 1980's gave rise to a new method of product design (Suchman, Blomberg, Orr, & Trigg, 1999). Due in part to this pioneering work, the process of integrating rapid ethnographic methods and the design process has been applied in industry settings, with growing recognition of its ability to improve product, service, and branding success (EPIC, 2018; Lloyd, 2000; Madsbjerg, 2017). Despite its theoretical step-by-step representation (Fig. 2.2), practicing designers have emphasized the iterative, fluid, messy and evaluative/critical nature of the process (Gould and Lewis, 1985; Jen, 2017; Schønheyder and Nordby, 2018). Increasingly, design-consulting firms (e.g. IDEO, ReD Associates, Gemic) have based their strategy on the use of rapid ethnographic data to advise high-profile companies such as Nike and Samsung, which has led to the development of products with higher value and usability for customers and increased returns for businesses (Flamingo, 2017). A 2015 study found that design-centric companies such as Apple, Nike, and IBM showed a 211% return over the S&P 500 (Rae, 2015).

In the domains of business and entrepreneurship, the lean startup methodology has also borrowed from the idea of integrating ethnographic techniques to assess product marketability. Despite similarities to design thinking, a comparative literature review found that while both domains used similar methods, such as qualitative interviews, they rarely interacted, cited one another, or referred to their methods with the same names (Müller and Thoring, 2012). Created in rejection of traditional rigid and un-evolving business plans based on ungrounded projections, the lean startup methodology uses the Business Model Canvas, a template for mapping out an iterative business plan, to formulate and test hypotheses about customer pain points and values by talking to potential customers (Blank and Dorf, 2012; Osterwalder et al., 2010). While not referred to as such, lean startup methodology relies on a combination of rapid ethnographic techniques such as observation, interviews, and surveys with potential customers and quantitative market data to inform a viable business model (Müller and Thoring, 2012). Initial research has shown benefits to the lean canvas approach, such as mitigating cognitive biases in decision-making processes (Eisenmann, Ries, and Dillard, 2012).

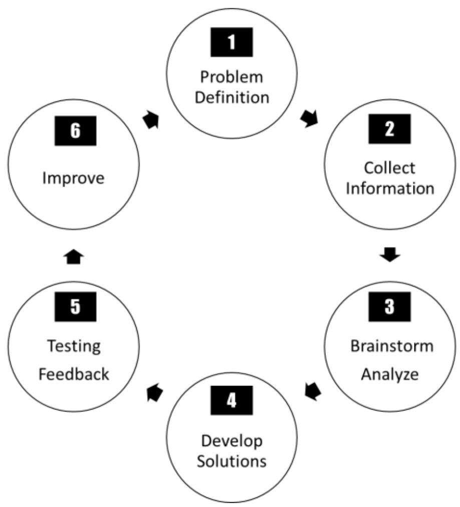

Figure 2.2 Engineering Design Process (Adapted from Tayal, 2013)

Both design thinking and lean startup methodologies can be applied to DfD projects to determine product usability and marketability. Despite acknowledgement of the value in integrating ethnographic methods into the design process and lean startup methodologies, there is a need for more empirical examples that formalize and systematize them (Jagtap, 2018; Stanistreet et al., 2015). Several studies on technology design for low resource contexts use rapid ethnographic techniques but generally focus on evaluating the already developed technology with less focus on the front-end of the development process (O'Reilly, Louis, Thomas, and Sinha, 2015; Zakaria et al., 2018), even though holistic front-end development that considers factors such as business vision, technical feasibility, and customer requirements has been found to introduce the most significant benefits to product design and reduce risk (Khurana and Rosenthal, 1998). In addition, engineers and designers are often not formally trained to conduct ethnographic research (Mink et al., 2018). Therefore, richer detail is needed on data collection and methods throughout the design process, interpreting and integrating mixed methods data, using these data to inform design specifications and balancing various stakeholder requirements (Kujala, 2003; Rosenthal and Capper, 2006). These types of in-depth method reporting can be used to substantiate, inform, and support existing DfD frameworks, such as user-value-based approach (Boztepe, 2007) and capability-driven design (Mink et al., 2018), which both emphasize understanding user values and aspirations to inform design and avoid replicating unsuccessful approaches.

2.2.6 Study Goals

This study will examine the design, development and testing of a solution to address a problem identified in the clean cooking and fuels sector through application of rapid ethnographic methods within the engineering design process. The ideation and development of the FUEL system will be outlined in four location-specific phases: Guatemala, Oregon/Global, Honduras, and Uganda. Using rapid ethnography as a methodological framework, we will describe the ethnographic study design, methods, and analysis used to support the design, development and testing of a cookstove impact monitoring system. From these analyses, we will provide reflections and design considerations that can contribute towards frameworks for integrating ethnography and design in multi-sited contexts.

2.3 METHODS

The design, development and testing of the FUEL system took place throughout four research phases, with the goal of fully articulating the problem and creating a usable solution that would adequately address needs in different geographic and monitoring contexts. The two regions we selected to conduct in-field testing, Central America and East Africa, are generally representative of other regions that face similar problems with clean cooking. Because the FUEL storage system deviated from local traditional fuel storage habits, it was crucial to evaluate system usability to verify that sensor results would accurately capture fuel use in the household. Therefore, we used a design science approach that integrated rapid ethnographic and sensor-based methods and roughly follows the stages of the design process. Specific methods will be outlined and justified for each research phase. Table 2.2 shows the overall progression of research phases, research goals, and methods used. Rapid ethnographic methods were employed selectively based on time and budget constraints of the study and their applicability to DfD contexts. They are also appropriate for assessing a specific, relatively narrow research question, in this case, identifying challenges with monitoring and potential solutions. To avoid limitations associated with rapid ethnographic methods, we worked with partner organizations that had established long-term relationships in the study communities, and triangulated multiple qualitative and quantitative methods.

All research with human subjects was conducted with oversight by the XXX Institutional Review Board under study number 7257.

Table 2-2 Research phases, objectives, and methods

Naming Convention	**Location & Time Frame**	**Steps in Design Process**	**Methods**	**Research Questions**	**Potential/Expected Insights**
Phase 1	Guatemala: June 2016	1. Problem Definition 2. Collect Information (sector issues)	1. Participant observation 2. Informal interviews	What are general challenges and barriers in the clean stoves and fuels sector?	Evidence highlighting a key challenge
Phase 2	Oregon/ Global: Jan 2017-April 2018	2. Collect Information (marketability, usability) 3. Brainstorm/Analyze 4. Develop Solutions	1. Informal interviews 2. Literature review	What are challenges practitioners face when trying to evaluate stove impact?	Brainstorm and evaluate design ideas
Phase 3	Honduras: May 2017	2. Collect Information (usability, feasibility) 5. Testing/Feedback 6. Improve	1. Participant observation 2. Informal interviews 3. Focal follow 4. FUEL monitoring	Evaluate technical feasibility and usability of solution	Potential need for system re-design
Phase 4a	Uganda: August 2017	2. Collect Information (usability, feasibility) 5. Testing/Feedback 6. Improve	1. Participant observation 2. Informal interviews 3. Focal follow 4. Semi-structured surveys 5. FUEL monitoring	Evaluate technical feasibility and usability at a larger scale in a different context (Eastern Africa)	# of sensor fully working Potential need for system re-design
Phase 4b	Uganda: May 2018	5. Testing/Feedback	1. Semi-structured surveys	Corroborate usability findings from Phase 4a	Understand long-term usability

2.3.1 Phase 1 – Guatemala, June 2016

The purpose of Phase 1 was to define a specific, addressable problem in the stove sector and collect additional background information. Problems within the sector were contextualized in part during a two-week study in central and southern Guatemala as part of a household energy course offered through the Humanitarian Engineering Program at OSU, with the objective of engaging students in the production and testing of clean energy technologies in an immersive setting (OSU). Approximately 70% of households in Guatemala use firewood for cooking, indicating a proportionately high need for clean cooking solutions and making it a representative study location for framing larger issues within the sector (Clean Cooking Alliance, 2014). StoveTeam International, an NGO that has supported factories in Central America since 2007 in the design, manufacture and distribution of improved cookstoves for rural households, partnered with the university to facilitate the course. OSU student researchers worked with the NGO to quantify various impact metrics using a combination of existing monitoring tools, including open-ended and Likert scale surveys and temperature sensors. Monitoring was conducted both at the stove factory in central Guatemala, and in two rural highland villages in southern Guatemala.

Although there was an overarching theme of identifying key challenges in the clean stoves and fuels sector, we took a grounded theory approach in which a research question is defined only after collecting and classifying data (Corbin and Strauss, 1990; Glaser and Strauss, 1967) to enable open-ended, non-prescriptive problem identification. The methods used during this research phase included participant observation and informal interviewing of clean cookstove practitioners, manufacturers, and Guatemalan stove users. These methods allowed us to collect a broader and more general range of information as compared to more standardized, specific approaches such as surveys. With a combined 15-year background in cookstove design and evaluation, and observing current setbacks in the sector, we were well-situated to grasp and define the problem.

2.3.2 Phase 2 – Oregon/Global, 2017-2018

The next phase was centered on the second step of the design process: collecting additional information, with the goals of further defining and quantifying the magnitude of the problem and evaluating current market needs in the stove sector. Issues with monitoring like those observed in Guatemala have been echoed by the cookstove sector at large, where stakeholders including researchers, NGOs, funding organizations, national governments, and climate financing organizations have voiced the need to increase transparency and better measure fuel consumption, collection time, cookstove usage, and impacts on education and health. To further define the problem and its scale, we conducted a narrative literature review in addition to semi-structured interviews with multiple stakeholders working across the globe. Semi-structured interviews allowed us to reach a wider number of stakeholders and draw more generalizable conclusions about challenges with monitoring in the sector, while the literature review corroborated these data and identified the gap in monitoring tools and methods.

A narrative review, in which the researcher synthesizes data on a topic or theme familiar to them, allows for in-depth insights, and was conducted to cover existing monitoring methods and limitations in the clean cooking sector. One potential limitation as compared to a broader meta-analysis is that this method is more susceptible to researcher bias and data could be missed (Sovacool et al., 2018). However, impact monitoring within the clean cooking and fuels sector is fairly new, meaning that there is not extensive documentation. We were thus able to aggregate a higher percentage of documentation related to this topic as compared to a more typical narrative review, thereby reducing bias of this type of review. Specific search keywords within academic and non-academic sources included ‘cookstoves’, ‘cookstove adoption’, ‘cookstove impact’, and ‘cookstove monitoring’. Search words within these articles included ‘monitoring’, ‘sensor’, and ‘challenges’. Once this initial background information was gathered, we brainstormed ideas for monitoring tools and methods of varying practicality, analyzed them against hypothesized, pre-defined technical, user, and customer requirements, and selected the option that seemed the most feasible and likely to address the highest number of requirements.

Following the literature review and initial brainstorming, the main challenges within the sector and the feasibility of the selected idea were assessed using semi-structured interviews with over 50 global stakeholders in the sector, either in person or through video or phone calls, following the methods outlined for customer discovery in the lean startup methodology and required as participants in the NSF I-CORPS program (Osterwalder et al., 2010). Interviewees were chosen through personal networks and the Global Alliance for Clean Cookstoves database of over 1000 partner organizations. A sample of practitioners was selected from each sub-field to obtain a more representative sample of the diversity of professions within the sector and were selected partly based on organizational scale and quantity of past projects. The lean startup method emphasizes the value of face-to-face meetings to better elicit and interpret information, so this was done whenever possible (Blank and Dorf:239, 2012). To capture more general information, open-ended questions were mainly centered on current challenges in the field and approaches taken to address them. More specific questions concerning the need for monitoring were also asked, including which impacts were most important and why, what methods had been used for monitoring in the past, and what worked well and what did not. All data were recorded manually, and post-conversations were further distilled for key themes that would inform the Business Model Canvas (BMC).

2.3.3 Phase 3 – Honduras, May 2017

Based on the ethnographic data collected during Phases 1 and 2, we chose the FUEL system as the most viable design alternative. Therefore, the primary goal of the remaining phases was to test the technical feasibility, usability, and market value of this solution, and to identify any prominent design issues with the sensor or storage system before scaling. Rapid ethnographic methods used during this phase included focal follow conducted by the lead researcher and a local translator and informal interviews for details on both the larger cooking and fuels context and for specific feedback about FUEL system usability, and were supplemented with sensor-based monitoring to assess system usage and technical feasibility. Methods within this phase followed several steps of the design process, including collecting information about the fuel collection/cooking system, testing/feedback, and improvement. Honduras was chosen as a future test site due to strong partnerships with StoveTeam, our previous partner in Guatemala. In addition, Honduras has been a focus region of clean stove programs, making it a representative area of study.

Following analysis of photographic data from Guatemala to inform the feasibility of the design and installation, four households from a rural village in western Honduras were chosen by convenience sampling. We partnered again with StoveTeam, who had recently implemented a stove project in the area and employed local field staff who were familiar with the region. The selected community, El Eden, is located about 30 km north of the city of Copan Ruinas in a valley where households planted their crops on steep mountainsides and regularly navigated the terrain to plant or harvest crops and collect growingly scarce firewood. FUEL sensors were installed over a period of two days and left to monitor for 30 days. Following the monitoring period, local field staff returned to collect sensor data and user feedback.

To ensure that the FUEL sensor was measuring accurate fuel consumption data, we needed to assess the usability of the fuel storage design and determine whether households would bypass or misuse it during the study period. Because this method of fuel storage deviated from local habit in many areas, usability testing was a primary focus during this phase. To guide usability testing of the storage system, a list of design questions and applicable ethnographic methods to provide insight was created, as seen in Table 2.3.

Table 2-3 FUEL System Design Attributes

Design Consideration	Questions Raised	Ethnographic Method(s)	Resulting Design Specifications
Sizing, capacity	What are current storage methods? What amount of wood is collected per event? What is the usual amount of fuel stored in household? What are problems with current storage methods?	Participant Observation Semi-Structured Interviews Focal Follow Photography	Dimensions of fuel holder Min/max weight capacity, holder Max weight capacity, load cell Min length, thermocouple Min weight threshold, algorithm
Fuel collection/storage habits	In what places is wood generally stored prior to cooking event?	Participant Observation Semi-Structured Interviews Photography	Adaptable to storage habits
Structural support	Are household roof structures available and sturdy enough to support system?	Observation Photography	Max weight capacity, system

A specific research objective was to evaluate if the holder for the fuel could be adapted to store and transport fuel during collection trips, and if doing so would provide added utility for participants. A focal follow of four participants was conducted to study the cooking and firewood collection process as a system and understand how the FUEL could integrate into the system with the least intrusion and highest utility. For the focal follow, the researcher is required to document sub-tasks and time spent for a person, the focal, to perform a specified task. One strength of the focal follow is its ability to obtain richer, in-depth detail that helps contextualize generalizable, statistically significant data. The lead researcher manually recorded observations and durations of several tasks including time spent walking to the area where wood was collected, methods of splitting, storing, and transporting, and conversations between participants during these tasks. Observation of challenges throughout the process was corroborated through conversation with the participants, to avoid the researcher's personal bias as to what constituted as a challenge.

Informal interviews were also conducted with each participant to elicit impressions of FUEL usability. During household check-in visits, participants were asked questions about what features of the system they thought could be improved about the system and what problems they experienced during use. To minimize response bias, participants were initially debriefed that the purpose of the study was to understand their perceptions of the system, and that both positive and negative feedback would be appreciated. Interview data were then triangulated with quantitative usage data from the FUEL sensors to corroborate whether positive answers were associated with higher use, and vice versa.

2.3.4 Phase 4a – Uganda, August 2017

Following the Phase 3 proof of concept test, a pilot study was developed to scale and assess system feasibility in a different geographic and cultural context. Uganda was chosen both because of a strong existing partnership with an NGO in that region, as well as the magnitude of its clean cooking agenda. For example, the UN Capital Development Fund has the goal of distributing 150,000 clean stoves to Uganda by 2020 and is actively seeking ways to measure and improve adoption rates (Clean Cooking Alliance, 2016). A three-week study of 85 convenience-sampled households of two villages in the rural Apac District of northern Uganda was conducted in collaboration with International Lifeline Fund (ILF), an NGO that manufactures and distributes improved biomass cookstoves in several countries. Both selected study villages had previously purchased ILF stoves, and the participants were all randomly selected from the larger convenience-sampled purchasing group to reduce sampling bias. Following installation, the FUEL sensors were left to log for 30 days.

Goals of this phase were to evaluate FUEL technical performance and system usability, and inform design changes on a larger scale across different cultural and geographic context, following the collection of information, testing/feedback, and resulting improvement steps of the design process. Rapid ethnographic methods used during this phase included participant observation, informal interviews, focal follow, and semi-structured surveys.

Training sessions were organized around the schedule of household participants in each village to explain the purpose of the study, teach participants how to use the system, and elicit initial feedback, questions or concerns in the form of an informal interview. Several Ugandan employees of the NGO were present as translators. The lead researcher recorded observational data and question responses manually, and voice recorded the research explanation in the first session, following participant consent, to maintain consistency between training sessions in each village. Upon explanation of the system and its functions, participants were asked several questions to clarify both the larger context as well as potential issues specific to the FUEL system. For example, to better visualize the fuel collection process, participants were asked to describe what it was like to collect firewood. To draw themes specific to FUEL usability, participants were asked questions such as whether they would prefer the firewood in the FUEL system to be stored hanging up or on the ground, and then to explain why. Data were then thematically coded for comments on firewood collection, which were used to assess the utility of adapting the fuel holder to collect firewood, and comments on concerns regarding the study. Concerns raised about the study in the first training session were then incorporated and addressed by the lead researcher and translators as part of the second training session.

To inform system usability and post-processing of data, participant observation and informal interviewing were integrated throughout the study. During sensor installation and follow-up, participants were individually asked if they had any questions or comments about the system. After a week-long uptake period, a short, semi-structured survey of eight questions was conducted with 50 participants randomly selected from the 85 total participating households to elicit more structured feedback on system usability and to evaluate the clarity and efficacy of the training session. The survey was designed with a mix of open questions, which allowed for more freedom in responses and were used to bring up themes not already considered in the survey design, and fixed choice questions to provide more guidance and clarity for participants. Surveys were translated into the local language and conducted by field staff in the presence of the researcher and took approximately 10-15 minutes each to conduct.

Focal follows of two participants were also conducted by the lead researcher and a local translator from ILF to study the firewood collection process and evaluate if the holder for the fuel could be adapted to collect and transport fuel in context other than rural Honduras. The lead researcher manually recorded the time and observations for several tasks including time spent walking to the area where wood was collected, methods of splitting, storing, and transporting, and conversations between participants during these tasks. Written observations were supplemented with time-stamped photographs, which were also used to supplement data during post-processing. For the second focal follow, the lead researcher and two field staff from ILF sat in the kitchen during meal preparation and cooking, which took approximately four hours, to look for potential difficulties or errors with using the fuel holder. While the staff chatted with the participant, the researcher recorded each step of the preparation and cooking process, refueling events, times where wood was either removed or added to the holder, and any errors or challenges faced when using the FUEL system.

2.3.5 Phase 4b: Uganda, May 2018

To measure long-term system usability, a 17-question follow-up survey was conducted eight months after the initial monitoring period with all participating households from Phase 3. The objectives of the survey were to collect feedback on system usability from every participant to increase representativeness and for enumerators to observe and record the current uses of the fuel holder when participants were not required to use them. The surveys were designed in Magpi, an online survey design platform that allowed local Ugandan field staff to remotely collect and transmit the data. Following conversations with us about the intention of the survey, Ugandan field staff translated the questions into the local language.

ILF field staff from Phase 4a conducted the surveys without the lead researcher present, spending approximately 20 minutes with each participant. Surveys included a mix of fixed choice and open-ended questions. Fixed choice questions were guided by the responses from open-ended surveys in Phase 4a. Participants were asked what worked well for them and were asked to answer yes or no to whether they perceived each given choice as a benefit. These fixed choice questions were followed by an open-ended question about perceived benefits, if the multiple-choice options did not cover what the participant intended to convey. For example, a benefit of the fuel holder mentioned by the highest number of people during the open-ended survey in 4a was that the holder kept wood dry. The corresponding fixed choice question for the follow-up was: “what worked well for you with using the fuel holder?” with available options: “kept wood closer to stove”, “kept wood dry”, “protected wood from termites”, “dries out the wood”, and “other”. To capture additional answers, the question was followed by an open-ended response: “if the participant answered ‘other’, please elaborate on what worked well for them with using the holder”. This method was used to for additional questions regarding both benefits and challenges with using the system.

A focus group of ten participants who used the FUEL less than 60% of the monitoring days as shown by sensor data from Phase 4a was also planned, with the objective of understanding why people did not use the system and feedback on what could have been done to improve their experience.

2.4 RESULTS

2.4.1 Phase 1, Guatemala, June 2016

Results from Phase 1 allowed us to define problems with monitoring in the clean cooking and fuels sector, and generate resulting solution ideas. Post-analysis of participant observation of fuel usage and meal preparations indicated the habitual and deeply rooted process of firewood collection, storage, and resulting meal preparation and cooking. While collecting firewood, cooking, or preparing a meal, women would often multitask, which created additional complexity in measuring the impact metric of time and determining towards what activities spare time was dedicated.

The use of ethnographic methods also highlighted aspects of the lifestyle, gender relations, and daily rituals of the sample population of rural Guatemalans. For example, in these regions, it was found that men were typically the dominant decision makers in the household. Understanding this power dynamic helped to determine how to interact with households and how to interpret responses. For example, it was anticipated that if the husband was present, a women's response to a survey question could be altered or her husband might speak for her, obfuscating results. The rainy season in Guatemala is from May to October, and farming practices revolve around these weather patterns, which informed the most convenient times for monitoring and surveying to be conducted. Details such as these further defined the context in which the problem of designing better monitoring tools was situated.

While in Guatemala, participant observation helped to reveal shortcomings of current monitoring methods commonly used in the sector. Baseline surveys were prone to bias and provided inaccurate guesses of time spent collecting firewood, amount of firewood used, and how often stoves were being used. Placement and installation of the temperature sensors was challenging as it was critical to place them in a location that received enough but not too much heat while the stove was in operation. Initiating the temperature sensors was intrusive, as it required bringing a laptop into each household, and resulting data were difficult for untrained users to interpret. Generally, participant observation allowed the authors to better contextualize the problem of monitoring stove impacts, and eventually derive more targeted ideas for addressing these issues.

To verify these findings, participant observation data were corroborated with a narrative literature review on challenges with monitoring in the cookstove sector. Existing methods for monitoring included surveys, manual fuel measurements, temperature sensors, and emission sensors. Our observations of inaccuracies in self-reported survey data agreed with the literature on inherent biases in surveys to measure cookstove performance and adoption (Gould and Lewis, 1985; Thomas et al., 2013; Wilson et al., 2015). Use of temperature sensors was found to provide more objective measurements than surveys and valued within the research community but often resulted in malfunction or data loss due to high cookstove temperatures, theft, and improper training (Ruiz-Mercado et al., 2012a). More robust tools for measuring and documenting long-term regional fuel consumption were also suggested (Masera et al., 2015). Specific requirements included a solution that would be cost and time-effective, accurate, long-term, to capture seasonal or other variations over time, and that it would be able to measure desired metrics, including health and environmental impacts. A comparison of some existing monitoring methods is shown in Table 2.4.

Table 2-4 Competitive Landscape, Cookstove Monitoring

	Manual Methods		Temperature Sensors			Weight Sensor
	KPT	**Surveys**	**SUMS, Berkeley Air**	**Stove Trace, Nexleaf**	**Sweet Sense**	**FUEL**
Function:	Manually weigh wood	Fuel consumption, usage	Temperature logger	Temperature logger	Temperature logger	Fuel consumption, temperature logger
Fuel usage	✓	✓				✓
Stove usage		✓	✓	✓	✓	✓
Wireless upload				✓	✓	✓
Autonomous		✓		✓	✓	✓
***Cost per Unit**	$0	$0	$30-150[a]	$130[b]	$500[e]	$175[f]
Lifetime	NA	NA	1 year[c]	5 years[b]	not listed	5 years[g]
Continuous logging	NA	NA	14-60 days[c]	72 hours (battery), indefinitely (solar)[b]	6-18 months[d]	3 months[f]

[a] iButtonLinkTechnology, 2018; [b]Engineering for Change, 2018; [c]Berkeley Air Monitoring, n.d.; [d]Thomas, n.d.; [e]SweetSense, n.d.; [f]LeFebvre, 2019; [g]Manufacturer data

*Here, we made the assumption that implementation cost (hiring field staff, transportation, etc) would be similar for each and therefore did not include that as part of the cost for easier comparison

Based on the literature review and observational data, a variety of concepts was then generated and then analyzed for feasibility and capacity for meeting listed requirements, shown in Table 2.5.

Table 2-5 Design Concepts from Brainstorming

Concept	Indicator(s)	Potential Issues
Mobile tracking	*Time*	Legal/privacy issues, high cost to provide phones
24-hour time diary	*Time, usage*	Bias, inaccuracy, not long-term
Motion sensor	*Time*	Inaccurate-difficult to differentiate purpose for entering or leaving
School records and test scores	*Time*	May not keep records, tests do not indicate regular attendance
Ask teachers	*Time*	Incentive for teachers to fabricate data if they do not show up to class
Load cell (device to measure weight)	*Fuel, time, usage*	May be invasive

The analysis also highlighted the central importance of fuel in both the cooking process and as an indicator of multiple metrics of cookstove performance, which informed the concept of measuring fuel weight. Upon evaluation of brainstormed ideas, it was decided that the load cell concept was most likely to meet initially defined requirements, be technically feasible, measure the most indicators of stove performance and adoption, and operate with a wide variety of fuel and cookstove types. The basic concept was that a household would store their firewood in a container that would then be continuously weighed with a load cell. As a household removed wood for cooking or added after collection, these mass changes would be registered by the system and indicate fuel use over time. Several design hypotheses were then formulated to guide system testing and development. We initially hypothesized that a logging load cell could be used to determine:

i. the frequency of fuel collection events and amount of fuel collected per event
ii. fuel consumption per cooking event
iii. duration of cooking events and number of events, with temperature as a backup measure
iv. emissions.

It was also hypothesized that the container for fuel could:

v. connect to a load cell in tension or compression (Figure 2.3)
vi. double as a carrier during fuelwood collection.

2.4.2 Phase 2, Oregon/Global, 2017-2018

On-site research included the development of the FUEL prototype for future testing, as well as conducting stakeholder interviews to define needs, corresponding value propositions, and resulting design implications. The initial prototype system included the load cell, electronics, thermocouple and storage holder. The following list demonstrates how the system was divided into sub-components.

a) *Fuel weight measurement and storage:* A load cell that could accommodate up to 50 kg of fuel was selected based on known typical fuel loads. As shown in Figure 2.3, both tensile and compressive load cell configurations were considered in the original system design. As a separate unit from the load cell, the storage system design was intentionally unconstrained to allow for flexibility for different locations and fuel types.

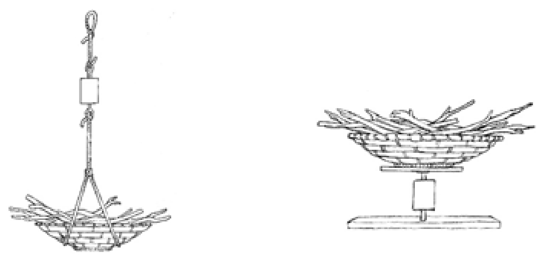

Figure 2.3 Initial concepts for tensile and compressive fuel storage

b) *Temperature measurement:* Off-the-shelf thermocouples were chosen based on the factors of cost (<$10/unit), high temperature rating (above 200 °C) to avoid malfunction, and length (2-3 m) to reach the stove.

c) *Electronics, data storage, transmission:* Circuitry design and manufacturing was outsourced to Waltech Systems, an Oregon-based company specialized in custom electronics. Two 1.5 V C batteries were selected as the initial power source due to low cost, high access, and easy integration. Low-power draw allowed for continuous data-logging periods of at least 30 days, which helped to meet stakeholder requirements of longer-term data that could capture seasonal and other patterns of variability. Various modes of wireless transmission were considered, but it was ultimately decided that the initial prototype would use SD cards, which required less R&D and were reliable, inexpensive, and required little training to operate. In a later version, wireless collection capabilities were added.

d) *Data analysis:* An algorithm was developed to convert the raw weight and temperature data to usable metrics (Ventrella and MacCarty, 2019). To determine the rate of fuel usage, reductions in mass are integrated over time and are then corroborated with temperature to verify that a cooking event is occurring. Fuel consumption can then be used in calculations for emissions, carbon credits, and averted Disability Adjusted Life Years (aDALYs), which are a measure of health impact (Smith et al., 2015).

Thematic coding of semi-structured interview data allowed us to identify key value propositions and map them to their intended stakeholder, using the BMC. Recurring themes included NGO practitioners feeling challenged by the demand to report useful metrics to their donors under significant time and resource constraints. Carbon credit project evaluators tended to emphasize challenges in gathering accurate fuel usage data with the Kitchen Performance Test (KPT), which requires manual measurements in households over several days, and is the only existing method to directly measure fuel use (Rob Bailis et al., 2018). An example of a subset of findings that map potential stakeholders to value propositions based on identified pain points and linking these to proposed design changes is shown in Table 2.6.

Table 2-6 Identifying stakeholders, value propositions, and resulting design implications

	Consultants/researchers	**Carbon credit project implementers/ evaluators**	**NGO monitoring/evaluation officer**
Description	• Early adopters • Rely on surveys or temperature sensors • Expected to deliver accurate data	• Responsible for setting standards and ensuring reliability	• Rely on surveys or temperature sensors to monitor • Must report impact findings to donors
Pain Points	• Obtaining accurate data that is inexpensive and fast	• Time, cost and difficulty in measuring and evaluating carbon project accuracy	• Time and cost to collect data • Proving impacts to donors
Value Propositions	• More accurate fuel use data • Streamlined data analysis	• Reduced cost to measure carbon credits • Streamlined data analysis	• Streamlined data analysis • Certification of cookstove performance
Design Implications	• Validation of FUEL system required • Intuitive GUI for data	• Algorithm that reports tCO_{2e}	• Algorithm that reports standardized metrics or cookstove performance

2.4.3 Phase 3, Honduras, May 2017

Results from Phase 3 provided insights on system sizing and usability. Photographic data from Guatemala, which shares similar geography and housing structures to Honduras, helped us to determine that the roofing structures in Honduran kitchens would be sturdy enough to support a substantial quantity of fuel, and that floor space in this context might be limited for a scale in compression. Examination of photographic data showed that a standard household fuel supply would generally not fit in the kitchen space, evidence towards invalidating hypothesis (i).

From the focal follow in Honduras, we found that fuel was not always brought directly into the kitchen, and that the amount of firewood collected during a typical trip would not fit in the fuel holders. These observations were additional evidence towards invalidating hypothesis (i). The data also indicated that hypothesis (vi), adapting the fuel carrier to a collection device, would be difficult because of sizing constraints, however, adaptation would not be a substantial change from normal practice because people already transported their wood in large sacks. During sensor collection at the end of the monitoring period, one participant questioned whether the holder could be used to collect fuel. Although the sample size was too small to be conclusive, larger scale testing should be conducted to fully validate or invalidate hypothesis (vi) in this region.

Informal interviews indicated that the participants were initially accepting of and interested in the fuel holder. Firsthand accounts from participants included the excitement of one participant's daughter, who rushed to bring back firewood to store in the holder. Another participant stated that as soon as he saw the system was installed, he began to collect firewood to store in the holder. However, although never verbally indicated, one participant seemed less accepting of the system based on initial resistance from her spouse on installing the system in their kitchen and observation of closed-off body language and facial expression during informal interviews. In contradiction to these non-verbal cues, follow-up questioning conducted by unaffiliated staff yielded only positive feedback from all participants. Although each household gave informed consent and we emphasized the desire for honest, uncensored feedback, there was still inherent bias in the qualitative results. Usage results from the FUEL system showed that the participant who seemed more uncertain about the fuel holder had only used it approximately 14% of the days monitored, despite temperature data reporting that the participant had been using the stove for most of the monitoring period. In comparison, the remaining three households used the holder 59%, 84% and 100% of the days.

2.4.4 Phase 4a – Uganda, August 2017

Results from Phase 4a provided information on system sizing, installation, and usability. During the training and informal interview session, participants provided generally positive feedback, although it was noted that certain participants were more vocal than others. Some participants voiced concern that the sensors might explode or negatively affect their health, and were assured that this would not happen. Some wood as collected was too large for the holder, and the finding from participant observation and informal interviews that women would often chop wood into smaller pieces only directly before cooking a meal suggested that wood might not be directly placed into the holder after collection. This was evidence towards invaliding hypothesis (i) for this study context. Participant observation of cooks preparing and cooking meals revealed some potential sources of uncertainty in data analysis, such as use of fire starter and smaller kindling that might not be stored in the holder and therefore not measured. Additional participant observation and a focal follow of a participant cooking a meal highlighted the potential difficulty of correlating weight reductions to cooking duration and that temperature measurement would be necessary for accurate data on cookstove duration, hypothesis (iii).

The intended focus group of participants who had used the FUEL system less than 60% of total monitoring days did not materialize, as several of these participants stated that they had used the system every day despite contrary sensor-based evidence. Several others claimed that the ropes/holder had been lost or stolen.

Survey results showed that when asked how the holder was working for them so far and given a scale of ✓-, ✓, or ✓+, the options were chosen 0%, 6%, and 94%, respectively. However, 10% of households stated that they had experienced a problem with the system. A total of eight households reported experiencing a problem, such as fear of the sporadic blinking green LEDs, which were an indicator of sensor battery life. A full breakdown of reported challenges from open-ended questioning is shown in Figure 2.4.

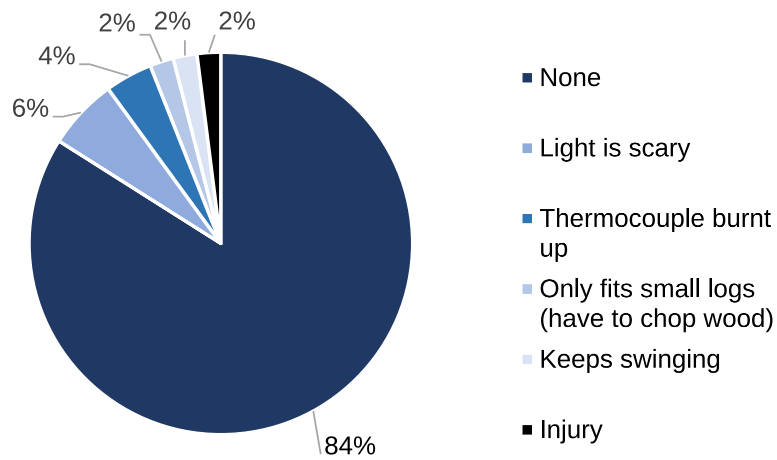

Figure 2.4 Perceived Challenges of Fuel Holder. Apac, Uganda, 2017

Reported benefits, as shown in Figure 2.5, were that the holder kept wood dry and organized. Participants provided generally positive feedback. During the training session, participants unanimously agreed that they preferred a hanging system to one on the ground, a finding that confirmed hypothesis (vi).. These

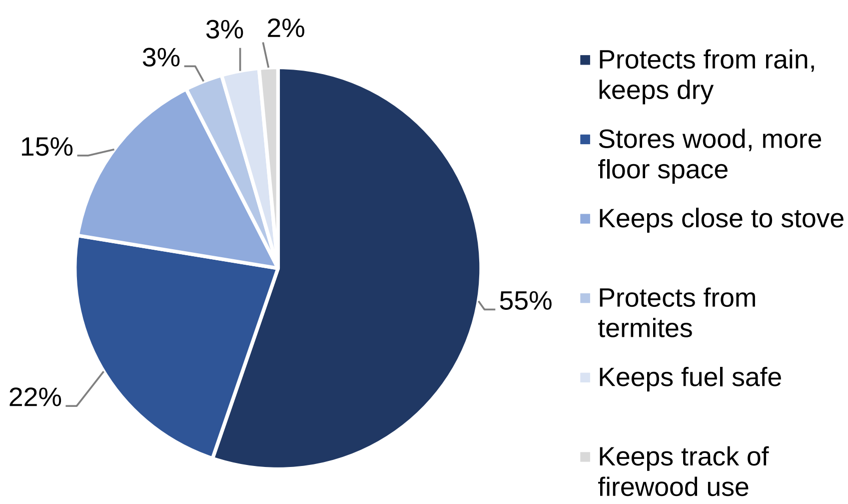

Figure 2.5 Perceived Benefits of Fuel Holder. Apac, Uganda, 2017.

data were corroborated by observations of typical wood storage habits, as several observed households were using bricks to elevate wood off the ground, evidence towards validating hypothesis (v).

The focal follow of two women collecting firewood yielded similar findings about difficulties in sizing the fuel holder for adaptation to a collection device as the focal follow data from Honduras. Unlike in Honduras, firewood was transported by tying into bundles and balancing on the head, a practice that was significantly deviant from storing in a bag and was additional evidence towards invalidating hypothesis (vi) in this context.

2.4.5 Phase 4b – Uganda, May 2018

Results and implications from the follow-up survey conducted 8 months after the initial monitoring are briefly discussed.

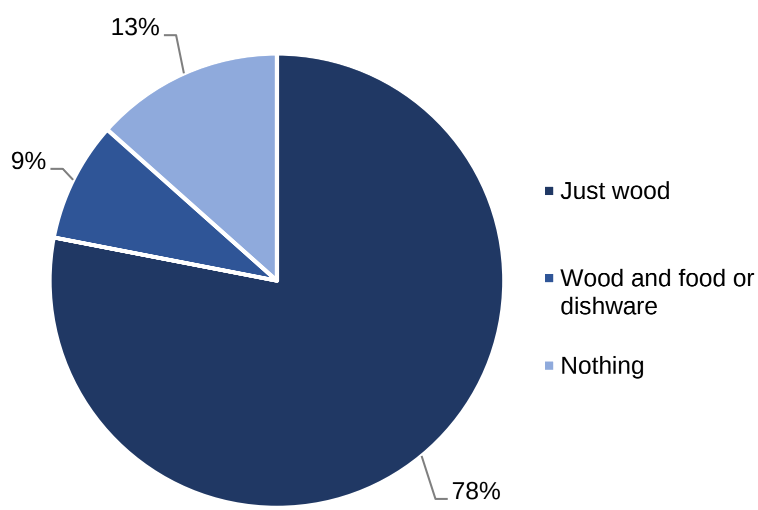

Figure 2.4 Observed Holder Storage Content after 8 months. Apac, Uganda, 2018

Storage content. Enumerators were asked to observe the contents stored in the holder as they conducted surveys in each household kitchen (Fig. 2.6). These observations were used as a metric to understand long-term, post study usage of the system when participants were not required to store wood in the holder. It was found that most households were still storing wood in the holder 8 months after the end of the study period. Of the remaining participating households, 9% of households were using the holder to store wood along with food items or dishware and 13% of households were not storing anything. In addition, 4 of the surveyed households no longer had their holder, for various reasons including moving the holder to another area to keep it protected, and theft. These results point towards acceptable system usability, as use continued long after the end of the study period.

Perceived benefits. 34% of respondents perceived the holder keeping wood closer to the stove as a benefit, 45% that it was kept off the ground, 61% providing protection from rain, and 67% that it helped to dry wood.

Perceived problems. 17% of respondents reported that chopping their wood into smaller pieces to fit in the holder was a problem, 5% that the light on the sensor was frightening, 3% that the system got in the way of cooking and other tasks, and 1% that it was difficult to remove wood from the holder. The most common problem participants had with the fuel holder was that it was necessary to chop their collected firewood into smaller pieces to fit into the holder. This agreed with results from open-ended questioning, where 9% of participants said that the fuel holder was too small. Although only one participant agreed that it was difficult to remove wood in the fixed choice question, 9% of participants mentioned that it was challenging to refill the holder with wood during open-ended questioning, which agreed with observation and experience with adding and removing fuel from the holder.

Usage results from the FUEL system showed that 82% of FUEL sensors were used consistently, where consistent use was defined as use of the FUEL system at least once per day with at least 1 kg of wood consumed for over 60% of the monitored days, to account for days when no cooking is conducted in the household. This finding agrees with the proportional trend of survey-reported benefits and challenges, where the highest reported issue, chopping wood, was a problem for 17% of participants.

In summary, Table 2.7 shows how methods used in each phase informed validation or invalidation of each hypothesis.

Table 2-7 Summary of Methods and Hypothesis (In)Validation

	Hypothesis	Phase	Method(s)	Evidence for validation?
Technical feasibility Load cell could be used to determine:	(i) frequency and amount of fuel collected	2, Honduras	photographic data	X
			focal follow	X
		4a, Uganda	participant observation	X
			informal interviews	X
	(ii) fuel consumption per cooking event	2, Honduras	sensor-based	✓
		4a, Uganda	sensor-based	✓
	(iii) duration and quantity of daily cooking events	4a, Uganda	participant observation	✓ (with temp)
			focal follow	✓ (with temp)
	(iv) emissions		not yet tested	
Usability Fuel container would:	(v) connect to a load cell in tension or compression (tension selected)	4a, Uganda	participant observation	✓[a]
			informal interviews	✓[b]
	(vi) double as a carrier during fuelwood collection	2, Honduras	focal follow	X
		4a, Uganda	focal follow	X
	(vii) be usable for participants	2, Honduras	informal interviews	✓[c]
			participant observation	✓
			sensor-based	X/✓[d]
		4a, Uganda	informal interviews	✓[b]
			survey	✓[e]
			participant observation	✓
			sensor-based	✓[f]
		4b, Uganda	survey	✓[g]

[a] Several households in the area had propped their wood off the ground using bricks for the stated purpose of keeping it dry
[b] Participants unanimously voiced that they preferred the system in tension because it would keep wood dry
[c] All four participants stated that they found the system usable
[d] FUEL reported that participants used the system 14, 59, 84 and 100% of monitoring days
[e] 84% reported no challenges, all participants reported at least one benefit
[f] 82% of participants used the FUEL system over 60% of the monitoring days
[g] 78% of households were still storing only wood in the holder eight months after the end of the study

2.4.6 Resulting System Improvements

Data from the testing and feedback phases were then used to inform design improvements to the system. Although currently ongoing, initial adjustments have been made to several system components.

a) *Fuel weight measurement & storage:* Although it was not a challenge to slide wood out of the side of the holder, several participants expressed challenges with filling. This could be fixed by adding a horizontal support beam to keep the holder open at the top, which one participant had already done to mitigate this problem.

b) *Temperature measurement:* The thermocouple wires were difficult to install and sometimes impeded cooking or removing/adding wood to the holder. In later iterations, wired thermocouples have been replaced by wireless sensors that are independent from the logging load cell.

c) *Electronics/data storage/transmission:* Based on participants' fear of the LEDs and uncertainty of whether the sensor was actually logging, a LED may be added to indicate when the sensor is logging, and the purpose of the additional lights will be explained to households in future deployment or removed altogether. In response to stakeholder requirements, a wireless data transmission system and analysis platform are currently under development to enable quicker data transmission.

d) *Data analysis:* In addition to hardware changes, the algorithm designed to interpret the data was adapted based on ethnographic data. For example, outlier data points were initially attributed to noise or accidental human interaction and cleaned from the data set. However, ethnographic evidence from a research member showed that certain intentional use cases could result in outliers and should be counted in the data. Based on this information, the algorithm was refined to distinguish between intentional and unintentional outliers. Results from a later study comparing daily average fuel consumption measured manually versus with the FUEL sensor showed that the reported R^2 value increased from 0.5992 to 0.7916 with the cleaning algorithm applied (Ventrella, MacCarty, LeFebvre, and Thivillon, 2019).

2.5 DISCUSSION

The ultimate result of this research was the development of a technology that could address an urgent need in the clean stoves and fuels sector. The results of this research highlight the value in integrating ethnography in the design process. Our discussion will identify overarching themes that can inform DfD frameworks, paradigms, and choice of methods.

2.5.1 Reflection on Effectiveness of Rapid Ethnographic Methods

In the context of this study, certain ethnographic techniques provided more service than others in informing product design and usability. For example, survey-based methods were found to work well for drawing large scale, high level conclusions about usability that included the input of all participants. Triangulation of sensor and survey data allowed us to better validate survey findings about the holder usability and make informed design changes. Results from sensor usage agreed fairly well with initial survey results, where 10% of users reported initial problems, and a resulting 16% of people did not consistently use the system. While not directly proportional or comparable, these results should be positively related. Triangulation between survey and sensor data confirmed similar findings from each source and necessitated further investigation to understand discrepancies in later phases. Observing localized tasks that were integral to the cooking and therefore monitoring process allowed for more targeted brainstorming, analysis, and follow-up questions. Participant observation and focal follow of current wood collection and storage methods highlighted the need to fully consider and evaluate system` usability. Observational data were critical to developing an algorithm that correctly accounted for various use cases. While the training session was valuable to explain the purpose and function of the FUEL system, it was found that the open-ended questioning at the end of each session encouraged participation from only the most outspoken members of the group and skewed results. An attempt to organize a focus group of non-users was unsuccessful, as not everyone who had been found to use the system inconsistently admitted to this.

Rapid ethnographic techniques were also used to better understand stakeholder pain points in cookstove monitoring and evaluation, and develop a solution that would most effectively meet these needs. Semi-structured interviews conducted to create the BMC allowed us to create testable customer hypotheses in tandem with developing and testing the system. Therefore, we argue that design changes that meet customer needs could be considered in the front-end of development to proactively reduce later cost of time and resources for re-design. However, we found that the BMC did not prompt consideration of social and environmental aspects of product design and delivery, which are especially important when evaluating design ethics and sustainability (Miller, 2014). Similar findings from other studies have led to the design of a triple layered BMC that incorporates economic, environmental and social aspects of product value (Joyce and Paquin, 2016).

Although a useful tool, ethnographic investigation raises several ethical considerations that should be addressed.

- A previous review of ethical concerns in ethnographic design research included supporting user inclusion, and consideration of impacts of design on the environment and society. One positive trend found was a shift of focus from the ‘object’ to the ‘user’, which is especially valuable in a market-based design approach that may tend to overvalue products and consumerism (Miller, 2014).
- The positionality of the researcher can also influence findings if the researcher is from a different cultural or socio-economic context. To mitigate this issue, we tried to have only local field staff collect data whenever possible, to limit the influence of the researcher. The field staff were well-

briefed on the research objectives and intentions behind each method, which helped to direct survey questioning. However, it should be noted that even if a staff member is from a similar region, there could still be significant socio-economic or cultural differences and power differentials between the staff and participants that affect responses. Therefore, careful survey design, staff debriefing, and occasional oversight by the lead researcher to take note of these issues can help to address them.

- A conflict of interest exists in that we had a personal investment as the developers of the sensor system, which could inhibit objective data collection and analysis. Bias was reduced by not expressly stating to stakeholders and participants that the lead researcher had developed the system and having local Ugandan field staff conduct the follow up surveys without the presence of the lead researcher.
- Another ethical concern identified in this study was the singling out of women who did not consistently use the sensor for a focus group. This concern was addressed through careful survey design to ensure that the language used in questioning was not accusatory, and that participants were encouraged to be open about their experience with using the sensor system. In addition, all researchers who originally implemented the system were not present. However, it was found that several participants claimed to use the holder every day, despite contrary sensor data evidence, highlighting challenges in organizing focus groups that participants feel may negatively implicate them.
- Several ethical concerns were addressed by gaining informed consent of all participants, and using multiple rapid ethnographic methods to try to collect as much feedback from as many participants as possible.

Follow-up surveys indicated that several participants had inquired about the FUEL data and the implications for their health. Further consideration for the democratization of tools and data and determining how best to share these with stakeholders is also needed (Sawicki and Craig, 1996). This approach also brings into question the ethics of a more “top down” model of design, which has been recently critiqued for its roots in colonization and post-colonialism (Gregory, 2018). Although less inclusive than co-design or community-based design, our approach may have been more applicable to evaluating a “secondary” product, as the sensor is not intended to fulfill a basic need, and is not expected to integrate into a household for a long time. While our use of rapid ethnographic methods to gain contextual understanding and engage participants was a step in the right direction, future work in DfD must consider the decolonization of ethnographic design work and more deeply engage users in critical feedback for further design stages, especially in the design of technologies that are intended to provide direct, long-term benefits (Forlano and Smith, 2018). Ethical considerations such as these have become increasingly relevant to designers, and further work is needed to assess and incorporate ethics into DfD contexts. In relation to inequality in design is the use of over-formalized methods, which may discourage more casual, open conversations and inclusivity of participants, and demands for a balance in more systematized, “statistically significant” data and informal but richer contextual data (Gregory, 2018).

These findings speak to the value of triangulating data to validate or invalidate results, as well as the potential benefits of using third party evaluators who may be less biased when conducting surveys and focus groups. Reliance on surveys or focus groups alone can introduce bias, and sensor data on its own did not explain how or why the system was or was not being used. A combination of triangulated ethnographic and sensor-based data helped to prove or disprove hypotheses. Previous research also substantiates this finding, arguing that objective empirical results must triangulate data from multiple sources (Ball and Ormerod, 2000). Triangulation also allowed us to more accurately interpret the cause of outliers in raw sensor data. This speaks to the value of using ethnographic data to inform “big data” analysis, which often disregards outliers that may be informative (Zhang, Zhao, and Ventrella, 2018). A limitation here is the repeatability of these results, as certain ethnographic methods work better for different contexts. However, researchers or designers can use these lessons to make more informed decisions about which specific methods might be most applicable to their research-design contexts. In addition, on the one hand, sensor-based on-site monitoring generated data that are aggregable and comparable across different geographic, cultural and economic contexts. On the other, ethnographic methods, especially participant observation, semi-structured interviews, and surveys, provided rich and critical data for corroboration with and contextualized understanding of sensor-based big data. Reflection of the design process also led to identification of more general design considerations that build on preexisting theory.

2.5.2 Reflections on Design Theory and Resulting Considerations

A synthesis of data from participant observation, focal follow, and informal interviews informed fuel holder development. Through analysis of these data, we determined that in the study context of Apac, Uganda, adapting the holder to a device for collecting firewood would most likely not be readily adopted and therefore not worth allocating R&D cost and time. Although in some contexts the fuel carrier could be of use, and further investigation is required for communities that use bags to transport firewood, it was not found to be a benefit in the larger-sample study location. Understanding the context before adding additional design attributes or functionality to a simple design can be a more effective method than creating initial complex solutions. A narrative review of existing solutions also aided in avoiding the common design pitfall of reinventing the wheel (Mulgan, 2014). This finding reflects the theory of pro-innovation bias, in which engineers and designers could be biased towards creating new, disruptive innovations instead of implementing more stable changes (Rogers, 1983; Sax, 2018). Critics of pro-innovation bias claim that the emphasis on disruptive innovation may lead designers to overlook failure and need for re-design based on grounded critique. The decision to create products with perceived higher utility, such as the fuel carrier that could double as a method of collecting firewood, can lead to time and resources depleted on an unneeded design. Using rapid ethnographic techniques early in the design process to better understand context-specific practices, habits and needs can help to reduce unnecessary innovation.

Findings of factors that influenced technology acceptance and uptake signified the importance of recognizing the cultural significance of what out-of-context designers may consider “everyday” objects and understanding how these objects may translate differently to people in different contexts. Through informal interviewing and surveys, researchers learned that the LEDs on the sensor scared some participants, they could not always tell if the sensor was working, and that some were concerned that the sensor would explode or affect their health. To a designer, the light represents a useful indicator of battery life and the wire is clearly a non-explosive device to measure temperature, but to a person in rural Uganda with no access to electricity/electrical devices or exposure to the dangers of unprofessional electrical wiring, these can convey an unknown or potential danger, and can induce fear. Findings of contextual and aesthetic concerns agree with earlier studies that have observed this phenomenon in similar settings and have called for emphasis on recognizing local cultural context and meaning in design (Kujala, 2009). For example, one study in Soweto, South Africa that studied adoption of washing machines found that despite the labor-intensive process of traditional handwashing and households’ financial capacity to purchase a washing machine, there was low uptake due to their cultural connotation of promoting laziness and undermining traditional gender roles (Meintjes, 2001). A combination of identifying the localized socio-cultural implications during early prototyping phases and adequate explanation of the technology’s function can help to increase user willingness to adopt.

Another finding was participants’ preference for indicators of when the sensor was correctly operating and pointed to the value in integrating visual or other sensory operating cues. For example, because there was no LED to indicate sensor use, several cooks voiced concern that they could not tell if the sensor was properly logging. Participants' unease of not knowing if the sensor was working led to an understanding of the value in indicators and visual cues that signal to people that a product is working correctly. This finding is replicated in other research, such as a study that evaluated the usability of a water purifier design in an eastern Ugandan school (Burleson et al., 2019). Informal interviews implemented during the testing/feedback phase revealed that many of the girls initially did not trust that the purifier was cleaning the water, because there were no sensory cues as the cleaning process occurs within non-visible copper pipes and the output water is cold. In a context where people primarily boil their water to kill harmful bacteria and rely on seeing bubbles and feeling the heat of the water, this initial mistrust represented a significant barrier to adoption. Depending on factors such as the cost of R&D and the stage of the design process, adding design features such as a light that turns on during correct operation or additional education on how the product works can increase user trust.

Results also pointed to the value in product adaptability and modularity. In this case study, the FUEL system was separated by component, such as fuel holders made using locally available materials and sized appropriately to the kitchens in the study location. Previous research has found adaptability to be an important consideration that can assist designers to more easily make design changes and accommodate context-specific, temporally-evolving user needs at any point in the design process. The concept of flexibility in design is rooted in the adaptable design (AD) paradigm (Gu, Hashemian, and Nee, 2004) and product modularity (Gershenson, Prasad, and Zhang, 2003), and could be further incorporated into DfD frameworks. For example, in the clean cooking and fuels sector, a base model stove design could then have additional, context-specific modular components, such as a chimney or a meat smoker.

2.6 CONCLUSION

This paper details the design, development and testing of a sensor system for measuring fuel consumption and cookstove use in low resource contexts, identifying appropriate tools and methods applicable through use of an integrated mixed-method ethnographic approach. Context-based data guided us to invent a solution that addresses business, technology, and user requirements in impact monitoring for DfD.

We found that triangulation of ethnographic data with sensor-based data improved our certainty of the survey results, as the general trends between sensor and survey-reported usage and perceived benefits were similar. Survey and participant observation results also helped to contextualize possible reasons for when sensor usage was measured to be low. Second, triangulation helped to inform the algorithm development, as spikes that were initially being removed from the dataset were determined through analysis of ethnographic data to be intentional fuel usage events. Incorporating these findings into our algorithm contributed to an increased R^2 value when comparing the FUEL measured fuel consumption to manual measurements, and we were then able to more confidently rely on our sensor data for more generalizable findings across cultural, geographic, and economic contexts. This method has broader applications in the realm of big data, where large quantities of data can easily be generated, but provide little or no context to why certain trends are occurring. In addition, errors in algorithm development can occur if intentional activity is mistaken as noise or an outlier, and can suffer from misinterpretation.

Ethnographic data also allowed us to recognize and address potential negative, context-specific connotations of technology that might not be perceived easily by outsiders. Upon identifying these problems, solutions could be devised, such as more descriptive education material that directly addresses concerns, as well as incorporating visual or other sensory cues into technology to increase user trust.

Broadly, results from this study contribute towards DfD frameworks and illustrate the challenges of designing technologies in these contexts, including the influence of pro-innovation bias on designers in creating unnecessary "novel" design, and the value in product adaptability, and modularity. Broader benefits of using ethnographic techniques within design frameworks include understanding of product usability, more informed design decisions, and ultimately, conceiving and developing a solution that is of value to a diverse set of stakeholders.

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CHAPTER 3

MONITORING IMPACTS OF CLEAN COOKSTOVES AND FUELS WITH THE FUEL, USAGE, AND EMISSIONS LOGGER (FUEL): FIELD TESTING AND REPORTING CAPABILITIES

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ABSTRACT

Objective, affordable, and unobtrusive monitoring tools are needed to quantify in-field performance and increase rates of user acceptance of clean cookstoves and fuels. To meet this need, researchers have developed the Fuel, Usage and Emissions Logger (FUEL), a novel sensor-based system that monitors household fuel supply mass and cookstove temperature to quantify cookstove adoption and use, fuel consumption, and extrapolate these to predict air quality and climate emissions. Following a proof-of-concept study of five sensor prototypes in western Honduras and an initial pilot study in northern Uganda, a field study of 68 sensors that logged for an average of 45 days each was conducted in rural Ugandan households. The purpose of these studies was to evaluate sensor usability and technical performance, inform algorithm development, and quantify key stove performance metrics. Usability results indicated that households used the FUEL system correctly for 85% of monitoring days. Key metrics include findings that stove stacking of an improved and traditional stove will contribute to higher fuel consumption per capita and up to 58% higher global warming commitment than households using a single improved stove. These results highlight the potential of the FUEL system to aid in more effective and accurate quantification of long-term technical performance and adoption, while increasing the transparency and impact of improved cookstove projects.

3.1 INTRODUCTION

In recent years, improved fuels and cookstoves have been designed and disseminated in 80 million households to help mitigate the harmful health and environmental impacts of traditional open fires (GACC, 2017). Despite actions to reduce harms through technologies utilizing improved fuels, heat transfer, and combustion efficiencies, the long-term adoption patterns of these efforts remain unclear, as does the extent to which improved stoves displace traditional methods. The technical performance of improved stoves in real-use settings has also not been fully characterized. Therefore, to inform more strategic design and policy decisions, accurate and comprehensive field data are needed.

Historically, surveys have been used as a relatively easy and inexpensive method to estimate desired cookstove performance metrics, but are subject to bias (Brooks et al., 2016) (Brooks et al., 2016). As a result, practitioners have started to introduce quantitative monitoring and evaluation tools to increase objectivity, resulting in development of several sensor-based technologies that monitor stove performance at the household level. (Harrell et al., 2016; Lozier et al., 2016; Pillarisetti et al., 2014; Ruiz-Mercado et al., 2013; Wilson et al., 2015). These include temperature and emissions sensors that measure cookstove body temperature as a proxy for use and quantify ambient air quality or personal exposure. While these data have been helpful to inform program implementers about adoption and emissions, temperature sensors can burn up, resulting in data loss, while emissions sensors only monitor for short times and can be difficult to transport. In addition, neither monitor what is arguably the most important metric to determining health and environmental impacts-- fuel consumption. Despite the need to evaluate fuel consumption in real-use conditions to correlate directly to cost, emissions inventories, and health predictions, only a handful of stove projects are currently able to do so due to challenges in capturing accurate and long-term fuel consumption data (Adkins, Tyler, Wang, Siriri, & Modi, 2010; Gifford, 2010).

This lack of available autonomous fuel consumption monitoring tools motivated the development of the Fuel, Usage, and Emissions Logger (FUEL), a sensor-based system that monitors the mass of a household fuel supply and cookstove body temperature to quantify cookstove use and fuel consumption, and extrapolate fuel consumption to emissions. This system was developed using user-centered ethnographic and entrepreneurial techniques over a two-year period in three countries (Ventrella, Zhang, and MacCarty, 2019). This paper will discuss the performance and use of FUEL prototypes to determine key performance metrics as compared to a review of current monitoring methods in the sector and their limitations. It will also outline the methods and results of development, testing, and analysis in a field study of 68 sensors in northern Uganda.

3.2 BACKGROUND

From project implementers to funding organizations, stakeholders in the global clean cooking sector are advocating for more objective, quantitative data to prove or improve project efficacy (Kees and Feldmann, 2011). There are hundreds of stove designs in existence that vary based on cultural context, fuel type, and local resources, which means that each stove program will vary in technical performance and adoption rates based on factors such as their design, given user population, and marketing strategies.

This requires that each stove design for each new program be individually evaluated to measure project efficacy, which is comprised of a holistic range of evaluation metrics including adoption and usage rates, displacement of traditional methods, stove stacking, time savings, fuel savings, firepower, and emissions reductions. Current methods to quantify these metrics include household surveys, standardized testing protocols, and sensors.

3.2.1 Program Monitoring & Evaluation Metrics

Technical Advisory Group 285 of the International Organization for Standardization (ISO) is working to develop international standards for clean cooking technologies (ISO, 2018). These standards include a set of metrics and testing protocols for evaluating cookstove performance, including cookstove adoption, displacement and stove stacking, time, fuel consumption, firepower, and emissions. Each of these metrics are important to quantify the holistic impact of a cookstove program and ability to meet the multiple objectives for each of the diverse stakeholders involved.

3.2.1.1 Adoption and Usage

Sustained adoption of a technology is a direct function of its usability (Moses, Pakravan, and MacCarty, 2019). A design that does not meet user needs will not be regularly used and therefore not generate anticipated impacts. Therefore, measuring cookstove adoption to understand usage rates is critical. The adoption process is outlined in the diffusion of innovation theory, which describes the dynamic variation in how a design is communicated and adopted over time (Rogers, 1983). For stoves and fuels, adoption can be divided into uptake stages of acceptance, initial use, and sustained use or dissadoption (Ruiz-Mercado, Masera, Zamora, and Smith, 2011a). Assessing this evolution of technology adoption necessitates long-term monitoring to fully capture sustained use and additional non-constant factors such as seasonal variability (Bhatt and Sachan, 2004; Rehfuess et al., 2014; Ruiz-Mercado et al., 2011; Stevenson et al., 2017). For example, a study in rural Mexico that measured clean cookstove adoption with temperature sensors in 259 randomly selected households found that full saturation of sustained use was reached after four months, highlighting the importance of long-term measurement (Pine et al., 2011).

The magnitude of adoption is generally quantified by the timing, variety, frequency, and consistency of use over time (Ruiz-Mercado et al., 2011). These parameters can be measured with cookstove temperature as a proxy for cooking events and duration, in which a cookstove body temperature raised above a specified threshold relative to ambient indicates a cooking event, or stove “on” condition. The number of events and event durations are aggregated over weeks or months to measure long-term adoption.

3.2.1.2 Displacement and Stove Stacking

Stove stacking occurs when a household uses more than one energy device for cooking and/or heating. Stacking is more common than complete displacement of traditional cookstoves in households that have access to multiple appliances, which they use for varying tasks and seasons. This is akin to households in higher income areas that have many cooking devices in their kitchens, each designed for a specialized task (e.g. stove, oven, coffee maker, microwave, toaster). Reasons for continued use of traditional stoves include the familiar and expected flavor for certain dishes, ease of use, and flexibility in firepower, among others (Dickinson et al., 2015; Rhodes et al., 2014; Stanistreet et al., 2015). Because stove stacking can greatly reduce potential health and environmental impacts, it is necessary to measure the use of all cooking devices in the household to fully capture the effects (MacCarty and Bryden, 2017). Displacement and stacking can be measured through survey-based methods or usage monitoring of each device present in the household.

3.2.1.3 Time

The total time expended towards cooking energy provision can be divided into several subtasks, including fuel collection, fuel preparation, fire-starting, cooking or reheating food, and tending the stove during the cooking process. Energy consumption also extends beyond cooking to additional tasks that require fuel, including space heating or boiling water for drinking (Ruiz-Mercado and Masera, 2015). During these subtasks, simultaneous chores or caring for children may also occur. Cooks that use a traditional stove generally spend at least five hours a day completing these tasks (Smith et al., 2007). If an improved stove has better combustion and heat transfer efficiency than the traditional stove, it could potentially reduce the amount of time spent collecting firewood, shorten cooking duration, or reduce tending time and allow for more free time to perform other tasks. Time spent on cooking can be measured using surveys, controlled cooking tests (Bailis, 2004), or time allocation studies where a researcher observes and records the duration of each task (Soeftestad, 1990). Sensor-based monitoring can provide a more accurate depiction of time spent on cooking-related activities.

3.2.1.4 Fuel Consumption

An integral component of the cooking process is the fuel collection or purchasing, and use, which represent cost, time, and significant effort for the user (Rehfuess, 2006). The type of fuel varies based on availability and users' socio-economic status, but can include regional wood types, charcoal, coal, biogas, and liquid petroleum gas (LPG). In areas of nonrenewable wood harvest, the current status for 55% of the global wood harvest, fuel collection can also lead to environmental degradation and deforestation (Bailis et al., 2015; Osei, 1993). Direct quantification of fuel consumption can indicate whether negative impacts are being decreased and by how much. Past studies have attempted to quantify fuel consumption with manual daily weighing through the Kitchen Performance Test (KPT) (Bailis et al., 2018) or survey-based methods (Granderson et. al, 2009; Osei, 1993; Smith et al., 2007). These methods often normalize fuel consumption to standard adult equivalence (SAE), which accounts for the age and gender of each household participant (Table 3.1) (Bailis et al., 2018; Openshaw, 1990).

Table 3-1 Standard Adult Equivalence (SAE) Factors
(Bailis et al., 2018; Openshaw, 1990)

Gender and age	**Fraction of standard adult**
Child: 0-14 years	0.5
Female: over 14 years	0.8
Male: 15-59 years	1.0
Male: over 59 years	0.8

3.2.1.5 Firepower

Measurements of time spent cooking and fuel consumption can be used to calculate stove-specific firepower, which is the energy released by a quantity of combusted fuel over a specified time (Eq. 1) (Bailis, 2004).

$$q = \frac{m_{fuel} HHV}{\Delta t} \tag{1}$$

Here m_{fuel} is the dry equivalent mass of combusted fuel during the cooking duration, *HHV* is the higher heating value of the fuel, and Δt is cooking duration. Firepower, *q*, is an indicator of the rate of heat output and can serve as a relative comparison metric between various stove types.

3.2.1.6 Emissions

Measurement of pollutant emissions from fuel combustion are of interest concerning both health and climate impacts. The impact of emissions on human health, often represented as Disability Adjusted Life Years (DALYs), is dictated by the concentration of pollutants in the air to which a person is exposed, which is a function of the cookstove, kitchen size, ventilation, chimney, and location of the person. Because of these variable factors, personal exposure from a variety of pollutants is often difficult to accurately measure (Smith et al., 2010). A second metric is the total pollutants released from combustion, which are used to measure climate impacts, often represented as global warming commitment or tons of equivalent carbon dioxide ($tCO_{2,e}$) mitigated. In this case, emissions are typically sampled directly as they exit the cookstove in terms of either emission factors, which quantify the mass of emissions per quantity of fuel burned, or emission rates, which quantify the mass of each emission species produced per unit of time. Limitations of using emissions factors include the possibility of error introduced by using lab measured values. However, in the absence of other measurement tools, this value can be a useful indicator to compare emissions in households using the same stove, and therefore more easily compared.

3.2.1.6.1 aDALYs

Household air pollution (HAP) from solid fuels accounted for an estimated 4.3 million premature deaths in 2012 (WHO, 2014). This figure is quantified in terms of DALYs, which is an estimate in the number of years of life lost due to poor health or disease-induced death. The non-linear nature of the integrated exposure-response (IER) curve, which links personal exposure to health, indicates that it takes a substantial reduction in emissions from the baseline (~80%) to significantly lower relative health risk (Burnett et al., 2014; Smith et al., 2014). Data on personal exposure, which informs the relative risk (RR) value from the IER curve, stove usage, and population health can be used to calculate Averted DALYs (aDALYs) attributable to an improved cookstove intervention (Eq. 2) (Smith et al., 2015).

$$aDALY = B \cdot Use \cdot SFU\left(PAF_{pre} - PAF_{post}\right) \quad (2)$$

In this equation, *B* is the underlying disease burden, *Use* is the fraction of households consistently using the intervention cookstove, *SFU* is the percentage of solid fuel users in the target population, and population attributable fraction (*PAF*) is a measurement of the reduction in population disease or mortality that would occur if an ideal reduction of exposure to the risk factor was achieved (Eq. 3) (Burnett et al., 2014; Pillarisetti, Mehta, and Smith, 2016). Subscripts *pre* and *post* represent PAF before and after a cookstove intervention, respectively.

$$PAF = \frac{SFU\left(RR-1\right)}{SFU\left(RR-1\right)+1} \qquad (3)$$

Here, *RR* is relative risk for various diseases calculated using IER curves for $PM_{2.5}$ exposure (Pillarisetti et al., 2016). This model in its simplest form does not account for stove stacking, which can lead to significant continued PM exposure if the traditional methods are used even a fraction of the time (Johnson and Chiang, 2015). Although fuel use measurements may not be directly required to calculate aDALYs, fuel use measurements can be paired with emission factors and cooking durations for the Monte Carlo Box model approach to predict air quality as used by the World Health Organization (WHO, 2014). In addition, researchers strongly recommend that fuel and usage measurements are conducted prior to an aDALY validation to verify stove performance and determine if the expected benefits in emission reductions can be achieved (Smith et al., 2015).

3.2.1.6.2 Carbon Credits

Clean stove programs have also been cited as a viable method to slow climate change, due to their potential to reduce emissions of short-lived climate pollutants (SLCPs) such as carbon monoxide and black carbon (Bailis et al., 2015). Solid fuels for cooking and heating contribute an estimated 25% of black carbon emissions globally (Rehman et. al 2011), a pollutant with a global warming potential (GWP_{100}) value that is 910 times higher than that of an equivalent mass of CO_2 (Bond et al., 2013). Clean cookstoves been estimated to provide the potential to reduce an overall estimated 1 gigaton of carbon dioxide annually based on offsets of 1 to 3 tons of carbon dioxide (tCO_2) per stove (Müller et al., 2011; Rehman et al., 2011).

Climate impacts of a cookstove project can be quantified in terms of tons of carbon dioxide equivalent reductions (tCO_{2e}), which can be sold on the voluntary or compulsory carbon markets as “carbon credits”. Depending on the state of the carbon trading market, carbon credits can be traded or sold at the current market price (Lee et. al, 2013) and therefore sales can be a promising source of financing for clean cookstove projects. However, in the past the accuracy of carbon measurement has been questioned and researchers have called for reputable standards to increase the credibility of these types of projects

(Simon, Bumpus, and Mann, 2012). Measurements of fuel savings and cookstove adoption paired with empirical emission factors can be used to determine annual emissions reductions (ER) as tons of carbon dioxide equivalent (tCO_{2e}) for a given stove implementation project (Eq. 4) (Gold Standard, 2013).

$$ER = N_{stoves} Use \left(1 - f_{dis}\right)\left(GWC_{pre} - GWC_{post}\right) \tag{4}$$

Here, N_{stoves} is the number of intervention stoves, *Use* is the fraction of households consistently using the intervention stove, and f_{dis} represents the fraction of cooking processes that are still conducted using the baseline stove and is included to account for stove stacking. *GWC* is global warming commitment, per Eq. (5).

3.2.1.6.3 Global Warming Commitment

The total climate forcing contribution for any stove type, *i*, can be calculated in terms of global warming commitment. To calculate annual global warming commitment, measured in tons of carbon dioxide equivalent (tCO_{2e}) per year, each stove-specific emission factor, $EF_{k,i}$, which is the mass of CO_2 and non-CO_2 pollutants emitted per kg or MJ of fuel combustion, is weighted by its global warming potential (GWP), which is a forcing unit relative to CO_2, and then multiplied by annual fuel use, AFU_i, measured for that stove (Eq. 5).

$$GWC_i = AFU_i \left(f_{NRB} EF_{CO_2\, i} + \sum_k GWP_k EF_{k,i} \right) \tag{5}$$

The value of the non-renewable woody biomass fraction, f_{NRB}, can be measured or taken from literature values based on the location where the stoves are implemented. GWP is typically analyzed at the 20 or 100 year time-scales (Table 3.2), accounting for the more immediate impacts of the short lived climate pollutants (SLCPs) (MacCarty, 2015). Long-term gases that remain in the atmosphere include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Additional short-term gases include carbon monoxide (CO), volatile organic compounds (VOCs), black carbon (BC), and organic carbon (OC).

Table 3-2 Global Warming Potential

Emission	GWP_{20}	GWP_{100}
CO_2	1	1
CH_4	72[c]	25[c]
N_2O	289[c]	298[c]
CO	10[b]	1.9 [c]
VOCs	4.9[b]	3.4 [c]
BC	3200[a]	910[a]
OC	-250[b]	-75[b]

([a]Bond et al., 2013; [b]T. Bond, Venkataraman, & Masera, 2004; [c]Forster et al., 2007)

3.2.2 Existing Monitoring & Evaluation Methods

There are several existing technologies and methods used to measure the in-field data required for the above evaluations of stove performance and impact, including household surveys, the Kitchen Performance Test (KPT), and temperature and pollutant sensors.

3.2.2.1 Surveys

Household surveys are frequently used as a low-cost option to understand attributes like household demographics, decision-making priorities, user preferences, adoption, stove stacking, and fuel use (Pakravan and MacCarty, 2018). While they provide critical data on user perceptions, surveys can introduce various biases into resulting analyses including recall and social desirability bias (Thomas et al., 2016). Another such bias is the Hawthorne effect, in which research participants will deviate from normal habits when they know they are being observed, and often increase uptake of the intervention technology during that period (Simons, Beltramo, Blalock, and Levine, 2017). The presence of the Hawthorne effect skews observational data for quantitative metrics like stove and fuel use, misrepresenting typical user behavior. To this end, researchers have found that self-reported survey data on cooking duration has little correlation with sensor-based usage data, and that participants overestimate both cooking duration and number of daily events (Ramanathan et al., 2017; Simons et al., 2017; Wilson et al., 2015). Therefore, to verify results, surveys should be coupled with quantitative measurements when possible.

3.2.2.2 Kitchen Performance Test

A protocol for quantitative in-field fuel use measurements was developed in the 1980s with the Kitchen Performance Test (KPT) (Bailis et al., 2018). The KPT combines qualitative survey methods with daily quantitative household fuel weight measurements over several days to determine household-dependent daily fuel usage. To conduct a KPT, field staff visit sample households to weigh a specified portion of fuel at the beginning of the testing period, and return every day for the study duration, generally 3-5 days, to manually re-weigh and determine daily fuel use. While this test does provide data on household fuel consumption, there are challenges to conducting an accurate and representative test. Barriers include biases in the survey portion, user errors, seasonal variability, a lack of standardization in measurement, logistics issues, time and resource intensiveness, and the possible disruption to daily activities from repeated intrusion into households (Granderson et al., 2009; VITA, 1985). Researchers who have used the KPT have cited the need for a method that reduces these complications (Bailis, Smith, and Rufus, 2007; Granderson et al., 2009; Osei, 1993; Smith et al., 2007).

3.2.2.3 Temperature Sensors

Sensor-based monitoring can reduce bias and has become increasingly common in stove and other development projects to provide more accurate impact data (Harrell et al., 2016; Simons et al., 2017). This type of monitoring was first introduced to the stove sector in the form of various autonomous temperature sensors, including SUMs (Stove Usage Monitors) and WiCS (Wireless Cookstove Sensors) (Graham et al., 2014; Ruiz-Mercado, Canuz, and Smith, 2012). Other temperature sensors currently on the market include StoveTrace by Nexleaf Analytics (McKown et. al, n.d.), Dots by Geocene (Wilson, 2017), EXACT by Climate Solutions Consulting (LeFebvre, n.d.), and SweetSense temperature sensors (SweetSense, n.d.). These devices measure the temperature of a cookstove body, and the data are then analyzed to determine the duration and timing of cooking events, and stove stacking if multiple cooking devices are monitored. Relating to the terms of (Eq. 1) and (Eq. 3), these temperature measurements can be used to quantify *Use* and f_{dis}.

Challenges with temperature sensors include malfunction due to high temperatures, time-intensive training on sensor placement and data upload, and data that are difficult to interpret due to the slow warm-up and lengthy cooldown time for cookstoves before and after a cooking event (Dickinson et al., 2015; Ruiz-Mercado, Canuz, and Smith, 2012; Simons et al., 2014; Wilson et al., 2016). For example, it was observed that cooks in Honduras and Uganda often kept their stove at a low firepower all day, and would put on water to boil directly after cooking a meal, making it challenging to determine discrete cooking events and their duration as a proxy for usage. In addition, cookstove temperature does not indicate fuel consumption, although efforts have been made to correlate temperature data to fuel consumption. One study utilizing the WiCS system applied an energy flux approach but reported high uncertainty (Graham et al., 2014). Because firepower is very much location- and application- specific, accurately predicting fuel use from temperature alone is challenging.

3.2.2.4 Pollutant Measurements

Air quality and emissions sensors measure household air pollution (HAP) in homes and total emissions from cookstoves, respectively. Pollutants of interest include fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), and black carbon (BC). Some examples of ambient air quality sensors used to monitor HAP include the University of California-Berkeley Particle and Temperature Sensors (UCBPATS) (Dickinson et al., 2015), HAPEx (LeFebvre, 2018), Aprovecho Indoor Air Pollution meter, and pump and filter systems (Edwards et al., 2006). Larger hood or emissions capture systems such as E-Pod, ARACHNE (Roden et al., 2009), or the Aprovecho Portable or Laboratory Emissions Monitoring System (PEMS or LEMS) (Roden et al., 2009; MacCarty, Still, and Ogle, 2010) are used to collect and measure multiple pollutants to quantify emission factors. While collection systems such as these are useful for short-term laboratory tests, portability, training, and practicality issues prevent their use for measuring over multiple days in a household.

3.3 FUEL System Design

Current monitoring methods in the cookstove sector (Table 3.3) are often time and resource-intensive, subject to high uncertainty, and do not provide the range of data necessary to fully understand stove performance. There is no existing technology that measures fuel use over time, from which impacts to time, health, and the environment are derived. For this reason, researchers and stove practitioners have called for more accurate methods to capturing long-term fuel use data. To meet this need, researchers at Oregon State University in partnership with Waltech Systems developed the Fuel, Usage and Emissions Logger (FUEL), an integrated sensor system to quantify usage and fuel consumption, (Figs. 3.1 and 3.2).

Table 3-3 Comparison of Available Monitoring Metrics

	Surveys	KPT	Temperature Sensors	Emissions Sensors
Stove Usage	X		X	
Stove Stacking	X	X	X	
Time	X		X	
Fuel Consumption	X	X		
Pollutants				X

The FUEL system monitors and records time-stamped data on mass of fuel added to and removed from the holder, cookstove temperature, and ambient temperature for several months at a time. The first-generation FUEL sensor design includes:

- S-type tensile or compressive load cell
- Internal temperature sensor
- External thermocouple port
- Integrated power supply, analog-to-digital converter (ADC) and control module with internal clock
- SD card port for data storage
- Battery power supply
- Plastic housing

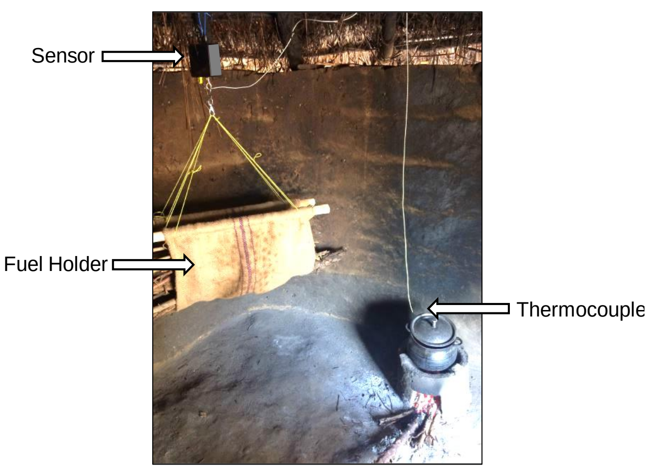

Figure 3.1 FUEL System Installed in Apac, Uganda

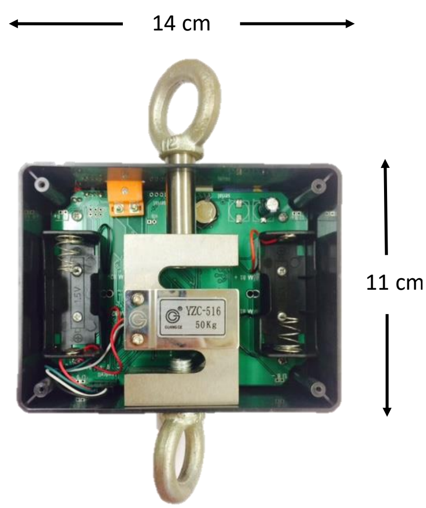

Figure 3.2 FUEL Sensor (1st gen)

The second generation developed with Climate Solutions Consulting uses wireless communication with a handheld launcher that can deploy and read data integrated streams from up to 12 FUEL, temperature, and air quality sensors in a single household. Current manufacturing cost is $75 per unit.

The FUEL system can operate in tension or compression depending on factors such as kitchen size and the fuel type being monitored. To operate, the system is installed as shown in Figure 3.1 in a sample of kitchens. Each cook is trained to store all or a portion of his or her fuel supply in the storage holder, remove fuel as it is needed for cooking, and restock with additional fuel when needed. Each reduction in weight recorded by the load cell as wood is removed for cooking is integrated over a specified time period to determine total wood use. An external thermocouple generates a continuous temperature profile over the logging period, which is analyzed to determine cooking events and duration. The temperature profile also serves to corroborate the weight data and identify user error by checking that the cookstove temperature is elevated when a weight reduction is detected.

Data from the FUEL are intended to report multiple metrics of cookstove performance, including adoption, stove stacking, time spent cooking, and fuel use, and extrapolate these metrics to health and climate impacts. Specifically, FUEL data can be used to directly calculate variables of interest in (Eq. 1) and (Eq. 3) including savings AFU_i, f_{dis}, and *Use*. This study seeks to determine if the FUEL system can work as intended to provide robust, quantitative data for more accurate, transparent, and verifiable measurements of cookstove performance.

3.3 METHODS

A series of studies was conducted between 2017 and 2018 to test the technical feasibility of the FUEL and then pilot test once feasibility was verified. In Phase 1 during April of 2017, the first prototypes of the FUEL system were tested in rural Honduras with StoveTeam International, a non-government organization (NGO) that distributes improved stoves in Central America. The purpose of this testing was to evaluate the in-field technical system performance and the usability of the fuel holder design. Results of this study provided proof of concept of the existing design and were also used to inform firmware updates such as logging rate. In August 2017, the research team partnered with International Lifeline Fund (ILF), a D.C.-based NGO that manufactures and distributes low-cost, increased-efficiency wood and charcoal stoves in east Africa to conduct Phase 2a, a pilot study in northern Uganda to evaluate usability and technical feasibility. Following this, a second trial, Phase 2b, was conducted in July 2018 to update hardware and obtain usable temperature data to analyze metrics such as global warming commitment, firepower, and comparative fuel consumption between stove types. All research with human subjects was conducted with oversight from the Oregon State University Institutional Review Board under study number 7257. The naming convention, time frame, location, sample size, N, monitoring duration, t, and naming convention of each research phase are listed (Table 3.4).

Table 3-4 FUEL Research Phases

Phase Name	*Timeframe*	*Purpose*	*Location*	*N Households*	*N Sensors*	*t (days)*
1	April 2017	Proof of Concept	Honduras	4	5	30
2a	August 2018	Pilot	Uganda	85	100	30
2b	July 2019	Pilot	Uganda	44	68	45

3.3.1 Samples

In Phase 1, a total of five sensors were installed in four households and logged for an average of 30 days. The same population consisted of three households that used the improved stove manufactured by StoveTeam, the Ecocina, and one household that used both the Ecocina and a traditional plancha stove.

In Phase 2a, 100 sensors were installed in 85 households. In this sample, households who owned one stove included 48 households with the ILF Rural Wood Stove (RWS), six households with three stone fires (TSF), and 18 with locally mudded stoves (LMS). Stove stacking households included eight with the RWS and TSF, and six with the RWS and LMS.

In Phase 2b, a total of 68 sensors were installed in 44 households and logged for an average of 45 days. Because the entire sample population had received an RWS in 2017, the 2018 sample population consisted of 20 RWS, 10 RWS and TSF, 13 RWS and LMS, and 1 RWS and RWS (Fig. 3.3). The distribution of stove types is shown (Table 3.5). To measure stove stacking in households with two stoves, two sensors were used.

Table 3-5 Sample Distribution and Stove Type

Stove Type	*Households*	*Percentage*
ILF Rural Wood Stove (RWS)	20	45%
Three Stone Fire (TSF) and Rural Wood Stove	10	30%
Locally Mudded Stove (LMS) and Rural Wood Stove	13	23%
Rural Wood Stove and Rural Wood Stove	1	2%
Total	44	

Rural Wood Stove (RWS) | Three Stone Fire (TSF) | Locally Mudded Stove (LMS)

Figure 3.3 Household Stove Types

3.3.2 Training

Operational details for Phase 1 were administered separately to each household. Participants were informed about the purpose of the system and each hardware component, and details of operation, which included:

- Place any collected wood in the holder before cooking
- Remove wood from holder as needed for cooking

An hour-long training session was conducted in Apac, Uganda during Phase 2a to inform users about the purpose and correct use of the FUEL system. Participants were told the overall intent to measure impacts of the stoves on their health and environment, the function of each system component, and details of operation, which were identical to Phase 1. Following these operational details, questions and concerns were addressed to ensure clarity of instructions.

Phase 2a and 2b had the same participants, and therefore a formal training session was not conducted. However, several participants from Phase 1 raised the question of whether or not they could place partially burned wood back into the holder. Therefore, an additional instruction was made during household installation visits to not place partially burned wood back into the holder.

3.3.3 Equipment and Calibration

Installation materials for Phase 1 included the sensor, thermocouple installation hardware, and fuel storage holders. Storage holders were made from 7/16” wooden dowels, cotton utility fabric, and parachute cord.

Type K thermocouples rated at 1250˚C with 3 m extensions were secured with aluminum heat-resistant tape. The sensor logging rate was programmed to record data every 15 seconds until a threshold weight change is detected, at which point the sampling rate increases to every 10 seconds until no additional changes in mass are sensed.

Installation materials for Phase 2a were the same as those used in Phase 1, apart from the storage holder design. A resident local to the Apac region produced the storage holders to reduce manufacturing and transportations costs and provide an opportunity for income generation in the community. They were made from readily available recycled burlap coffee sacks and dowels cut from wood traditionally used as housing supports (Fig. 3.4). Type K thermocouples rated at 200 ˚C with 3 m extensions were hung directly in the combustion chamber. The sensor logging rate was programmed to record data every 15 seconds until a threshold weight change is detected, at which point the sampling rate increases to every 3 seconds until no additional changes in mass are sensed.

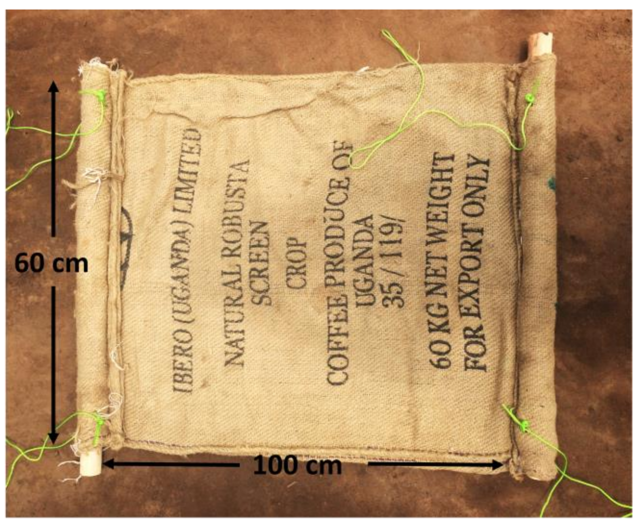

Figure 3.4 Fuel Holder and Dimensions

In Phase 2b, metal brackets were added to secure the thermocouples to the stoves and reduce heat exposure. Fuel storage holders from Phase 2a that had remained in households were reused when possible and replaced when needed.

Type K thermocouples rated at 750 °C with 2 m extensions were used to monitor cookstove temperature, and calibrated in ice (0 ˚C) water and boiling (100 ˚C) water. Stainless steel brackets with several holes to thread the thermocouple wire through and attach to the stove body were manufactured. Each load cell was calibrated individually to account for variation in calibration curves using a 2-point calibration at 1 kg and 30 kg. The sensor logging rate was reduced from Phases 1 and 2a to increase battery life, and programmed to record data every 49 seconds until a threshold weight change is detected, at which point the sampling rate increases to every 7 seconds until no additional changes in mass are sensed.

3.3.4 Installation and Data Collection

In Phase 1, the sensor systems were installed in kitchens to log for the specified monitoring period with two routine visits to check on households directly following installation. The sensors were hung from preexisting support beams in the roofing structure. The thermocouples were first attached with only tape, and then more securely attached with 1/16" aluminum wire wrapped around the stove body after several failed to adhere. After the logging period, local field staff returned to collect the sensors and data were uploaded to a local computer and sent to researchers for analysis. Raw data output from the FUEL includes time (Unix), weight (ADC), thermocouple temperature (ADC), internal sensor temperature (ADC), and battery life (ADC).

Figure 3.5 Thermocouple installation

In Phases 2a and 2b, the sensor systems were installed in cooking areas to log for the specified monitoring period, with routine visits to check on households during the first week. For installation, the sensors were hung from preexisting support beams in the roofing structure. In Phase 2a, the thermocouples were hung directly into the combustion chamber. In Phase 2b, the thermocouples were attached to the stove using the brackets (Fig. 3.5). After the logging period, local field staff returned to collect sensors and data were uploaded to a local computer and sent to researchers for analysis. To account for variation in household size using the SAE chart, (Table 3.1) the age and gender of each household member was collected as part of a survey conducted on Magpi, a mobile data collection platform.

3.3.5 Algorithm Development and Analysis

A primary goal of field testing the FUEL system was to collect and analyze actual use data to report quantitative cookstove performance metrics. The algorithms developed from these data corroborate correct use of the system by checking that elevated temperatures correspond to reductions in fuel load, integrating fuel weight losses to determine fuel consumption, and extrapolating this data to overall energy use, firepower, and global warming commitment.

3.3.5.1 Fuel Consumption

Fuel use is calculated by integrating mass reductions over a specified time period (Fig. 3.6). A mass reduction is identified by assigning a weight threshold value, W_0, for the difference, ΔW, between two consequent data points, W_i and W_{i-1}. To detect fuel changes and avoid noise-related fluctuations, a threshold value was set for ΔW. If ΔW is above a specified threshold value, it is then checked against the the temperatures, T, within range T_i-T_{i+25}, to see that it is elevated above the baseline (non-cooking

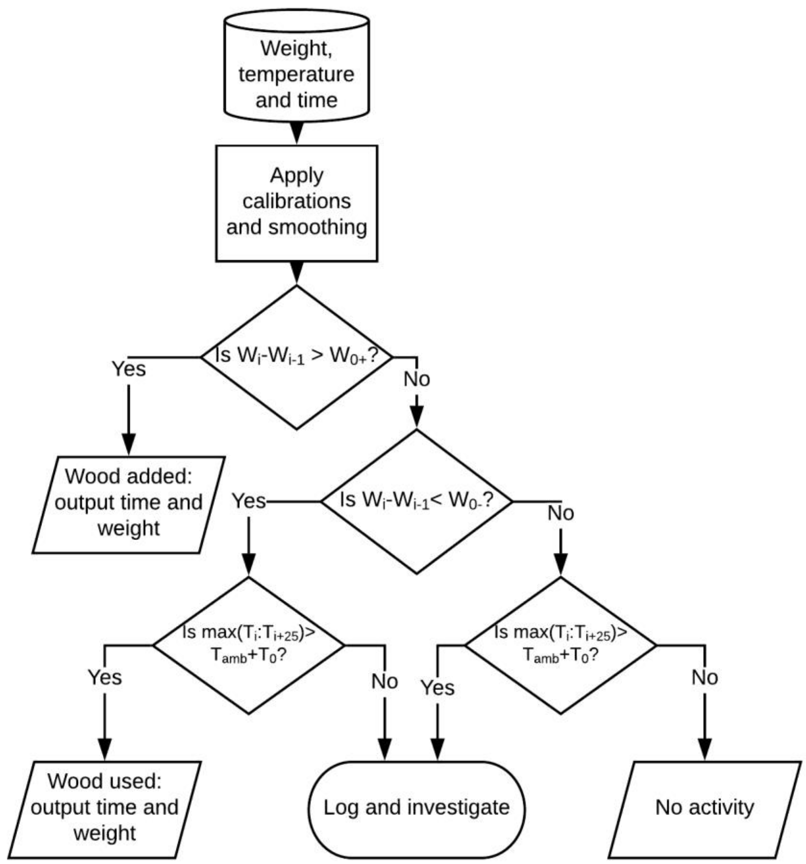

Figure 3.6 Algorithm to convert raw weight data to fuel use

temperature) to verify an actual cooking event. The temperature range accounts for the time it takes for the cookstove temperature to rise to a detectable difference from ambient following a cold start. If a weight reduction is not verified or a cooking event occurs with no corresponding weight reduction, it may require manual interpretation, corrective action, or correlating temperature and energy flux to account for unrecorded fuel weight (Graham et al., 2014).

With wood fuel, fuel moisture content can vary between geographic regions and households due to fuel type, age, and condition of wood, and is typically between 5% and 30%. The wood moisture content of 720 independent readings taken from 20 households over the course of 4 days was averaged. Wood moisture content was measured using a General MMD4E moisture meter, reporting at an accuracy of ±2% and a range of 5-50% moisture content on a dry basis. Moisture content on a wet, or as-received, basis can be calculated (Eq. 6).

$$MC_{wet} = \frac{MC_{dry}}{1 + MC_{dry}} \tag{6}$$

Equivalent dry wood consumed is needed for calculations of firepower and global warming commitment. Dry fuel mass is determined using (Eq. 7), where m_{wet} is the mass of fuel recorded by the FUEL sensor.

$$m_{dry} = m_{wet}\left(1 - MC_{wet}\right) \tag{7}$$

3.3.5.2 Usage

A combination of peak detection and time-window clustering was used to determine cooking events and duration following a similar method used by (Ruiz-Mercado et al., 2012). Peaks were clustered in time windows based on survey data of average reported cooking time per meal.

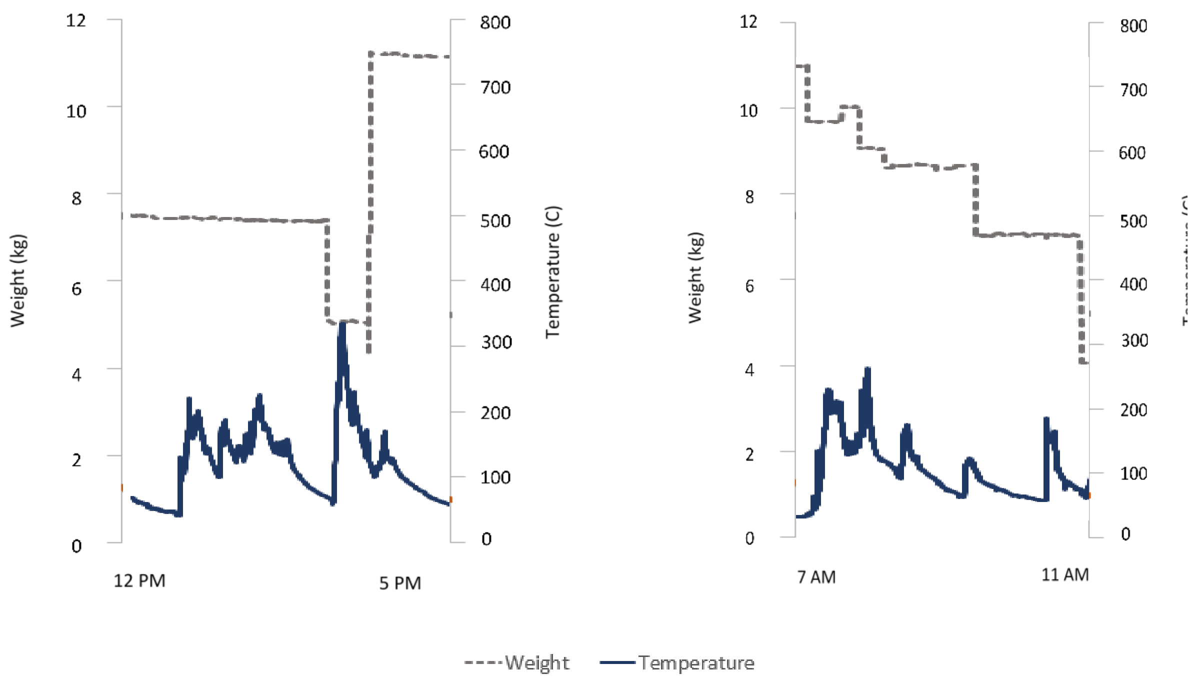

Figure 3.7 (A) Household not using fuel holder; (B) Using fuel holder correctly (Ventrella, 2018)

3.4.3 Temperature/Fuel Use Corroboration

Temperature data from the FUEL system are used to determine cooking events and duration and corroborate with weight data to check for user error. There are three conditions that can be applied to account for potential errors:

(1) when weight decreases, temperature increases. If false, discount this weight value
(2) when temperature increases, weight decreases. If false, flag
(3) there is a temperature increase above ambient any time during a 24-hour period. If false, consider a non-cooking day.

To illustrate, a 24-hour data sample from a household in El Eden, Honduras, Phase 1 is shown in Figures 3.7A and 3.7B (Ventrella, 2018). In Figure 6A, the thermocouple temperature is above ambient, indicating a cooking event, but there is no corresponding decrease in fuel weight, condition (2). This signifies that the cook has used fuel that was not stored in the holder, and would require using temperature data to calculate the energy flux and correlating it to fuel consumption (Graham et al., 2014). Figure 6B represents a logging period with correct use, in which decreases in weight are corroborated with a thermocouple temperature elevation. Although not represented in Figure 6, there is also the potential use error in which there is a decrease in fuel weight but not a corresponding temperature increase, indicating that fuel was removed but not used in the stove, condition (1). Identification of incorrect use events in the algorithm allows for verification of acceptable data and flagging of suspect data, which can be omitted and/or alert researchers to the need for corrective action.

3.3.5.4 Emissions

Table 3-6 Emission Factors (EF) (g/MJ)

Stove Type	**EF CO_2**	**EF CH_4**	**EF N_2O**	**EF CO**	**EF NMHC**	**EF BC**	**EF OC**	**Source**
Three Stone Fire	101.9	0.240	0.012	5.16	0.458	0.073	0.169	a-n
Locally Mudded Stove	99.8	0.220	0.014	4.01	0.500	0.080	0.150	average
Rural Wood Stove	97.7	0.200	0.016	2.85	0.533	0.089	0.124	b,c,f,h,i,j,l,n,o

Compiled by (MacCarty, 2015)

a (Brocard, Lacaux, and Eva, 1998); b (Smith et al., 2000); c (Venkataraman and Uma Maheswara Rao, 2001); d (Bertschi, Yokelson, Ward, Christian, & Hao, 2003); e (Ludwig, Marufu, Huber, Andreae, & Helas, 2003); f (Bailis, Ezzati, and Kammen, 2003); g (Johnson et al., 2008); h (MacCarty et al., 2008); i (Roden et al., 2009); j (MacCarty et al., 2010); k (Christian et al., 2010); l (Grieshop, Marshall, & Kandlikar, 2011); m (Akagi et al., 2011); n (Jetter et al., 2012); o (J. Zhang et al., 2000)

Measurements of cookstove use and fuel consumption are also analyzed to report energy use per person and extrapolated to firepower, global warming commitment, carbon credits, and aDALYs. Emission factors determined through lab or field testing are shown as mass of each pollutant emitted per MJ of fuel consumed (Table 3.6) and used to calculate the mass emission of various pollutants, k, for a given stove, i, and fuel consumed (Eq. 8). EF values for the three stone fire and improved stove were chosen from the literature, and averaged to predict emission factors for the LMS, which was local to the region and therefore not universally available in the literature. The value for higher heating value (HHV) was selected for *eucalyptus camaldulensis*, a common wood-type in northern Uganda (Kilimo Trust, 2011).

$$m_k = m_{fuel} HHV_{fuel} EF_{k,i} \tag{8}$$

3.4 RESULTS AND DISCUSSION

The objectives of this study were to evaluate the usability and technical performance of the FUEL system, and report findings of metrics including comparative fuel consumption, firepower, and global warming commitment between various stove use cases.

3.4.1 Usability Evaluation

Preliminary qualitative data from community meetings and household surveys suggested that the system was usable for households, and that storing fuel in the holder was not an issue, with in-depth methods and results described in a separate paper (Ventrella, Zhang, and MacCarty, 2019). Interviews revealed the weighing of wood was intuitive to users as the concept of the scale was well understood from purchasing weighed food items at the market. A portion of the sample population reported that they considered elevating the fuel in the holder as a positive attribute. Observation corroborated these findings, as some households elevated their wood supply on rocks to keep it off the ground and away from moisture and termites. This indicated that storing wood in an elevated holder would not require significant habit change but is context specific and will vary depending on fuel storage needs.

In the study locations, the FUEL sensor was hung directly from each household roofing structures. This enabled a streamlined installation process that eliminated the need for additional hardware, such as support beams. The holder was sized to reduce intrusiveness and allow for ample cooking space. Participants also specified the desired placement and height of the holder, which could increase the chance that the system will be used correctly.

Usability for the program staff was also acceptable. Installation of the FUEL system took two staff members approximately 15 minutes per household on average, including walking time between households. Although transporting the fuel holders was cumbersome at times, this issue could be mitigated by distributing the holders to participants during the initial community meeting.

Analysis of sensor data showed that in phase 2a of the pilot study, 82% of FUEL sensors were used consistently, where use was defined as use of the FUEL system at least once per day with at least 1 kg of wood consumed for over 60% of the monitored days. An analysis of usage in Phase 2b reported that with temperature check applied when possible, 88% of sensors were used consistently, where use is defined as removing a threshold amount (1 kg) of wood for at least 60% of the monitoring days, to account for days when no cooking is conducted in the household.

3.4.2 Technical Evaluation

Observational and survey data from Phase 2a showed that instead of storing their fuel in the holder after collection, some households would chop their wood into smaller pieces only directly before cooking, place the wood in the holder for a short time period, and then remove the entire portion for cooking. This resulted in near-instantaneous, linear spikes in data that were originally attributed to noise. These could then be differentiated from unintentional interaction with the system, which generally resulted in a discrete point above a certain threshold. After determining this use case, the algorithm was updated to identify spikes in weight data using a rolling median filter and replace each spike with a nearby point. In addition, days that reported fuel usage of over 16 kg were removed from the dataset. This value was determined using a subset of data and calculating the outlier value using the interquartile range.

Following 30 days of monitoring, performance results from Phase 2a showed that 31% of sensors had failed due to faulty SD cards or poor battery connection. Most thermocouples also failed because they were not rated for a high enough temperature to withstand direct placement in the combustion chamber. A second trial, phase 2b, was conducted in July 2018 to update hardware and obtain usable temperature data to analyze cooking duration, usage, and firepower. From the 68 sensors installed in this phase, a total of 53 sensors functioned as anticipated throughout the duration of the monitoring period, logging a cumulative 37,392 hours of continuous data. Results from functioning sensors include analysis of fuel consumption, cooking duration, firepower, and global warming potential.

An analysis of overall sensor use and functionality showed that some of the sensors did not log data for the entire monitoring period due to various prototype hardware failures. Of the 68 sensors, three did not initiate logging. Another eight stopped logging after a short period, five had noisy signals and one data set was not transferred to the researchers. The uninitiated or terminated logging could have occurred from coin cell battery discharge, the 1.5 V batteries becoming dislodged from the holder, or faulty SD cards, which are issues that can be resolved in future deployments. These data points were therefore not included in the analysis.

3.4.2.1 Temperature/Fuel Use Corroboration

To understand the effect of temperature corroboration on the algorithm output, the average daily fuel with and without condition (1) temperature check was compared. When temperature check was available, a change in fuel weight would not be integrated unless it was detected during or soon before a corresponding temperature increase. Figure 3.8 shows that using the temperature/fuel corroboration had no significant difference on results, indicating that temperature measurements are not needed to check reported decreases in weight. However, this analysis does not account for the events flagged when a cooking event is detected without any change in fuel weight, condition (2).

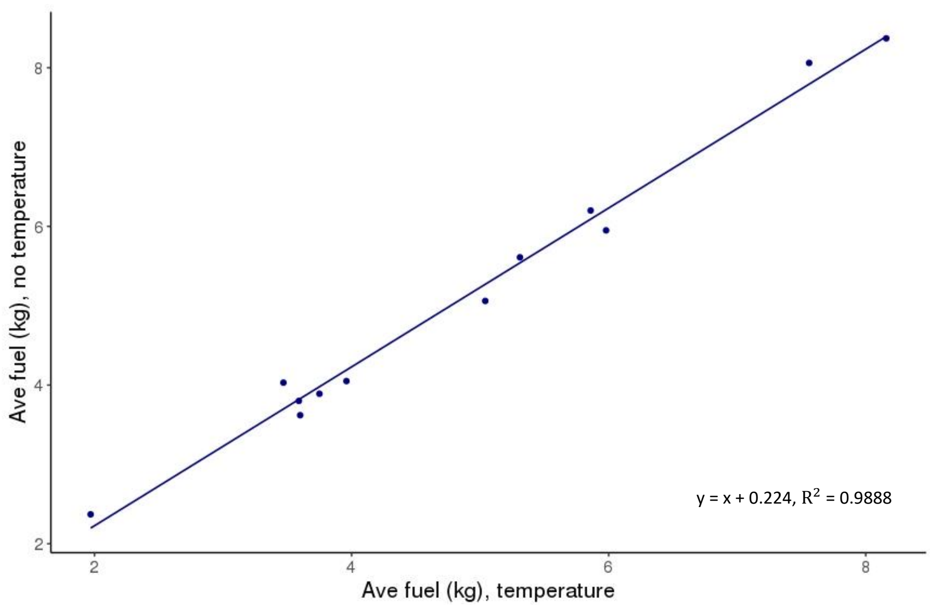

Figure 3.8 Comparison of daily average fuel calculated with and without temperature/fuel use corroboration (absence of cooking event only), R2 = 0.998, offset = 0.22, slope = 1:1

Temperature/fuel use corroboration, conditions (1) and (3), was also evaluated for algorithm output of sensor usage. Percent use with and without temperature/fuel use corroboration was compared for all sensors with working thermocouples and was defined as the ratio of days where a change in fuel mass was detected to total cooking days and total logging days, respectively, where total cooking days was counted as days when cookstove temperature was elevated above a specified threshold, indicating that the stove was on and in use (Eqs. 9 and 10).

Condition (1) was found to have no significant effect. However, without applying condition (3), the algorithm classified all days where no fuel was used, regardless of if the stove was used, as incorrect use days. When temperature check was available, days where no fuel was used would not be counted as incorrect use days if there was no corresponding temperature increase on that day. Calculated average percent usage with and without condition (3) temperature corroboration was 85.1% and 79.4%, respectively, which indicates that non-corroborated fuel data noticeably underestimated correct use.

3.4.2.2 Monitoring Duration

Analysis of the effects of monitoring duration on average daily fuel consumption results was conducted to determine variation in average fuel as a function of time (Fig. 3.9). Daily average fuel consumption was calculated over durations of 4, 10, 15, 20, and 25 days and compared to the average fuel consumption over 30 days. Results from Figure 3.9 show that the standard deviation decreased from 1.20 kg over a four-day monitoring period to 0.093 kg for a 25-day monitoring period. The average percent error also decreased between the four-day and 25-day monitoring period, from 0.720% to 0.065%, respectively. The percent error and standard deviation decreased logarithmically as monitoring duration increased, indicating that shorter monitoring periods do not capture longer term variability.

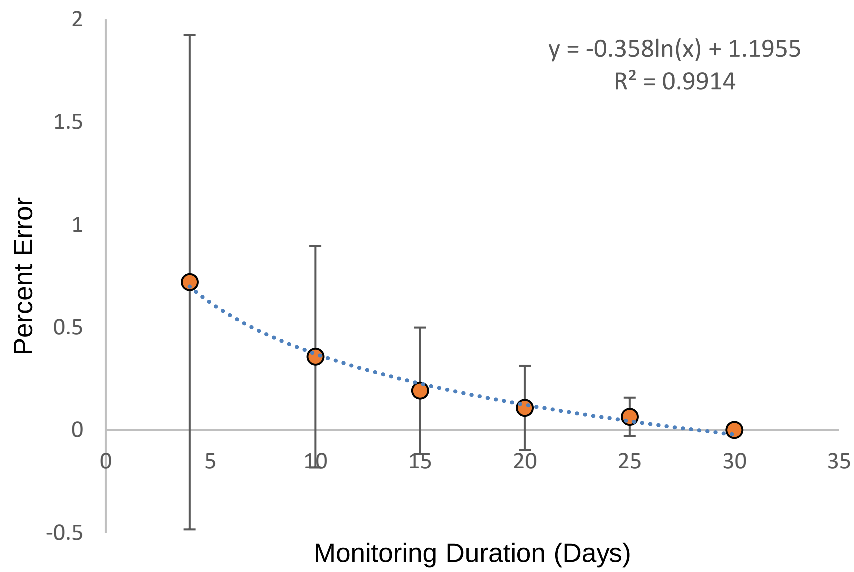

Figure 3.9 Percent error vs monitoring duration up to 30 days

3.4.2.3 Cooking Duration

To understand the correlation between household size and daily cooking time, a logarithmic regression of daily cooking hours per family size was computed, as shown in Figure 3.10. Daily cooking time increases but begins to plateau as household size increases, indicating increasing economies of scale.

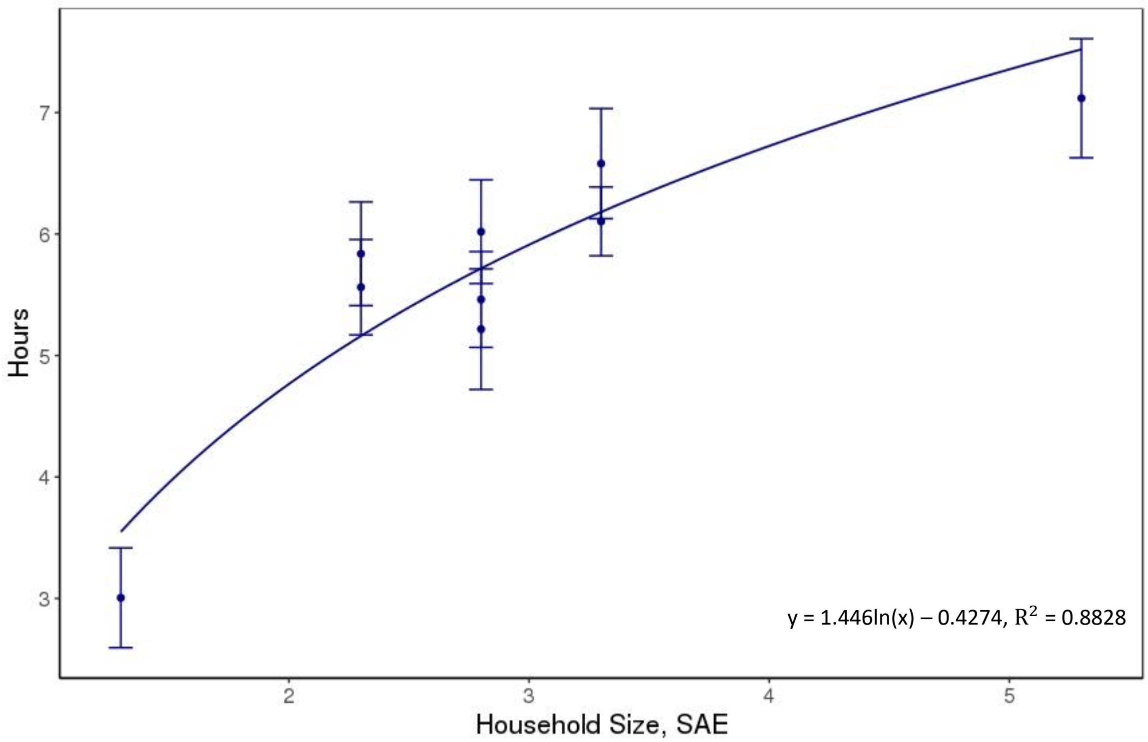

Figure 3.10 Daily cooking duration vs. household size normalized to SAE, with standard error

On average, cooking occurred for 5.36 ± 2.67 hours per day. This agrees well with collected concurrent survey data of reported cooking time per meal, where users reported an average 5.9 hours of cooking per day. Shorter cooking times could correspond to days where cooks quickly reheated food for a meal, which was found to occur in the Apac district, as one participant and the field staff reported.

3.4.2.4 Fuel Consumption

The daily average fuel consumption per person, adjusted for household size and aggregated by cookstove type is reported in Figure 3.11.

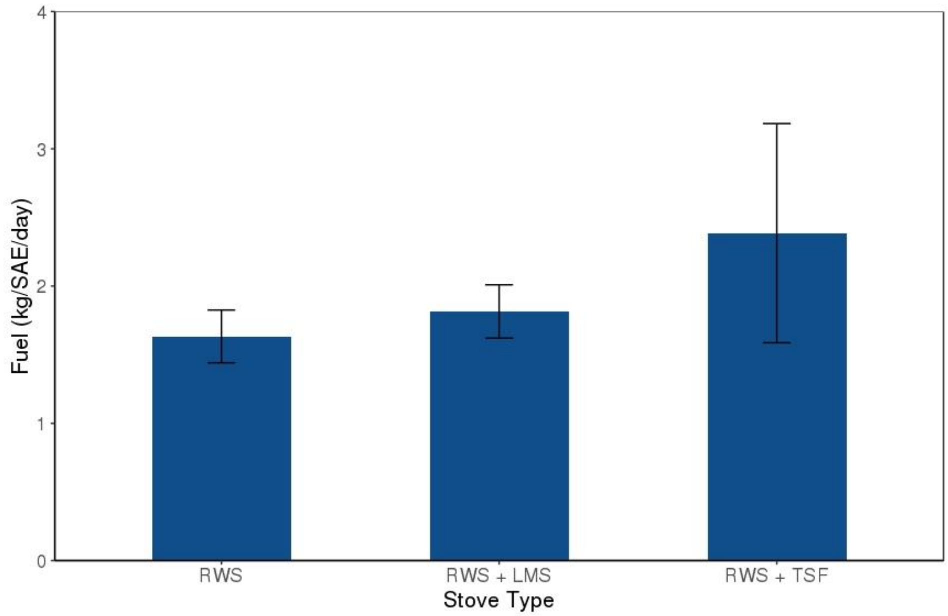

Figure 3.11 Daily average fuel consumption normalized to SAE, aggregated by stove type, with standard error

RWS = Rural Wood Stove, RWS+LMS = Stacking Rural Wood Stove and Locally Mudded Stove, RWS+TSF = Stacking Rural Wood Stove and Three Stove Fire

Results report an average daily fuel consumption per person aggregated for all stoves present of 1.63 ± 1.12 kg for RWS households, 1.84 ± 0.66 kg for RWS and LMS stacking households, and 2.51 ± 1.93 kg for RWS and TSF stacking households. These results imply that in this study, households that cook with more than one stove use on average 0.88 kg more fuel per person when stacking the RWS with the TSF, and 0.21 kg more fuel per SAE when stacking the RWS with the LMS.

Because each stove is monitored with its own sensor, results from households that stove stack may also be disaggregated to report fuel consumption and additional metrics for individual stoves. Disaggregation can be useful to compare stove use and adoption within individual households. For example, Figure 3.12 illustrates the daily variation in fuel use for a single, stove stacking household of 3.4 SAE that uses both a RWS and LMS. Results show a total average fuel consumption of 8.65 ± 3.65 kg/day, 5.96 ± 2.88 kg/day for the RWS, and 2.68 ± 3.49 kg/day for the LMS. Data also show that the RWS was used 98% of logging days, while the LMS was used only 67% of days, implying that while daily average fuel use was higher for the RWS than the LMS, this could be attributed in part to higher usage as opposed to lower fuel efficiency.

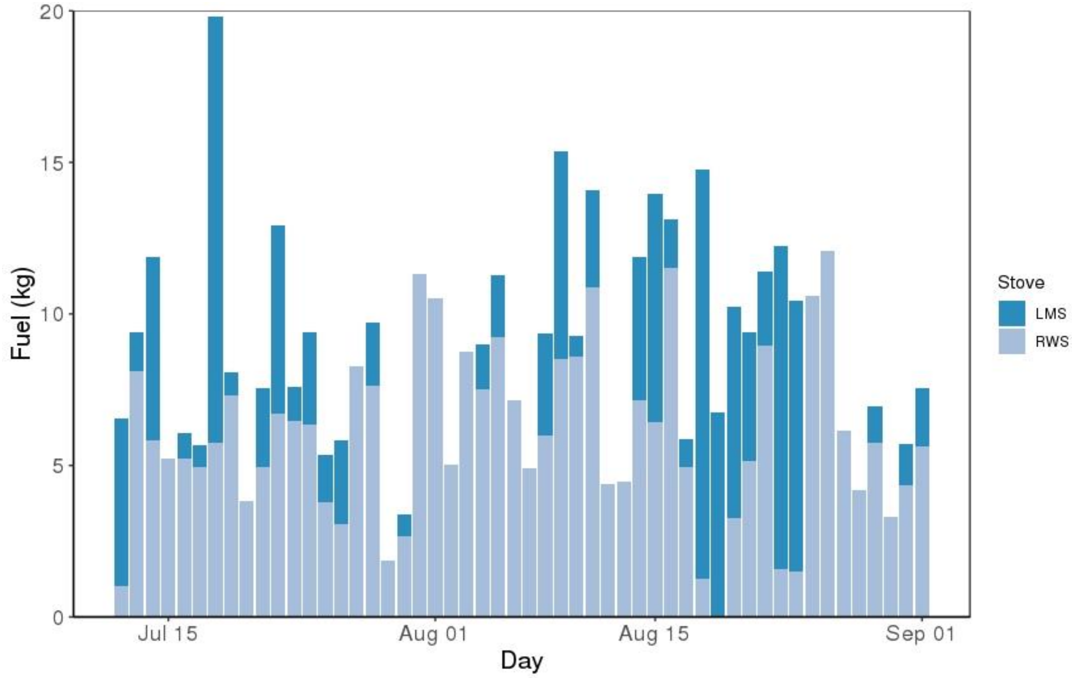

Figure 3.12 Fuel use (kg) per day for a single, stove stacking household, SAE = 3.4

To examine variability in day-to-day fuel use, Figure 3.13 shows a box and whisker plot of the spread of daily average fuel use per person for each household over an average of 45 days each. Fuel consumption was aggregated for households with multiple stoves. The overall average daily fuel consumption was 1.61 kg/SAE/day ± 1.22 kg/SAE/day, with a minimum of 0.06 kg/SAE/day and maximum of 8.31 kg/SAE/day. Single RWS users reported an average of 1.75 ± 1.28 kg/SAE/day. These wide data spreads show that there was significant variation in day-to-day fuel use in most households. Daily variation could be caused by several factors, including consumption factors such as changes in the number of people cooked for or number and type of meals cooked each day, or measurement factors such a cook removing more wood than needed for a single cooking event and using some the next day. For example, Figure 3.14 shows the daily variation of fuel use and cooking duration in household number 1. This high day-to-day variability in fuel use and cooking duration may require longer duration measurements to capture accurate fuel use averages, suggesting that the 3-5 day KPT may be insufficient.

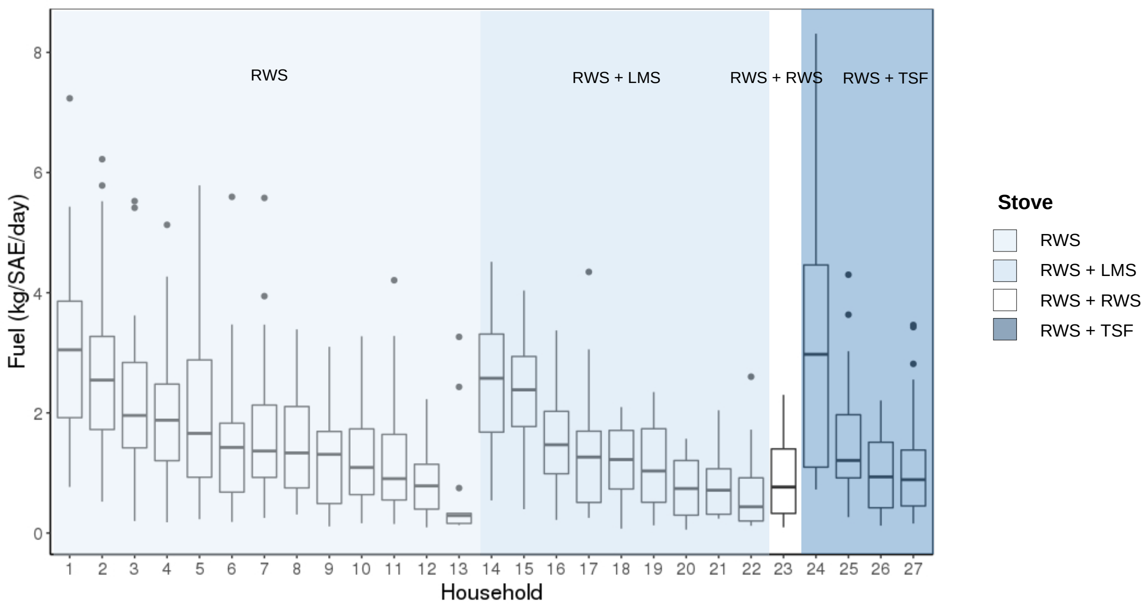

Figure 3.14 Variation in daily household fuel use per person, normalized for household size, discrete points are outliers in dataset

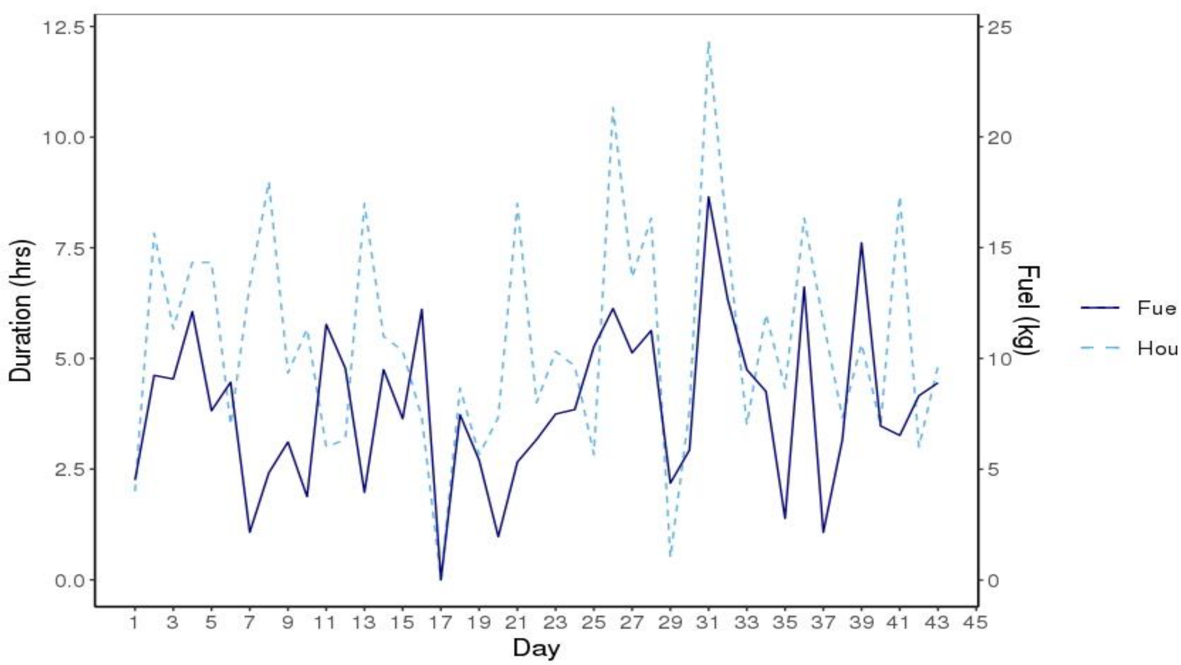

Figure 3.13 Daily variation of fuel use and cooking duration for three-person, single RWS household

Firepower is a measurement of the rate of fuel consumption and therefore cooking power of the fire. Figure 3.15 shows the operational firepower used in the 11 RWS households, indicating a mean of 4531.5 ± 1398 W. The stoves are mass-produced and the combustion chambers are fairly uniform, indicating that the variability in firepower between stoves of the same model is mainly caused by variation in fire tending habits and cooking power needs varying from household to household. The values are well aligned with expected values, suggesting the FUEL system can accurately monitor firepower through the combination of fuel and temperature (cooking duration) measurements.

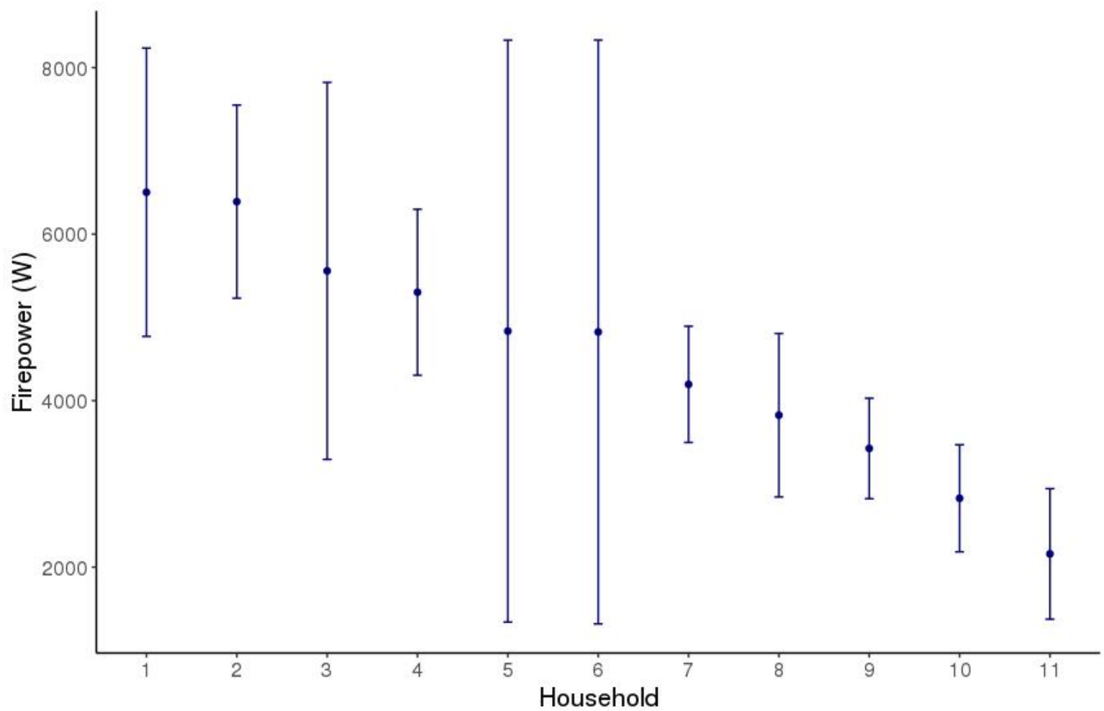

Figure 3.15 Firepower of RWS in each household, with standard error

3.4.2.5 Global Warming Commitment

Projections of annual tCO_{2e} per household normalized for an average household SAE of 3.84 over 20 and 100 years are shown in Figure 3.16. On a 100-year time frame, use of both a RWS and LMS will emit 10% more tCO_{2e} than use of a single RWS, while stacking of a RWS with a TSF will emit 218% more tCO_{2e} than use of a single RWS. On the 20-year time frame, these values are 9% and 58%, respectively. Although these preliminary results are not statistically significant due to low sample size, initial data imply that stacking multiple stoves will result in higher climate-forcing emissions.

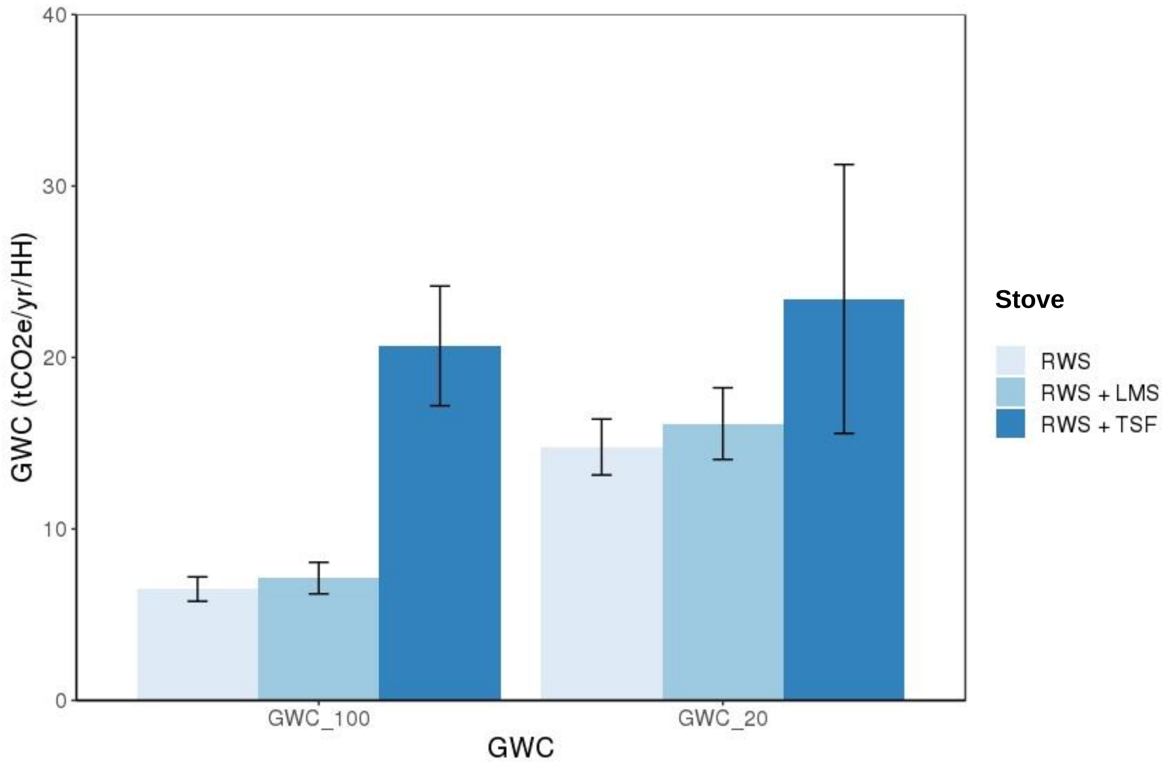

Figure 3.16 Global warming commitment per household projected over 20 and 100 years for various stove combinations, with standard error

RWS = Rural Wood Stove, RWS+LMS = Rural Wood Stove and Locally Mudded Stove, stacking, RWS+TSF = Rural Wood Stove and Three Stove Fire, stacking

Because pre-intervention baseline data were not available, reduction in carbon emissions (carbon offsets/credits) and aDALYs were not calculated in this analysis. Carbon credits could be calculated using temperature as a proxy to determine *Use* and fuel consumption data from the baseline and intervention stoves would be used to determine savings AFU_i as referenced in Equation 5. In addition, aDALYs could be calculated using temperature as a proxy to determine *Use* in (Eq. 2) if underlying disease burden (*B*) were known.

3.5 CONCLUSIONS AND FUTURE WORK

These proof-of-concept and pilot studies demonstrate that the FUEL system operates as intended and that data from FUEL can be used to calculate key cookstove performance metrics including fuel consumption, cookstove usage, global warming commitment, and firepower for each household or an entire community on a per-meal, daily, monthly, or annual basis. Stove stacking can be identified and quantified, as can correct or incorrect use of the FUEL system. As compared to temperature measurements on their own, integrated FUEL data provide a better overall understanding of cookstove impacts, cooking habits, and stove usage. Monitoring fuel consumption enables direct prediction of potential emissions reductions for health and climate as well.

Data generated in the pilot study suggest that stove stacking households will use more fuel per person than a single improved stove household cooking for the same amount of people, and therefore generate higher long-term emissions. A set of baseline data is needed to draw additional conclusions about the improved stove model as compared to the traditional stove and will be the subject of future studies. Disaggregated stove stacking results for a single household indicate that daily average fuel consumption for the RWS was higher than the LMS for that household, but that the RWS was also used for 31% more monitoring days as compared to the LMS. This points to the value in obtaining data on cooking duration to make comparable comparisons of fuel consumption over a known cooking time between different stove types. Results also illustrated the significant variability in day-to-day fuel use in households, firepower, and frequency and duration of cooking events. Even daily fuel use per person varied from an average of 1.75 ±1.28 kg/SAE/day across households using the same stove (RWS). This implies that longer duration monitoring and larger sample sizes than are traditional practice in the cookstove sector may be needed.

Obtaining accurate data from the FUEL system requires systematic strategies. While initial issues with hardware failures of SD cards and thermocouples have been resolved with a new wireless system that uses a wireless launch and data readout paired with wireless infrared temperature sensors, issues with correct installation and use must be addressed in each new application. In addition to those presented in (Ventrella, Zhang, and MacCarty, 2019), a list of several considerations has been created to conduct an effective study with the FUEL system:

- Before conducting study, identify the most effective method of hanging depending on kitchen size and structure, and thermocouple attachment for each stove type
- Before installation, hold a training session with all participants to answer any questions or concerns and demonstrate how to use the system. This includes important guidance for participants such as
    - When adding wood, fill holder with as much wood as possible, refill when near empty (helps to reduce noise in data)
    - Do not put wood back in holder after removal (includes partially burnt wood)

  - Wood must be in the holder for at least 30 seconds before removal
  - All wood used for cooking must be stored in the holder before putting in stove
- Arrange several check-ins from field staff to ensure correct usage and troubleshoot potential issues
- If conducting a study with participants who have not previously used the FUEL system, conduct a usability survey and preliminary data analysis 1-2 weeks into the monitoring period to ensure the system is being used correctly and consistently.

Although the algorithm to determine cooking events and duration was modeled from previous research, the algorithm could be further refined for increased accuracy using specified positive and negative slope thresholds to identify the stop and start times of each cooking event, instead of peak clustering. Slope thresholds will be stove dependent and can be best calculated through observation of the cooking process, recording when cooking starts and ends, and comparing that to the temperature profile slopes at those times.

Lastly, it is expected that FUEL can be used equally as effectively for other fuels such as crop residues, coal, charcoal, and LPG. Therefore, future work includes a validation of the FUEL system as compared to the KPT with a variety of fuel types. The long-term goal of this work is to develop a system that is available and usable for cookstove practitioners and researchers to more easily monitor and report long-term impacts of clean cookstoves and fuels in diverse settings.

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CHAPTER 4
TECHNO-ECONOMIC COMPARISON OF THE FUEL SENSOR AND THE KITCHEN PERFORMANCE TEST TO QUANTIFY IN-FIELD COOKSTOVE FUEL CONSUMPTION

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ABSTRACT

Quantifying the empirical impact of improved stoves and fuels designed to combat the health and environmental burdens of traditional cooking is a necessity but can be a challenge for practitioners. The manual Kitchen Performance Test is the standard method to determine household fuel consumption, but is costly, time intensive, and error prone. To address these challenges, researchers at Oregon State University developed the Fuel, Usage and Emissions Logger (FUEL), a sensor-based system to autonomously monitor fuel consumption in households. The accuracy, granularity, and cost of the FUEL system were compared to that of the standard Kitchen Performance Test, which were simultaneously conducted with 10 households in Burkina Faso stacking LPG, charcoal, and wood stoves, and with 20 participants in Uganda using wood stoves, monitoring over four and five consecutive days, respectively. Results show good agreement between the two methods on an aggregate level, with an average R^2 value of 0.93, and less agreement when comparing fuel consumption on a day-to-day basis, with an average R^2 value of 0.33. The coefficient of variation was found to generally decrease with increasing monitoring length, with an overall average reduction of 43% for the FUEL, suggesting that conducting fuel use monitoring over a longer duration will capture more variability than 1-2 days. There was no systematic over- or under-prediction of fuel consumption from FUEL relative to the manual measurements, suggesting any errors are likely coming from both methods. Reasons for these differences are discussed, as well as potential errors in each method and resulting suggestions for developing an effective study with the FUEL system. An economic analysis shows that the FUEL system becomes increasingly economical as monitoring duration increases or new studies are conducted. Overall, these results point to the viability of the FUEL system to quantify long-term, in-situ fuel consumption with similar accuracy to current methods and the capability for more granular data over longer time periods with less intrusion into households.

4.1 INTRODUCTION

Over 2.8 billion people rely on inefficient traditional technologies to meet their cooking and heating needs, resulting in negative health and environmental impacts from harmful emitted pollutants (Bonjour et al., 2013; Lim, 2012; WHO, 2014). While extensive laboratory testing has been conducted on hundreds of stove models with improved efficiency, practitioners have faced challenges in validating the impact of these devices when they are used in real-world households. Although laboratory testing provides best-case scenarios of potential impacts, improved stoves often have less than perfect adoption rates, are used alongside other traditional technologies that reduce benefits, or are used with different fuels or tending practices that decrease expected performance. For these reasons, among others, the difference between expected and measured outcomes can be significant. It is therefore necessary to quantify in-field usage and performance to gain an accurate understanding of in-household impact to inform program implementers and evaluators, funding organizations, and researchers.

Autonomous sensor-based methods that reduce the cost and time for monitoring and increase data quality have been used recently to monitor both adoption and emissions. However, the process for monitoring fuel consumption has not been automated, despite being a key indicator of a stove's technical performance. Current tools to determine fuel consumption include manual measurements such as the Kitchen Performance Test (KPT), and qualitative or quantitative surveys that rely on imprecise household estimates that can be costly and time-consuming with limited statistical power. To create a more accurate and cost-effective process for monitoring fuel use, researchers at Oregon State University have developed a sensor-based system to automate fuel monitoring. The Fuel, Usage, and Emissions Logger (FUEL) enables continuous logging of fuel consumption data in a household for up to three months. While the technical performance and usability of the FUEL system have been successfully evaluated (Ventrella and MacCarty, 2019; Ventrella, Zhang, and MacCarty, 2019), the system has not yet been compared to current common practices for measuring daily fuel consumption and potential savings. The contribution of this paper is to compare the accuracy, cost, and granularity between the KPT and the FUEL system to inform practitioner decisions when choosing a monitoring method. Two studies were conducted to compare these methods simultaneously over four monitoring days: one in Uganda with wood stoves in a sample of 20 households, and a second in Burkina Faso in 10 households with wood, charcoal, and LPG stoves. Results demonstrate the range of the FUEL's capabilities and advantages for practitioners that need to monitor a wide variety of fuel and stove types.

4.2 BACKGROUND

4.2.1 Impacts of Traditional Cookstoves and Fuels

Traditional cookstoves and fuels used by 40% of the world contribute to both human health and environmental damage (Bonjour et al., 2013). Smoke from inefficient combustion causes 4.3 million premature deaths from lower respiratory illness, and up to 8% of anthropogenic climate change (Lim, 2012; WHO, 2014). Improved stoves increase combustion and heat transfer efficiencies, but their in-home performance and adoption can vary significantly depending on the design and context. Therefore, it is necessary to measure in-home stove impacts, and not just performance in laboratory testing, to verify project effectiveness. These data can be used to demonstrate impacts to donors, monetize savings in the form of carbon credits or averted disability adjusted life years (aDALYs), or if goals are not being met, reevaluate the program or technology design.

4.2.2 Current Monitoring & Evaluation Methods

In addition to laboratory testing such as the Water Boiling Test (WBT) or in-field testing such as the Controlled Cooking Test (CCT), researchers have recognized the importance of monitoring in-home impacts, which can greatly differ (MacCarty, Still, and Ogle, 2010; Roden et al., 2009). Laboratory and other controlled testing are insufficient to predict real impact because it does not account for adoption rates or local stove usage practices that may decrease stove efficiency, such as using wet wood, over-filling the combustion chamber, or leaving the fire to burn for long periods of time with minimal tending. There are several existing manual and sensor-based methods that are currently used to monitor in-home stove technical performance and adoption. These monitoring techniques and methods can be used to determine metrics such as adoption and usage, stove stacking, fuel consumption, and emissions. A summary of current tools and their attributes are listed in Table 4.1. Each of these tools is used to measure various metrics of either in-home stove performance or user adoption, both of which dictate overall stove impact.

Table 4-1 Summary of current in-home monitoring tools in the clean cooking and fuels sector

	Surveys	**Kitchen Performance Test**	**Temperature Sensors**	**Emissions Sensors**
Metrics	Adoption, cooking duration, fuel use	Fuel use	Adoption, cooking duration	Pollutants
Benefits	Relatively inexpensive	Direct measurement of fuel use	Higher objectivity	Direct at-source measurements
Sources of Error	Survey biases	Manual measurement errors	Data loss from broken sensors, accounting for heating and cool-down time	Noise (PM sensors), sensor drift, background pollution
Data Type	Qualitative, quantitative	Quantitative	Quantitative	Quantitative
Data Collection	Manual	Manual	Automated	Automated

4.2.3 Measuring Fuel Consumption

Although several techniques exist to monitor in-home cookstove performance, it is evidenced by Table 4.1 that there is currently no method to autonomously measure fuel consumption. A key indicator of project impact, fuel consumption indicates the time and financial burdens in households, and can be extrapolated to emissions that impact health and climate via emission factors. Stove stacking, in which a household uses multiple stoves or fuel types, is common and must also be accounted for when determining aggregated household fuel use (MacCarty and Bryden, 2017; Masera, Saatkamp, and Kammen, 2000). Fuel consumption data can also be used in the carbon market, where fuel savings are translated to mitigated carbon dioxide equivalent ($t_{CO2,e}$) that are traded or sold as carbon credits on the voluntary or compulsory market as a source of financing for larger-scale clean cookstove programs (Lee et al., 2013). The most commonly used tool for determining fuel use is currently the KPT. Because sensors can increase accuracy while decreasing associated monitoring cost and time (Pillarisetti et al., 2014; Ruiz-Mercado et. al, 2011), the FUEL sensor has been developed as an alternative method.

4.2.3.1 The Kitchen Performance Test

Developed in the 1980s, the KPT is a protocol that combines qualitative surveys with daily manual measurements of household fuel consumption both before and after an improved stove intervention (Bailis et al., 2018). The procedure for the KPT includes sample selection, debriefing participants, determining fuel supply source, and conducting surveys and manual measurements. The Gold Standard, a regulatory body that sets global standards for quantifying carbon savings of development projects, provides recommendations for selecting a sample size that will ensure statistically significant results: for project beneficiary group size < 300, 30 participants; group size > 300 and >1000, 10% of group size; group size > 1000, at least 100 participants (The Gold Standard Foundation, 2011). After selecting the sample, participants should be debriefed as to the purpose of the test, to maintain typical cooking practices, and to be available at the time of measurement each day. To conduct a KPT, field staff visit a sample of households to ask survey questions on estimated cooking time per meal and cooking preferences, and conduct daily measurements of fuel weight, generally over a period of 3-5 days. If households stack with multiple stoves or fuels, the weight of each fuel type is recorded and separated by stove. Fuel supply can either be provided to families or they can be asked to collect enough fuel for the duration of the test. Participants are also asked to estimate the cooking length of each meal they prepared over the previous 24 hours, the gender and age of each person cooked for, and whether they collected or need any additional firewood. The gender and age of each person is used to calculate standard adult equivalence (SAE) that normalizes fuel consumption (Table 4.2).

Table 4-2 Standard Adult Equivalence (SAE) Factors (Bailis et al., 2018; Openshaw, 1990)

Gender and age	**Fraction of standard adult**
Child: 0-14 years	0.5
Female: over 14 years	0.8
Male: 15-59 years	1.0
Male: over 59 years	0.8

Manual fuel use measurements are conducted using a hanging scale with 10-30 kg capacity, accuracy 5% of the reading or better and 0.1 kg resolution. Fuel moisture content readings are taken with a moisture meter with accuracy 10% of the reading or better and 1% relative humidity (RH) resolution. Each day, the entire fuel supply in a household is weighed and recorded. If using wood, moisture readings from a meter on a dry basis (MC_{dry}) are taken to calculate moisture content on a wet basis (MC_{wet}) (Eq. 1) and resulting dry fuel equivalent m_{dry} (Eq. 2), where m_{wet} is mass of wet fuel. Wood moisture can vary significantly depending on geography, type, and season. Daily fuel consumption is then determined by taking the difference between the initial and final dry fuel mass.

$$MC_{wet} = \frac{1}{1 + \left(\frac{MC_{dry}}{100} \right)} \tag{1}$$

$$m_{dry} = m_{wet} MC_{wet} \tag{2}$$

KPTs have been used extensively in the past to quantify in-home fuel consumption and savings. Several published academic studies include a study conducted in rural Mexican communities that conducted a longitudinal KPT with 23 households over 7 days to determine in-field stove performance and estimate fuel savings of the improved Patsari cookstove as compared to traditional stoves (Berrueta, Edwards, and Masera, 2008). Another study used a KPT to examine the fuel savings of a plancha stove as compared to traditional open fires in rural Guatemala in a sample of 12 households over four days, with results showing no significant difference in fuel usage (Granderson et al., 2009). Many other unpublished KPTs have been completed by projects to provide reports to funders or seek carbon credits.
Documented difficulties include biases in surveys, inability to capture seasonal and or even daily variability, lack of standardization in measurement, disruption of daily household activities, and time and resource intensiveness, prompting a call for improved methods (Bailis, Smith, and Rufus, 2007; Granderson et al., 2009; L'Orange, DeFoort, and Willson, 2012; Putti et al., 2015; Smith et al., 2007). Measurement errors are especially common in fuels with high energy density such as LPG, where very little mass of fuel is needed per cooking event-, making it difficult to manually measure accurately. The KPT can also represent a significant financial burden, requiring funds for personnel, daily travel and fuel, equipment, and hiring an external consultant or spending personal time to analyze data.

4.2.3.2 FUEL Sensor

Motivated by the lack of robust and less labor-intensive fuel measurement options, the FUEL system is the first sensor-based system to directly monitor fuel consumption in households. FUEL autonomously monitors and records time-stamped data on fuel mass using a logging load cell (Ventrella and MacCarty, 2019). To date, two versions of the system have been developed, one manufactured by Waltech Systems that relies on SD cards (1st generation), and an updated model manufactured by Climate Solutions Consulting that collects data wirelessly (2nd generation). Wireless data collection allows for faster data collection, and enables troubleshooting at the source. System components include:

- Off-the-shelf S-type tensile or compressive load cell with eye bolts for attachment
- Internal temperature sensor

- Integrated power supply, analog-to-digital converter (ADC) and control module with internal clock
- Battery power supply
- Plastic housing
- Fuel storage container

Components specific to 1st generation (Fig. 4.1A) include:

- External thermocouple port
- SD card port for data storage

Components specific to 2nd generation (Fig. 4.1B) include:

- Wireless data launcher
- Initial pre-processed data analytics
- Wireless IR temperature logger (EXACT)

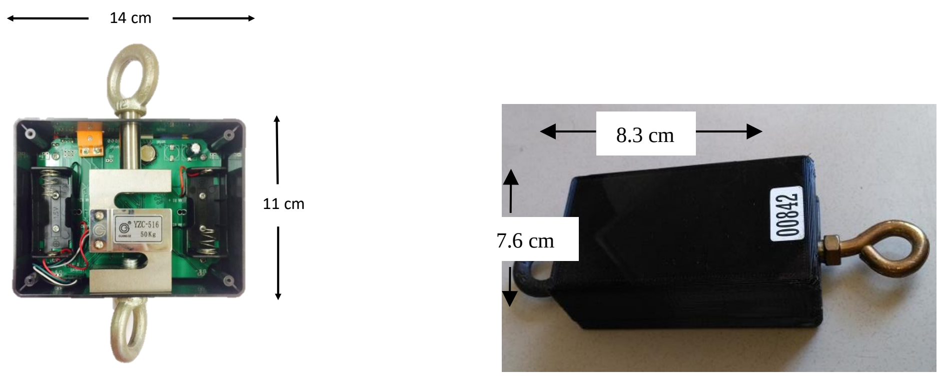

Figure 4.1 FUEL system, 1st generation (A) and 2nd generation (B)

The FUEL system can operate in tension or compression depending on the type of fuel being monitored, including firewood, LPG, charcoal, and agricultural residues, with any variety of stove model. If households stack with multiple stoves or fuels, a separate sensor can be installed for each stove or fuel type. To operate, a household cook is trained to store his or her fuel supply in the storage unit, remove fuel as needed for cooking, and refill when empty. These actions result in discrete reductions in weight, which are recorded by the load cell and integrated to determine total wood use over a specified time. A coupled temperature sensor generates a continuous temperature profile over the monitoring period, which is used to determine cooking duration and serves as a corroboration for the weight data by verifying that the cookstove temperature is elevated, i.e. “on”, when a weight reduction is detected.

The FUEL has been previously tested for usability and performance in proof-of-concept and pilot testing in Guatemala, Honduras, and Uganda. Results from a study of 85 households in rural Uganda showed that 82% of users consistently engaged with the FUEL systems, and a usability survey revealed that participants found benefits to using the holder, including drying their fuel wood and keeping it organized (Ventrella, Zhang, and MacCarty, 2019).

4.2.3.3 Fuel Consumption Measurement Accuracy

There are several factors that can affect the accuracy of measurements reported by the KPT and FUEL methods. Measurement error can come from the following factors:

i. Using fuel that was not weighed by the sensor or enumerator (i.e. burning fuel from a non-measured source). In the KPT, this can occur if the household runs out of fuel before the enumerator comes to weigh it. With FUEL, this can occur if fuel is burned without first placing it in the fuel holder.
ii. Not using fuel that was weighed by the sensor or enumerator (i.e. giving fuel away)
iii. Enumerators not accurately weighing the amount of fuel
iv. Not accurately measuring the moisture of the fuel
v. Not accurately accounting for the number of meals served each day to calculate fuel use per SAE
vi. Not capturing daily and seasonal variability in number of people served, number of meals cooked, or seasonal cooking practices

4.2.4 Study Aims

The goal of this study was to compare the FUEL and KPT in terms of measurement accuracy, granularity, and cost by conducting them simultaneously in a sample of households. Specific objectives were to compare calculations of daily and aggregated fuel consumption based on both FUEL and KPT data, verify and validate the FUEL algorithm, and determine best-use practices for the FUEL system. Testing was conducted in two study locations, Uganda and Burkina Faso, with multiple stove and fuel types.

4.3 METHODS

Comparison testing of the FUEL and KPT methods was conducted in Uganda and Burkina Faso using 1st and 2nd generation FUEL sensors, respectively. While the FUEL sensors were deployed, the KPT was simultaneously conducted to directly compare measurements. Testing in Uganda was conducted with 20 convenience-sampled households in July 2018 with households using wood-fueled stoves and 1st generation FUEL sensors, and in Burkina Faso with the 2nd generation FUEL sensors in 10 households in August 2018 with households that were stacking wood, charcoal, and LPG stoves with. Both studies were conducted with oversight by the Oregon State University Institutional Review Board for protection of human subjects under study number 7257.

4.3.1 Sample Size

4.3.1.1 Uganda

International Lifeline Fund (ILF), an NGO that works on clean stove and water projects in East Africa, partnered with OSU researchers to conduct a trial of the KPT and FUEL monitoring in the Apac district of Uganda with 20 convenience-sampled households over a five-day period, Table 4.3. In Uganda, the initial sample size was 20 households, but due to prototype sensor malfunction, the sample included in the analysis was 16 households. The traditional stove types in the region are the three stone fire (TSF) and locally mudded stove (LMS), and the improved is the ILF rural wood stove (RWS), Figure 4.2.

Figure 4.2 Stove Models (from left to right): Three Stone Fire, Locally Mudded Stove, Rural Wood Stove, Uganda

Households in the study sample rely primarily on collected firewood, and the three stove models monitored were all wood stoves. Participants were compensated with a portion of food and a set of dishware. All stoves were fitted with wired thermocouples to measure temperature. A fully installed system is shown in Figure 4.3.

Table 4-3 Sample Distribution and Stove Type, Uganda

Stove Type	***Households***	***Percentage***
RWS	13	65%
TSF and RWS	3	20%
LMS and RWS	4	15%
Total	20	

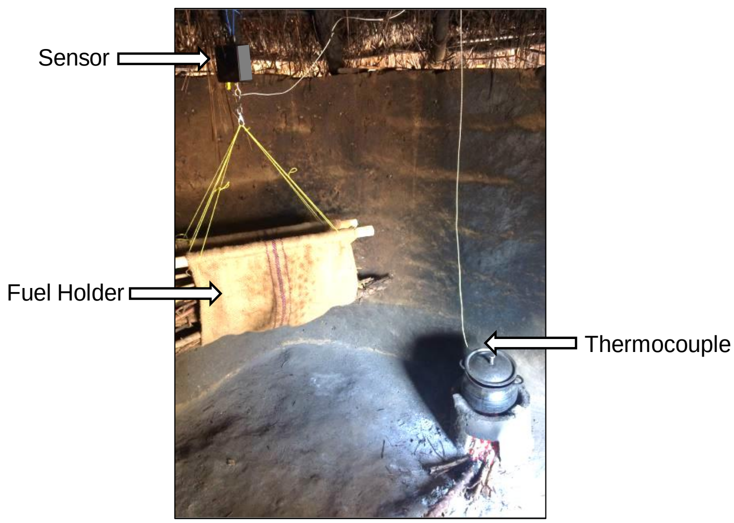

Figure 4.3 Fuel System Installed in Apac, Uganda (Ventrella, 2018)

4.3.1.2 Burkina Faso

Nafa Naana, an NGO that works on clean stove projects in Burkina Faso, partnered with OSU researchers, Entrepreneurs du Monde, and Climate Solutions Consulting to conduct a trial of the KPT and FUEL monitoring with 10 convenience-sampled households over a four-day period, Table 4.4. The fuel/stove types in the area include LPG, charcoal, and wood, with FUEL installation for a household using all three shown in Figure 4.4. The Telia LPG stove is the NGO intervention stove, the Roumde is a slightly improved stove that can be used with either firewood or charcoal, and the traditional stoves include the three stone fire for wood and “Malagasi” rebar brasero for charcoal. EXACT temperature sensors were installed on each stove to simultaneously record usage (LeFebvre, n.d.).

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Table 4-4 Sample Distribution and Fuel Type, Burkina Faso

Fuel Type	***Households***	***Percentage***
LPG	1	10%
LPG, Charcoal	4	40%
LPG, Wood	1	10%
LPG, Charcoal, Wood	4	40%
Total	10	

Figure 4.4 FUEL installation for (from left to right): wood, LPG, and charcoal, Burkina Faso

4.3.2 Hardware

Hardware was needed for installing the FUEL systems in kitchens and for conducting the KPT and was location-specific.

4.3.2.1 Uganda

4.3.2.1.1 KPT Hardware

Hardware used to conduct the KPT included a digital scale and a moisture meter to determine wood moisture content. A Brecknell Electro Samson digital scale with a 45 kg capacity ± 0.2 kg accuracy and 0.05 kg resolution was used to weigh fuel. A General MMD4E moisture meter with measurement range 5 to 50%, ±2% accuracy and 1% RH resolution was used to determine wood moisture content. All data were recorded manually on paper and later entered in Excel for analysis.

4.3.2.1.2 FUEL Hardware

Hardware used for the FUEL system included an integrated load cell and thermocouple, SD card data storage, and installation equipment. The 1st generation FUEL system used an off-the-shelf tensile load cell with a 50 kg capacity, 0.1% of full-scale accuracy with two-point calibration (1 and 30 kg), and 0.005% resolution. Type K thermocouples rated at 750 °C with 2 m extensions were used to monitor cookstove temperature, and calibrated in ice (0 ˚C) water and boiling (100 ˚C) water. The integrated system was powered with two C batteries. The logging rate was programmed to 49 seconds, and decreased to 7 seconds when a specified weight change was detected, until no additional changes in mass were detected. To attach the thermocouple to the stoves, stainless steel brackets were manufactured. Equipment to install the FUEL system in kitchens included S-hooks and rope. To reduce difficulties in transportation, fuel holders were manufactured in Uganda using recycled burlap sacks (Fig. 4.5), dowels, and nylon rope local to the area. Data were stored on SD cards as .csv files.

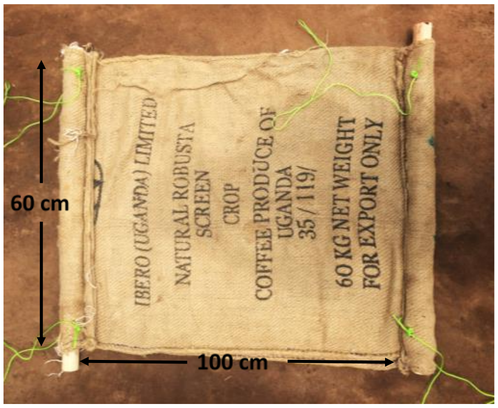

Figure 4.5 Fuel holder and dimensions

4.3.2.2 Burkina Faso

4.3.2.2.1 KPT Hardware

Hardware used to conduct the KPT included a digital scale and a moisture meter to determine wood moisture content. A digital luggage scale with a 50 kg capacity and 0.01 kg resolution was used to weigh fuel. A General MMD4E moisture meter with measurement range 5 to 50%, ±2% accuracy and 1% RH resolution was used to determine wood moisture content. All data were recorded on the Kobo Collect smartphone app and later exported to Excel for analysis.

4.3.2.2.2 FUEL Hardware

Hardware used for the 2nd generation FUEL included a load cell, IR temperature sensor (EXACT), wireless launcher, SD card data storage, and installation equipment. An off-the-shelf tensile load cell with a 50 kg rated capacity and 10 g resolution was used in each sensor, and each cell was calibrated with a 4 kg reference mass. The logging rate was programmed to 30 seconds, with data logging every minute. The data were stored in the device internal memory and then downloaded wirelessly to the launcher SD card as a .csv file.

4.3.3 User Training

Training was consistent throughout both studies and was held for both the KPT and FUEL at the same time, prior to the beginning of the study to inform participants of the study requirements. For the KPT, households were informed that they would be visited every day for four days by enumerators to weigh their fuel. In Uganda, participants were then asked to collect approximately enough firewood to last for a four-day period, store in a pile, and collect additional wood as needed. Participants were instructed to store as much fuel as could fit in the FUEL system holder from the larger pile, remove from the holder as needed for cooking, and refill as desired. In Burkina Faso, participants were asked to collect or purchase enough fuel to last for the entire testing duration. Explicit guidance for participants included:

- Maintain as close to normal cooking practices as possible.
- When adding wood, fill holder with as much wood as possible, refill when near empty (helps to reduce noise in data).
- Do not put wood back in holder after removal (includes partially burnt wood).
- Wood must be in the holder for at least 30 seconds before removal.
- All wood used for cooking must be stored in the holder before use in the stove.

4.3.4 Installation & Data Collection

While the KPT execution was generally consistent between study locations, FUEL installation differed slightly between Uganda and Burkina Faso.

4.3.4.1 KPT Procedure

The procedure for fuel consumption measurements included weighing fuel and recording moisture content. Participants were visited at roughly the same time each day to maintain a 24-hour difference between each daily measurement. Each household was assigned an ID number that corresponded to the

FUEL sensor number. Participants were also administered a survey for each monitoring day. The measurement procedure and survey questions for the KPT are shown in Table 4.5.

Table 4-5 Daily KPT Procedure

Daily Measurements	Daily Survey Questions
1. Record the moisture content of three samples from the fuel supply, taking readings from three locations on each sample.* 2. Record weight of fuel stockpile. 3. Record weight of fuel in FUEL system holder. If stove stacking, record weight of fuel in other holder separately, indicating stove type.** 4. Record weight of any partially burned fuel in kitchen or stove combustion chamber.**	1. Record household visit time. 2. Record number of meals cooked in the past 24 hours, and approximate start and end times of each as reported by participants. 3. Record the gender and age of each person cooked for in the past 24 hours (to inform standard adult equivalence (SAE)). 4. Ask participants if any additional wood was collected, borrowed, or lent to other households. If any of these conditions are true, record stated amount.

*Not included in day four
**Not included in day zero

4.3.4.2 FUEL Procedure

4.3.4.2.1 Uganda

In Uganda, the FUEL systems were installed by hanging from pre-existing internal roof supports. Thermocouples were attached to stoves using stainless steel brackets. SD cards were programmed and initiated at the start of the KPT/FUEL monitoring. Following the four-day KPT and FUEL monitoring, SD cards were collected and data uploaded, and the sensors were then re-launched to continue monitoring for an additional 30-45 days.

4.3.4.2.2 Burkina Faso

In Burkina Faso, the FUEL systems required external wooden support for installation, constructed by a local carpenter (Fig. 4.4). EXACT temperature sensors were attached to stoves using pre-attached stainless steel brackets. A wireless launcher was used to program the logging rate and collect short-range data over the four-day monitoring period.

4.3.5 Post Processing

Survey and sensor data from the KPT and FUEL were analyzed to determine daily and aggregated fuel consumption for households in both locations, using manual and algorithmic processing. Daily KPT data were entered in an Excel spreadsheet, corrected for average moisture content and analyzed on a daily and aggregated basis. Following FUEL data collection, the sensor data were first cleaned by hand to remove the changes in weight caused by the enumerators removing all fuel from the holder to weigh and then reloading the fuel in the holder during the KPT. Data were then analyzed using the FUEL algorithm,

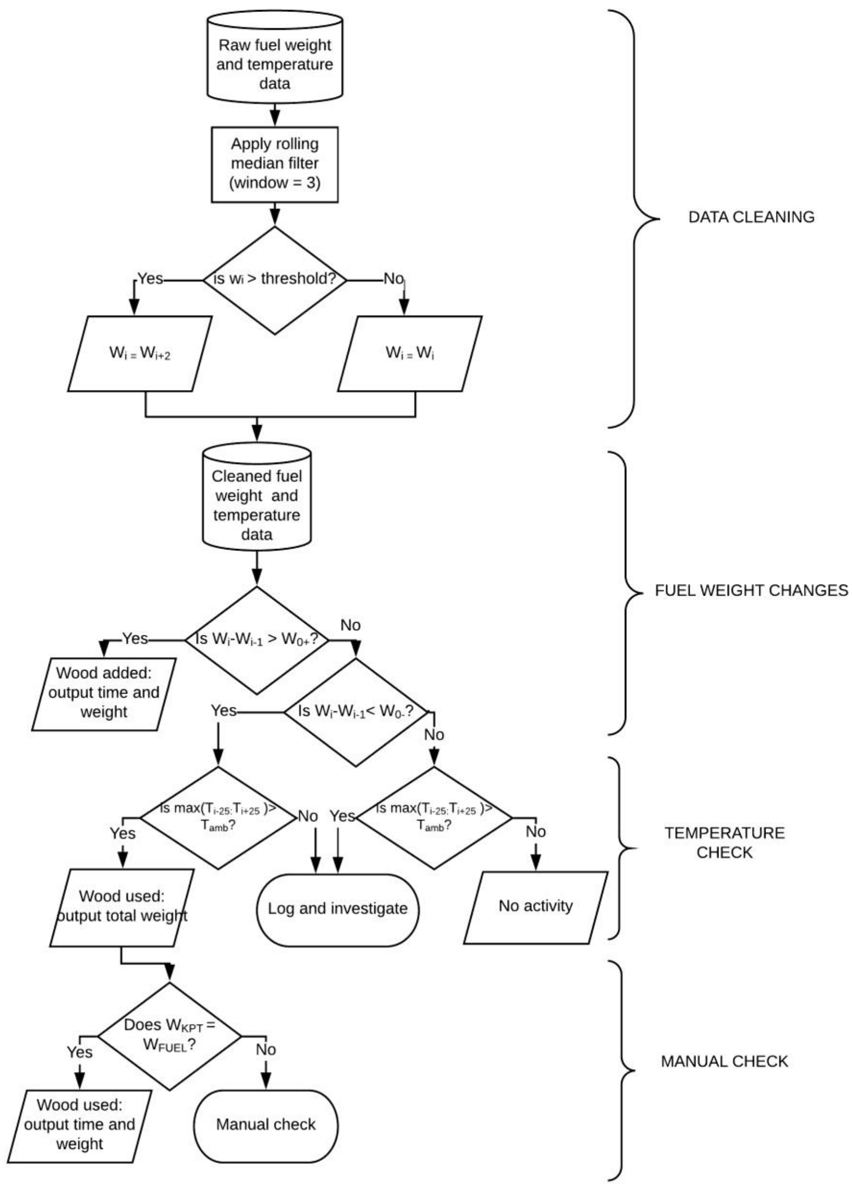

Figure 4.6 Algorithm for FUEL data analysis

which applies a sensor-specific calibration curve and then integrates mass changes over a specified time, corrects for discrete outliers using a rolling median filter, and corroborates weight data with cookstove temperature, Figure 4.6 (Ventrella and MacCarty, 2019). The 2nd generation FUEL system applies calibration internally. Temperature was not used to corroborate fuel use in the LPG stoves because the LPG tanks were only attached to the FUEL sensors when the enumerators came to weigh them for the KPT. Therefore, temperature would not correspond with decreases in weight. Cooking duration was determined from temperature data by identifying temperature peaks, measuring the duration between each peak, and grouping the durations into approximately 3-hour windows. These measured cooking duration data were then compared to reported cooking duration per each meal prepared in the past 24 hours, collected as part of the KPT survey in Uganda.

3.7 Algorithm Verification and Validation

The algorithm was verified and validated using a combination of KPT and FUEL data. For verification, fuel use as measured by the FUEL in Burkina Faso was graphed and interpreted manually. The same data set was then run through the algorithm and results were compared and expected to be the same. To validate the algorithm, both daily and aggregated fuel consumption data from the FUEL sensors calculated using the algorithm were compared to the KPT measurements of fuel consumption. To test the data cleaning function, FUEL data were analyzed with and without cleaning and also compared to the KPT measurements.

4.4 RESULTS

Results of daily and aggregated fuel consumption measured by the FUEL as compared to the KPT, as well as analysis of moisture content variation, reported vs. measured cooking duration, and algorithm verification are presented.

4.4.1 FUEL vs. KPT Fuel Usage

4.4.1.1 Burkina Faso

A comparison of daily and aggregated fuel consumption measured by FUEL vs the KPT for all fuel types in each study location are shown. Best fit and 1:1 trendlines are shown for comparison, and R^2 values are reported for best fit lines.

Figure 4.7A shows a comparison of wood fuel as measured by FUEL vs the KPT in Burkina Faso, aggregated over the monitoring period, with a reported R^2 value of 0.9858. Values agreed within 12% on average.

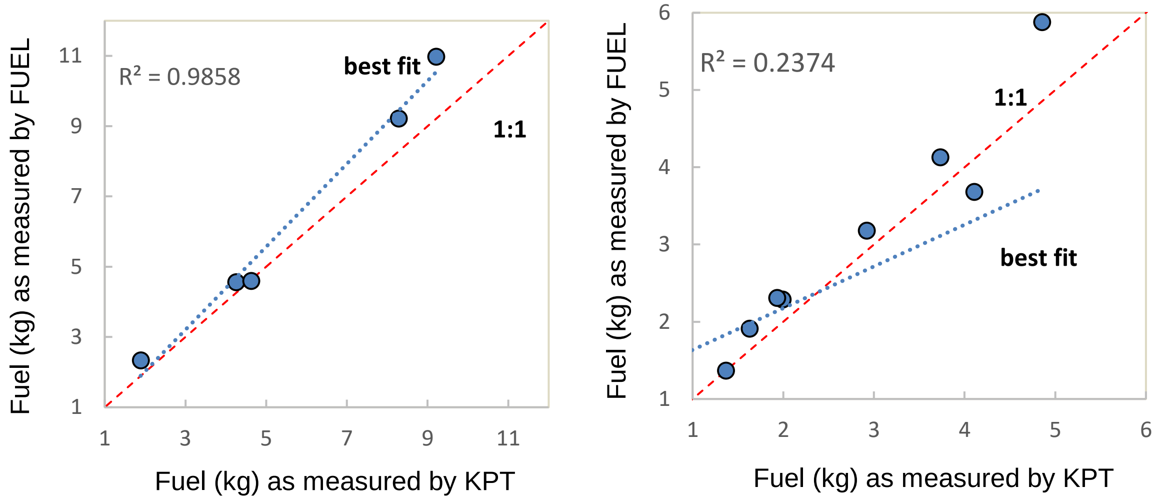

Figure 4.7 FUEL vs. KPT aggregated over monitoring period (A) and daily (B), wood, Burkina Faso

Figure 4.7B shows a comparison of wood fuel as measured by FUEL vs the KPT in Burkina Faso by day, with a reported R^2 value of 0.2374.Figure 4.8A shows a comparison of LPG fuel as measured by FUEL

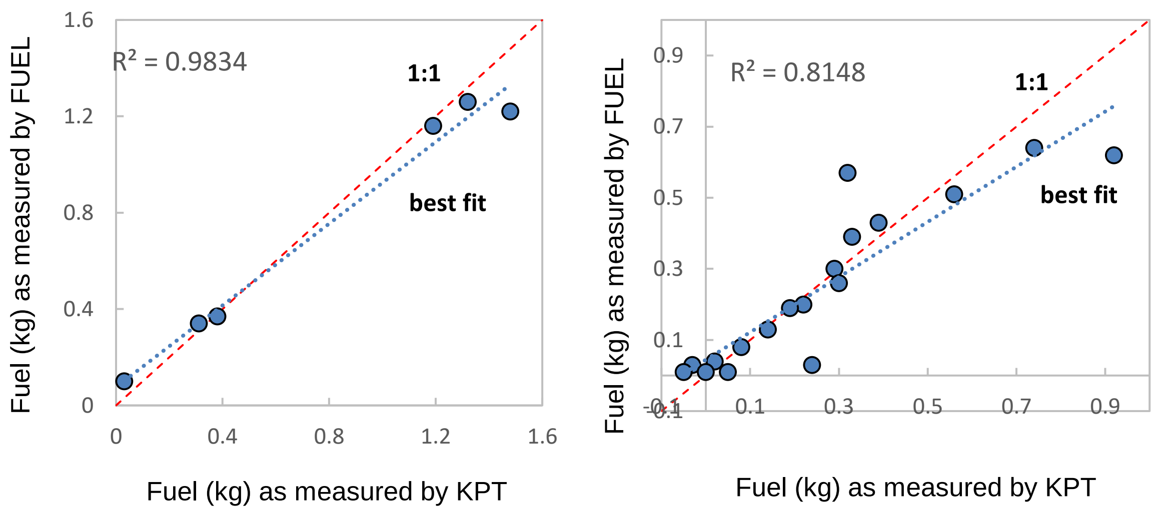

Figure 4.8 FUEL vs KPT aggregated over monitoring period (A) and daily (B), LPG, Burkina Faso

vs the KPT in Burkina Faso, aggregated over the monitoring period, with a reported R^2 value of 0.9834. Values agreed within 7% on average. Figure 4.8B shows a comparison of LPG fuel as measured by FUEL vs the KPT in Burkina Faso, per day, with a reported R^2 value of 0.8148. Negative numbers for 9B indicate a measurement error in the KPT due to the resolution of the scale and relatively low mass change for LPG usage.

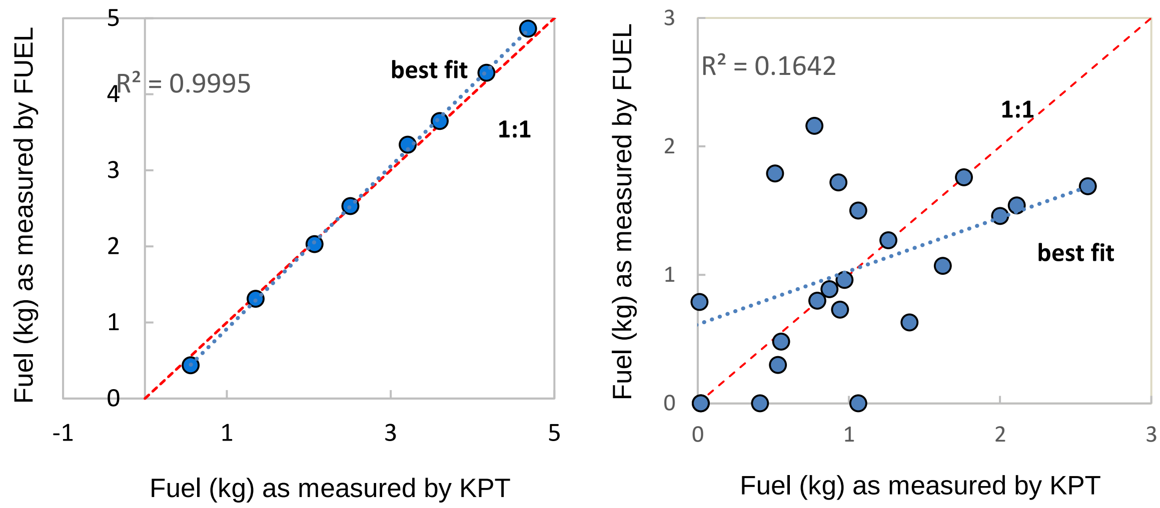

Figure 4.9 FUEL vs KPT aggregated over monitoring period (A) and daily (B), charcoal, Burkina Faso

Figure 4.9A shows a comparison of charcoal fuel as measured by FUEL vs the KPT in Burkina Faso, aggregated over the monitoring period, with a reported R^2 value of 0.9995. Values agreed within 6.9% on average. Figure 4.9B shows a comparison of charcoal fuel as measured by FUEL vs the KPT in Burkina Faso, per day, with a reported R^2 value of 0.1642.

Overall, in Burkina Faso, aggregated fuel as measured by the KPT was in good agreement with fuel as measured by the FUEL. There was more variation in agreement when comparing daily measurements of the KPT and FUEL. Daily LPG may have the highest R^2 value because it requires the least user interaction as compared to the wood and charcoal, which can both be removed or re-added to the FUEL holder.

4.4.1.2 Uganda

Figure 4.10A shows a comparison of wood fuel as measured by FUEL vs the KPT in Uganda, aggregated over the monitoring period, with a reported R^2 value of 0.7916. Values agreed within 15% on average. Figure 4.10B shows a comparison of wood fuel as measured by FUEL vs the KPT in Uganda by day, with a reported R^2 value of 0.1085.

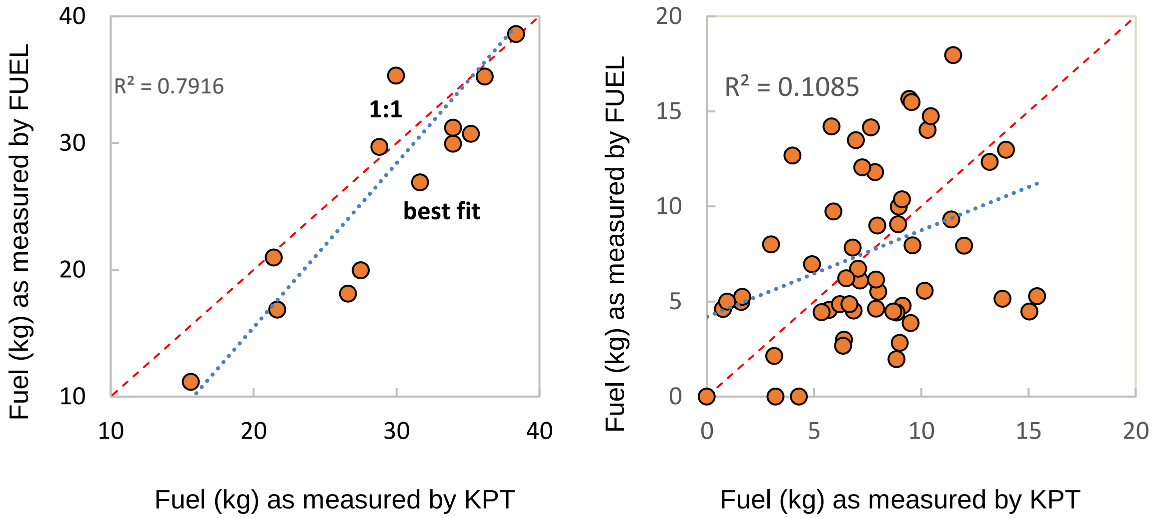

Figure 4.10 FUEL vs KPT aggregated over monitoring period (A) and daily (B), wood, Uganda

In Uganda, aggregated fuel as measured by the KPT was in fairly good agreement with FUEL, with an R^2 value of 0.7916. The agreement may be lower than in Burkina Faso because of differences in fuel collection and use of the fuel holder between the two locations. In Burkina Faso, households were supplied with enough fuel to last for the entirety of the monitoring period and were thus not required to refill the holders as needed, thereby minimizing human interaction and potential measurement error. Each household in Burkina Faso also only had one or less of each type of stove. In comparison, the participants in Uganda were asked to collect their own wood and refill the holder as needed, necessitated because they used much higher quantities of wood than in Burkina Faso since it was the sole fuel type in that community. Increased fuel gathering can result in a higher chance of user/enumerator error, and therefore fuel measurements for both the KPT and FUEL system have greater uncertainty. In addition, several households used two wood stoves and were asked to choose fuel from the holder that corresponded with the correct stove, which could have also resulted in higher error.

There was low agreement when comparing daily measurements of the KPT and FUEL, again most likely due to participant usage patterns. For example, a household might remove more fuel than needed for one meal, and use it later on, as was observed with a participant in Burkina Faso. This kind of usage habit could result in inaccurate daily measurements if the fuel was not used until the next monitoring day.

4.4.1.3 Combined

Figure 4.11 shows a normalized comparison of all fuels as measured by FUEL vs the KPT in both study locations, aggregated over the monitoring period, with a reported R^2 value of 0.7886 and average difference of 19%.

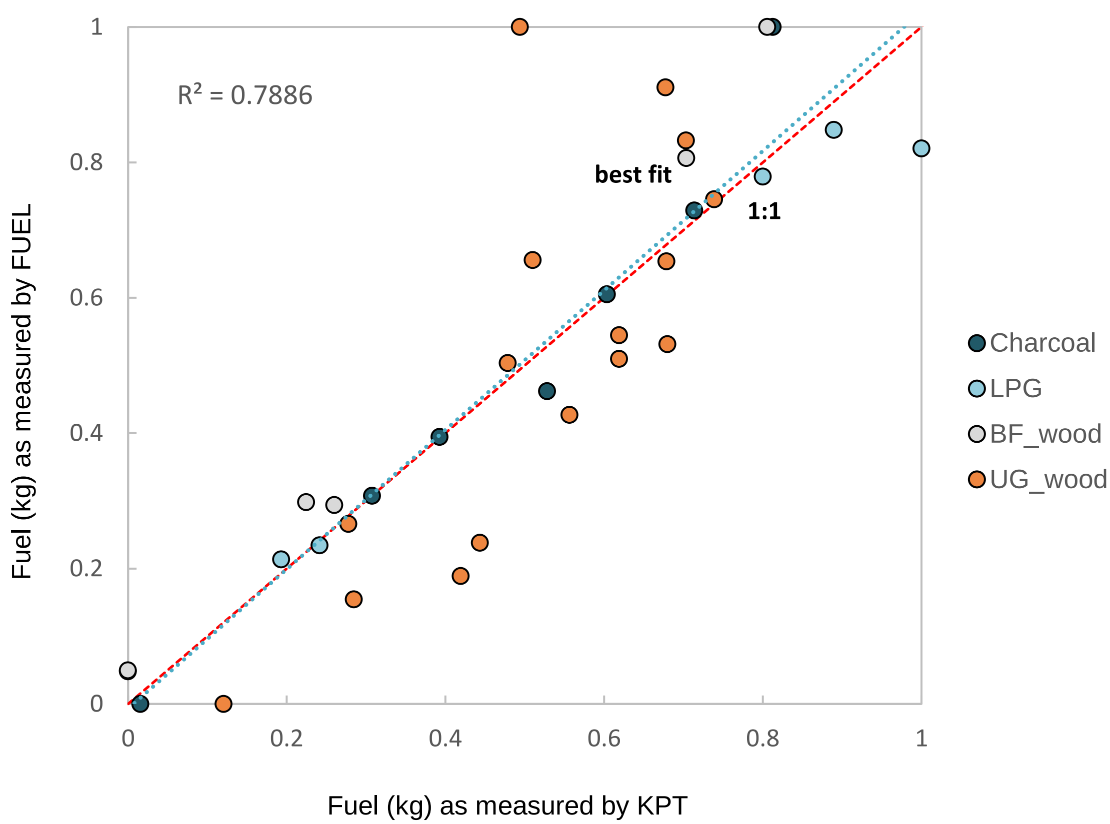

Figure 4.11 FUEL vs KPT aggregated and normalized, all stove types and locations

Figure 4.11 indicates that there is no systematic over predicting or under predicting by FUEL. Since the data are not biased in one way or another, this suggests that there is no consistent mode of user error, such as not putting fuel in the holder, and no trend in which method seems to be more accurate.

4.4.2 Qualitative vs. Measured FUEL Cooking Duration

An analysis of reported versus FUEL measured cooking duration in Uganda with a 10-participant single-stove sample size is shown in Figure 4.12.

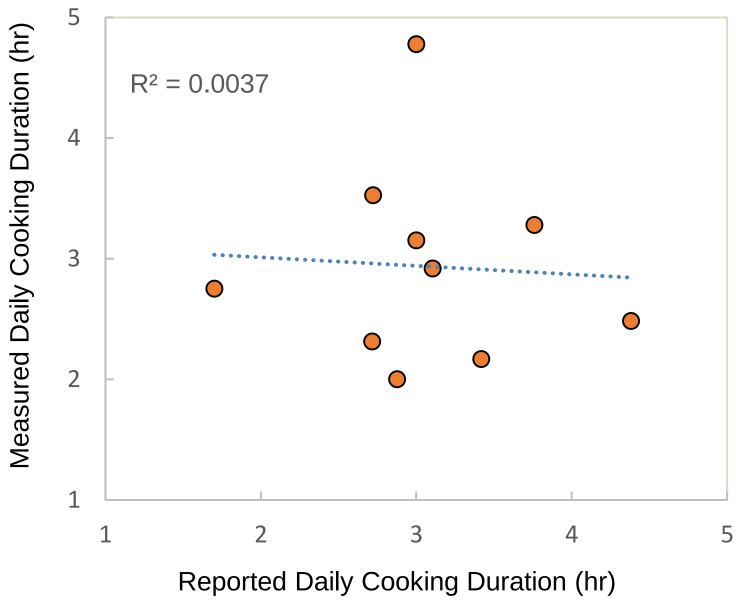

Figure 4.12 Measured vs reported daily cooking duration, Uganda

Results show that there is little correlation between reported and measured values (R^2 = 0.0037), suggesting that the qualitative method may not be a reasonable indicator of cooking duration. If the measured cooking duration by the FUEL sensor is taken as the more accurate value, participants who overestimated did so by 0.85 hours/day, and those who underestimated did so by 0.95 hours/day, on average, with a pooled standard deviation of 0.78 hours/day. While not statistically significant, this finding agrees with results from previous studies conducted on recall and other types of biases in survey reporting for cookstove projects (Thomas, Barstow, Rosa, Majorin, and Clasen, 2013). This points to the value of using temperature sensors to measure cooking duration as opposed to surveys, and may highlight potential bias when trying to measure other impact areas with surveys.

4.4.3 Algorithm Verification & Validation

To verify the algorithm, aggregated fuel consumption of wood stoves in Burkina Faso as measured by FUEL and calculated using the FUEL algorithm was compared to aggregated fuel consumption when the

FUEL data were graphed and interpreted by hand (Fig. 4.13). The reported R^2 value of this verification was 0.9941.

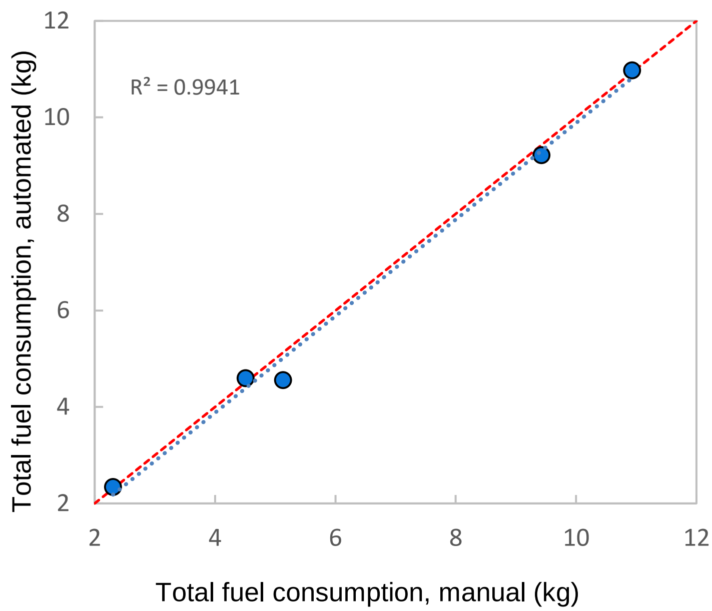

Figure 4.13 Automated vs manual fuel consumption data, wood stoves, Burkina Faso

For validation of the data cleaning algorithm which removes outlier points not caused by intentional fuel removal and decreases in weight not corroborated with a corresponding increase in temperature,

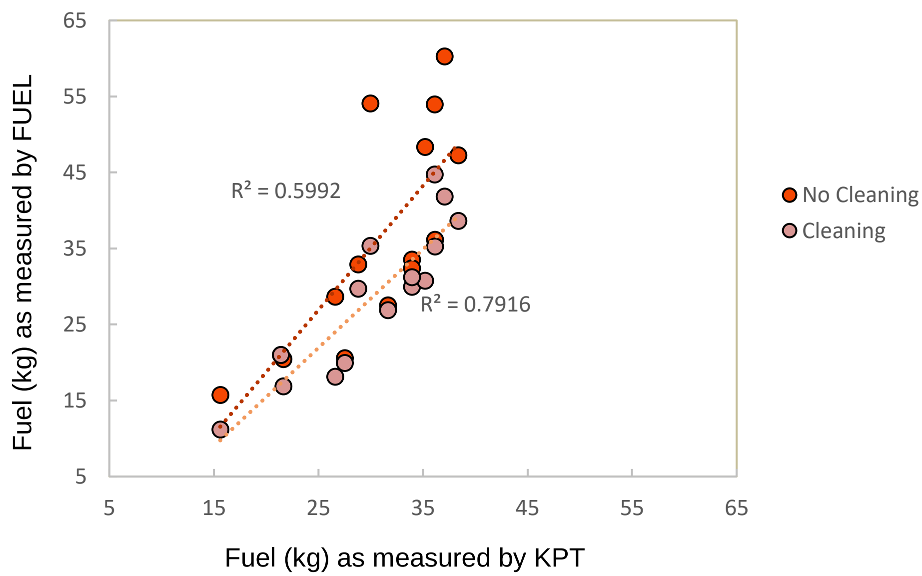

Figure 4.14 Comparison of FUEL vs KPT with and without algorithm data cleaning, Uganda

aggregated fuel as measured by FUEL was compared to fuel measured by the KPT with and without data cleaning (Fig. 4.14). Results from show that with no cleaning, the reported R^2 value was 0.5992 and with cleaning, 0.7916.

Verification and validation results showed that the data cleaning and temperature corroboration algorithms have appropriate thresholds and work as intended. Applying a median filter to smooth weight outliers with a set threshold value improved the R^2 value, indicating that the algorithm is working well. More work is needed to validate the algorithm for cooking duration.

4.4.4 Moisture Content

Moisture content readings for KPT compared to FUEL were characterized by comparing the difference between taking moisture content readings every day (KPT) versus the average of the first and last day of monitoring (FUEL), to represent what would happen in practice for a monitoring session with FUEL exclusively (Fig. 4.15). Results for Burkina Faso reported an R^2 value of 0.8909, while in Uganda, the reported R^2 value was 0.7453.

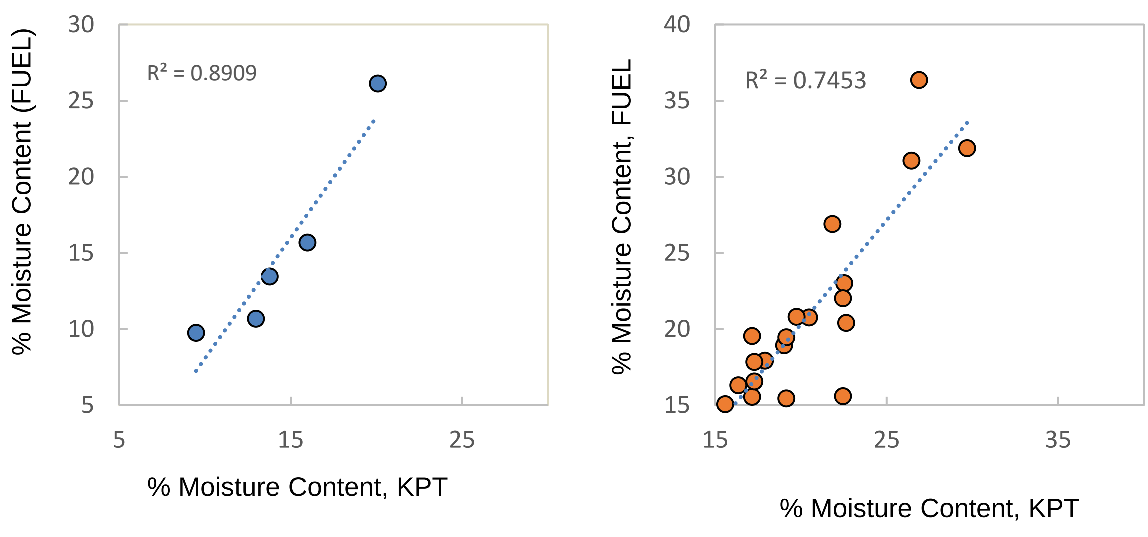

Figure 4.15 Percent moisture content for days 1 & 4 of monitoring (FUEL) vs. all days (KPT), Burkina Faso (A) and Uganda (B)

In Burkina Faso, the average moisture content across households for all four days was 15.1 ± 1.2% as compared to 14.5 ± 1.0% for moisture content measured only on days 1 and 4. In Uganda, the average moisture content across households for all four days was 20.6 ± 3.8 % as compared to 21.07 ± 6.1% for moisture content measured only on days 1 and 4. This indicates that there was not a significant difference between average household moisture content for all four days (KPT) versus the first and last days (FUEL), and suggests when using the FUEL, it is sufficient to measure wood measure content on the days of installation and system removal. However, these results may vary for longer monitoring durations, especially if there are seasonal variations within the monitoring period. Taking moisture content readings in intervals throughout the desired monitoring time could capture potential variations. The higher R^2 value for moisture content in Burkina Faso could be attributed to a more stable climate in the region or during that monitoring period, or a more accurate and consistent moisture meter.

4.4.5 Standard Adult Equivalence

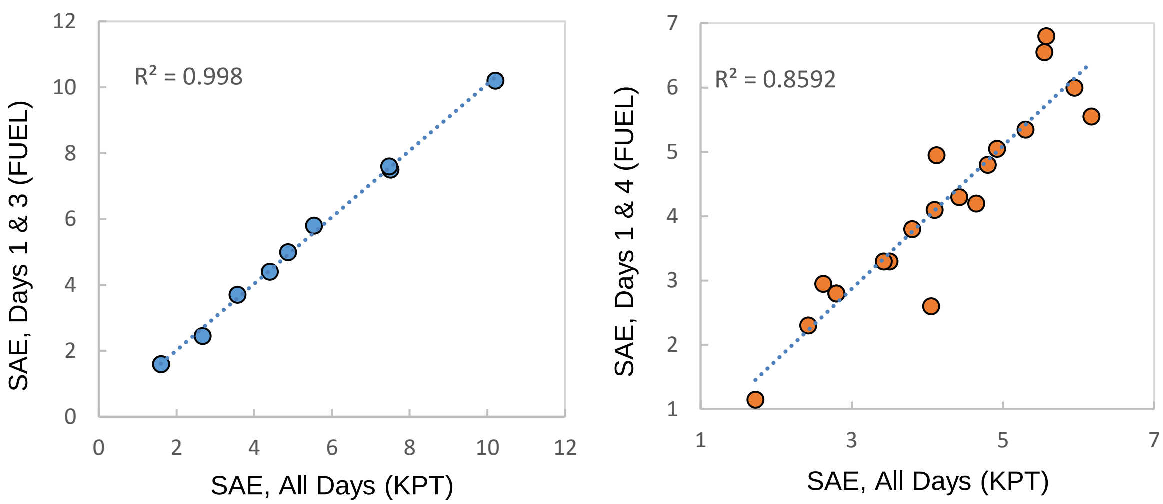

Figure 4.16 SAE for days 1 & 4 of monitoring (FUEL) vs. all days (KPT), Burkina Faso (A) and Uganda (B)

It is also illustrative to compare the SAE based on daily measurements or average of start and end period in the case of an exclusive FUEL monitoring session when an enumerator does not need to visit the household every day (Fig. 4.16). In Burkina Faso, the SAE recorded on all four days agreed with the SAE for days one and three within an average of 0.5% and had a pooled standard deviation of 0.037 for the 10 households. In Uganda, the SAE recorded on all four days agreed with the SAE for days one and four, within an average of 1% and had a pooled standard deviation of 0.0995 SAE. The reported R^2 value was 0.8592. The comparison of SAE as recorded on all four monitoring days, as per the KPT, and SAE recorded on the first and last day, as per the FUEL, showed close agreement, suggesting that taking the average at the beginning and end of a FUEL monitoring session should be sufficient. Higher variation might be found with longer monitoring durations and should be further investigated in future studies.

4.4.6 Monitoring Duration

An analysis of the coefficient of variation (COV) of average daily fuel use per capita was conducted for each monitoring day. A cumulative average over each consecutive day was taken to control for potential user error in FUEL. Table 4.6 shows the household-level average daily fuel use, standard deviation, and COV for each fuel type for the KPT and FUEL, and the overall R^2 to assess the fit between FUEL and the KPT. The trend shows that the COV generally decreases with increasing monitoring length, with an overall average reduction of 43% for the FUEL and 36% for the KPT, suggesting that conducting fuel use monitoring over a longer duration will capture more variability than 1-2 days. This is corroborated with similar findings from a study that found that conducting a KPT for 7 days decreased the COV by about 56% (Berrueta, Edwards, and Masera, 2008).

Table 4-6 Aggregated Analysis

			FUEL			KPT			DAILY	AGG
Location	Fuel	n days	AVE	SD	COV	AVE	SD	COV	R^2	R^2
Uganda	Wood	1	2.18	1.96	0.90	2.57	1.16	0.45	0.1085	0.7916
		2	2.23	1.30	0.58	2.47	1.05	0.43		
		3	2.24	1.07	0.48	2.31	0.94	0.41		
		4	2.24	0.87	0.39	2.14	0.73	0.34		
Burkina Faso	Wood	1	0.26	0.21	0.84	0.22	0.20	0.88	0.2374	0.9858
		2	0.31	0.15	0.48	0.33	0.12	0.36		
		3	0.24	0.13	0.55	0.25	0.11	0.45		
Burkina Faso	LPG	1	0.05	0.05	1.07	0.06	0.08	1.30	0.8148	0.9834
		2	0.06	0.03	0.50	0.06	0.04	0.63		
		3	0.06	0.03	0.54	0.06	0.04	0.66		
Burkina Faso	Charcoal	1	0.17	0.15	0.84	0.21	0.17	0.81	0.1642	0.9567
		2	0.12	0.08	0.62	0.17	0.12	0.72		
		3	0.16	0.10	0.59	0.16	0.09	0.58		

4.4.7 Sources of Error

4.4.7.1 FUEL

During manual interpretation of the FUEL data, there were several sources of error observed. Diurnal drifts in weight of up to 200g were recorded, likely due to temperature. In one household, firewood was removed early and used slowly over time for three cooking events. In another household, firewood was removed from the holder and then replaced with no cooking event taking place. These events were identified by the algorithm due to the corroboration check between temperature and weight changes.

4.4.8 KPT vs. FUEL Cost

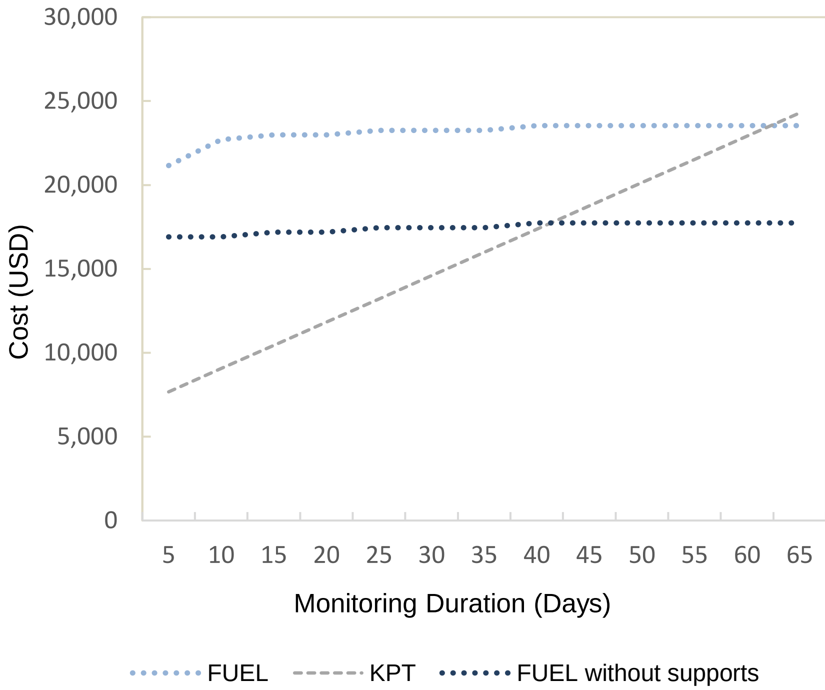

Figure 4.17 Cost vs. Monitoring Duration, FUEL and KPT, 1st study

Figure 4.17 shows a cost analysis between the FUEL and KPT for increasing monitoring duration based on data from Burkina Faso. Cost data factors in the cost of sensors, installation equipment, KPT scales, supplies, and field staff-related expenditures. If an external structural support for the FUEL system installation is not needed, the breakeven point where the KPT cost begins to exceed the FUEL is after 40 monitoring days. If supports are needed as they were in Burkina Faso where there were not sufficient roof beams in place, the breakeven point will increase to 60 monitoring days. However, if a second, third, etc. study is implemented later on and sensors and installation equipment are a sunk cost, the cost of the

FUEL will be less than the KPT regardless of the monitoring duration, and with increasing gains as duration increases, Figure 4.18.

4.5 DISCUSSION

4.5.1 FUEL Best Practices

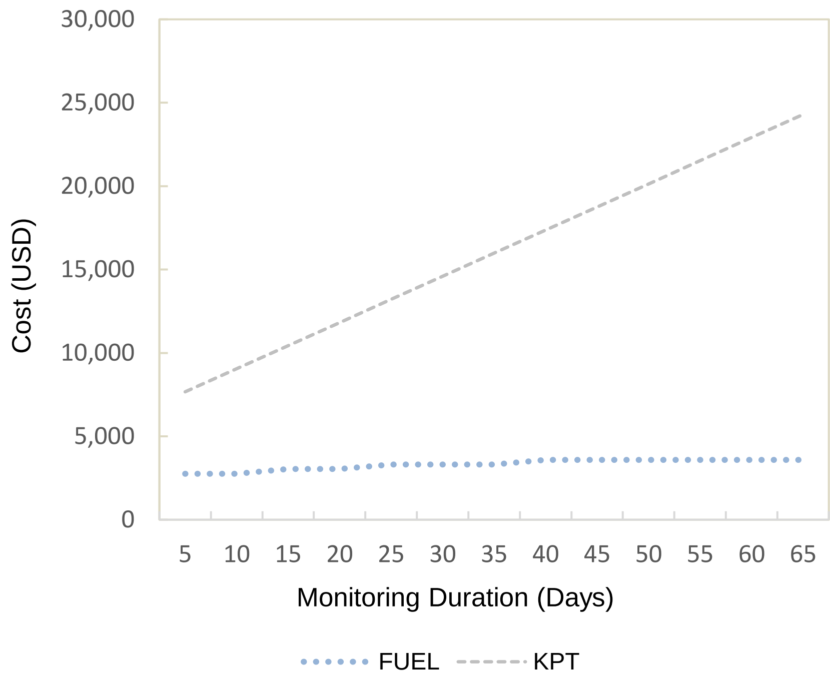

Figure 4.18 Cost vs Monitoring Duration, FUEL and KPT, 1+nth study

Results showed that the FUEL sensor worked optimally for certain monitoring conditions and fuel types. For example, the FUEL was more accurate when there was less reloading of the fuel holders, such as when monitoring LPG or when households were provided enough fuel that the holder did not have to be reloaded during the study, as in the Burkina Faso study. In conditions where households use a large amount of fuel, minimizing human-holder interaction could be achieved by increasing the size of the fuel holder to hold more fuel at a time. It was also noted it could be more accurate and easier to measure LPG using a compressive scale, as it would require less structural support and effort than hanging the tank from a tensile scale.

In the planning stages of a fuel usage or savings study, researchers or practitioners should gather location-specific information to better understand the context of where the monitoring will occur. This includes:

- Data on all cookstove and fuel types in the study community to determine how many sensors are needed per household.
- If cooking occurs indoors, outdoors, or both to decide where to install the FUEL system and what materials are needed.
- Typical kitchen size and available space for system sizing, sturdiness of roofing or other available structures for installation, and availability of local materials for manufacturing the fuel holders on-site to reduce shipping costs and time and design a holder that is more contextually and culturally integrated.

Analysis of the effects of monitoring duration on average daily fuel consumption results was conducted with the data from Uganda, where FUEL sensors were set to monitor for up to 45 days (Ventrella and MacCarty, 2019). Daily average fuel consumption was calculated over durations of 4, 10, 15, 20, and 25 days and compared to the average fuel consumption over 30 days. Results showed that the standard deviation decreased from 1.20 kg over a four-day monitoring period to 0.093 kg for a 25-day monitoring period, and the average percent error also decreased from 0.720% to 0.065%, respectively.

User training should also be implemented prior to conducting a study to ensure that the system is used correctly. This includes briefing participants on the purpose and functionality of the FUEL system, providing explicit instructions on use, and eliciting and answering clarifying questions following the session. Use instructions should include:

- Remove fuel from holder in small amounts as needed for cooking.
- Refill the holder with fuel when close to empty.
- Do not put any fuel back into the holder after removal, including partially burned or unburned fuel after cooking -- save it for the next cooking event.

4.5.2 Limitations

One limitation to the study is basing the comparison of the FUEL and KPT on the assumption that the KPT is accurate. As was outlined in the literature review, it is known that the KPT has inherent errors and does not always measure the "actual" fuel use. This is addressed by referring to the study as a 'comparison' rather than a validation, and acknowledging the potential sources of error in both methods. The intention was to compare the most common and currently accepted method of measuring fuel use with the new FUEL method. Another concern is that both survey and sensor-based methods have been found to have inherent biases, and the presence of a sensor system or visiting enumerator may modify typical usage behavior. A four-week study in Rwanda that measured the difference in usage patterns of sensor-monitored water filters and cookstoves between groups that were and were not aware that the sensors were being used found that while there was a significant difference between the water filter groups, there was no significant difference in usage between open and blind groups with cookstoves (Thomas et al., 2016). However, usage for all groups decreased over the four-week monitoring period, suggesting the value in longer-term monitoring. Overall, behavioral reactivity should be taken into consideration when conducting a sensor-based study.

The installation process for FUEL was not trivial, as the fuel holders were heavy and difficult to transport. In Burkina Faso, kitchen roofing structures were not available, which necessitated field staff to construct free-standing supports and cost unanticipated time and money. A possible solution is for field staff to give participants their sensor and holder during the training session and then visit each kitchen for installation. Fully understanding the context before study implementation can help to prevent these unanticipated outcomes, but more work is needed on ways to streamline and simplify the installation process.

4.6 CONCLUSION

Two studies were conducted to assess the viability of the FUEL sensor as compared to the KPT. On an aggregate level, FUEL was found to perform well and was comparable to the KPT, with no systematic over- or under-prediction between the two methods. The correlation on a daily level was lower than the aggregated data, which could be due to several sources of error in either the FUEL or the KPT, such as if time between household visits was slightly longer than the intended 24 hours. A cost analysis found that the breakeven point between the KPT and FUEL costs for one study was 40 monitoring days if extra infrastructure materials are not needed for FUEL. However, for any following studies where the FUELs have already been purchased, the cost for the FUEL will be below that of the KPT for any monitoring duration, suggesting long-term cost gains when using the FUEL.

It is hoped that the FUEL can be used in future studies to measure long-term fuel consumption and savings in households. Future work may include additional studies with alternative fuels, determining fuel savings as compared to a baseline stove, and conducting further validation by directly observing fuel usage in several households over a period of days to then compare to the FUEL and KPT.

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CHAPTER 5
CONCLUSION

This work has resulted in the development and testing of a sensor system to measure household level cookstove performance. To interpret data, the creation of a custom processing algorithm for data analysis was developed, verified, and validated. Initial results of a clean stove project in northern Uganda revealed insights on fuel use, stove stacking, and global warming commitment. Last, the FUEL was compared to the commonly used KPT in terms of both cost and accuracy. Chapter 2 of this thesis outlined the process of using rapid ethnographic techniques in product design, with a specific focus on the context of international development. Chapter 3 described the testing and evaluation of the FUEL system in northern Uganda, with reported metrics. Chapter 4 compared the FUEL to the KPT using studies in Uganda and Burkina Faso.

It was found that a mixed-method approach that triangulates sensor-based and ethnographic data can lead to a clearer understanding of user perspectives and avoidance of some of the issues that can cause development projects to fail. Use of ethnography can help not just to better design a technology but to examine technology development as a form of aid – perhaps certain barriers other than user acceptance are difficult to overcome (climate, political structure, etc), perhaps a program could be more effective, and perhaps nothing needs to be designed at all. Another influencing factor is the lack of regulation or standardization in this sector. To begin shifting this culture, national governments and funding organizations need to incentivize the reporting of more rigorous data on technology impact before and after a technology is disseminated. It is also of value to examine who should be leading development of technology and services. Overall, the use of rapid ethnographic methods helped to increase the methodological soundness and efficacy of the design and development of the FUEL system.

Preliminary data from Apac, Uganda indicate that the FUEL system works from a technical standpoint, was accepted by users, and can provide a range of usable performance metrics. Raw data were processed to analyze fuel consumption at the household and village level, cooking duration, global warming commitment, and firepower. Patterns of stove stacking were examined and indicated that households ‘stacking’ one improved and one traditional stove would ultimately use more fuel and produce more emissions than households cooking for the same number of people with just an improved cookstove. Although somewhat intuitive, this highlights the importance of measuring all energy devices in a household to quantify actual environmental and health effects of stove stacking. Because the sensors are transportable and intuitive to use, it is possible to conduct collaborative, ongoing projects with multiple partners to evaluate a multitude of stove and fuel types in various contexts. While the work conducted thus far has been preliminary, it demonstrates that the FUEL can be accepted and correctly used by participants and monitor for vital impact metrics, paving the way for further in-depth studies.

Comparisons between the FUEL and KPT to validate the system showed that the FUEL operates optimally under specific conditions and several key user training points, which are outlined in Chapter 4. Overall, the FUEL agreed very closely with the KPT in Burkina Faso, and slightly less well in Uganda. Lower agreement in Uganda was most likely due to increased chances for missed measurements or weight recordings in either method, as they had to fill and re-fill them several times throughout the duration of the study, whereas in Burkina Faso all fuel was provided at the beginning of the monitoring period. A cost analysis showed that implementation of the FUEL system will be significantly less costly after the second and on study using these sensors.

Future work will include adapting the system to different fuel types and geographic and cultural contexts, further validating the FUEL system, and upon validation, designing long-term studies that use FUEL to calculate regional fuel use and emissions inventories, measure the effects before and after an improved stove is implemented in a given community, and/or calculate carbon credits or ADALYs.

Regardless of whether the FUEL becomes the gold standard method for monitoring cookstove fuel consumption, it is clear that better standards, regulation, and tools are needed in the sector. It is no excuse to say that there is not enough funding in place, because no funding at all should be given unless a project can prove that it is benefitting communities. Furthermore, the desired benefits should be defined directly by the user, not just the donor or project. The development sector in general has suffered from an inability to determine what an appropriate solution is in the eyes of the user. Perhaps a useful qualifier can be adapted from Aldo Leopold's land ethic, in which he posits, "a thing is right when it tends to preserve the beauty (e.g. health and vitality), stability, and integrity of the biotic community. It is wrong when it tends otherwise" (Leopold, 1987). The same can be said for socio-cultural communities. While somewhat vague, this quote provides a starting point for a systematic assessment of technologies and services from social, environmental, and economic perspectives. As one of my applied anthropology colleagues, Nick Fisher, put it, "a reflexive development industry that primarily addresses the wants, needs, and ideas of marginalized peoples has a much greater potential to create collaborative and effective interventions than an approach in which outsiders think of an idea and use the global south as a testing ground." When working with human research subjects, ethical considerations are especially important when working with marginalized communities who may not have access to the same protections for their rights. Questions such as how should research results should feed back into communities could be further investigated to develop a standard practice for the design for development sector.

Despite these critiques, strides have been made towards improving the efficacy of the sector. DfD frameworks proposing the integration of rapid ethnographic techniques have been developed, sensor-based monitoring tools and analytics platforms are becoming increasingly common, and there is a growing demand for transparent reporting of accurate impact metrics. More work is needed in this sector, but it is hoped that this system will provide a faster, more accurate method to determining cookstove performance and adoption impacts in households.

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