An international, multi-site, longitudinal case study of the design of a sensor-based system for monitoring impacts of clean energy technologies

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The Design for Development sector, particularly in the area of clean cookstoves and fuels, has called for better monitoring tools to evaluate and promote impacts of new products. This paper presents the development and testing of the FUEL sensor designed to meet this need. A multi-site, longitudinal case study that used a mixed-methods approach was employed in Guatemala, Honduras, and Uganda to evaluate technical feasibility, system usability, and market value. We found that triangulation of ethnographic and sensor-based data improved our certainty of results, which indicated acceptable technical performance, high usability, and potential market fit. Theoretical discussions include the prevalence of pro-innovation bias and ethical considerations. Broadly, this study encourages the design community to incorporate sensor-based data and rapid ethnographic methods in Design for Development.

Keywords: user centred design, product development, engineering design, case study, cookstoves

1 Introduction

1.1 Design for Development

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Design for Development (DfD) focuses on designing technologies and services for underserved 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, such as clean water or household energy (United Nations, 2015; VanderSteen, 2008; Wood & Mattson, 2016). Technologies developed to meet these needs

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should be cost-effective and reflective of user preference while delivering high technical quality (Moses, Pakravan, & MacCarty, 2019; Wai & Siu, 2003). Because there is often a considerable geographical, socio-economic, and cultural distance between the designer and end-user, it can be challenging to design technologies and services for these contexts that sufficiently address user needs (Thomas, 2017). The inability to address these knowledge gaps can result in reduced impact and a drain on resources. Due in part to its relatively recent (post-WWII) beginnings, decentralized market (Prahalad, Di Benedetto, & 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 allocation of resources and impact evaluation in the DfD sector.

One common development project that could benefit from additional monitoring and evaluation (M&E) tools is the implementation of clean cookstoves designed for 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). In comparison, 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. Unsustainable fuel harvesting can also contribute to forest degradation and is exacerbated by the use of inefficient stoves (Lim, 2012; Masera, Bailis, Drigo, Ghilardi, & Ruiz-Mercado, 2015). Despite thousands of clean stove models developed to reduce these health and environmental impacts, adoption rates have been lower than anticipated (Mobarak, Dwivedi, Bailis, Hildemann, & Miller, 2012) due to a mismatch between the design and user preferences (Hanna, Duflo, & Greenstone, 2012). In addition, clean stoves are more commonly tested in a laboratory setting, and in-field performance often lacks standardized verification. It is typically much more challenging to evaluate stove performance and adoption under real-world conditions, which can vary significantly depending on the local context. Because of the gap between theoretical and actual outcomes, the sector, including researchers, non-government organizations (NGOs), funding organizations, and climate financing institutions (e.g. Gold Standard), 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).

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 of real-world performance indicators (Lozier et al., 2016; Ruiz-Mercado, Canuz, Walker, & Smith, 2013; Thomas et al., 2013; Wilson et al., 2015). To monitor cookstoves, sensors that autonomously measure cookstove temperature as a proxy for usage and adoption, and indoor air pollution monitors have been deployed (Pillarisetti et al., 2017; Ruiz-Mercado, Canuz, & Smith, 2012). However, there has been no sensor-based technology developed to directly measure fuel consumption, which is a key predictor of stove performance. This unaddressed need ultimately motivated the development of the Fuel Use Electronic Logger (FUEL), a sensor system that helps to quantify the impacts of clean stoves on human health and the environment in terms of cooking duration, fuel consumption, and emissions (Figure 1). The system uses a logging load cell to monitor and record fuel weight and an algorithm to translate these raw values into aggregated measures of fuel consumption. To capture all fuel use activity, the system requires that fuel be added and removed by the user in a designated container. Accurate monitoring required usability testing to evaluate whether the system could be integrated with current user practices. To assess usability, technical feasibility, and market value, a multi-site, longitudinal case study was conducted.

1.2 Rapid ethnographic methods

Stemming primarily from the field of anthropology, ethnography is the study of people and their culture, and anthropologists rely on ethnographic methods to systematically understand these domains. The concept of rapid ethnographic methods was created as an adaption of and deviation from the longer, more in-depth traditional ethnography for the specific purpose of product design (Ball & Ormerod, 2000; Hughes, King, Rodden, & Andersen, 1995) and is characterized by a substantial narrowing of research scope, data triangulation, and collaborative, computerized data collection and analysis (Millen, 2000). Rapid ethnographic data can be incorporated into case study methodology, which is empirical, context-specific, and used to address 'how' and 'why' questions (Yin, 2009). Once collected, ethnographic data can be interpreted using thematic coding where the researcher identifies and systematizes common themes or patterns in their data (Attride-Stirling, 2001).

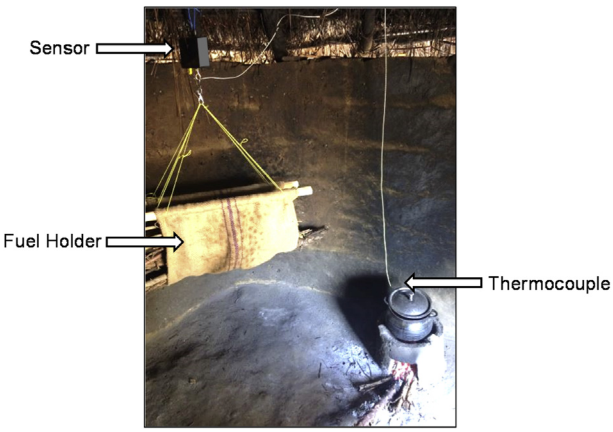

Figure 1 FUEL system (Ventrella, 2018)

Rapid ethnographic techniques are useful as compared to conducting a traditional ethnography in terms of providing time and cost savings, making them a good fit for DfD projects with strict timeline and budget constraints (Bernard, 2006; Coleman, Clarkson, Dong, & Cassim, 2007; Daae & Boks, 2015; Isaacs, 2013). However, these techniques can sacrifice rigor in terms of representativeness, accuracy, and validity (Isaacs, 2013; Shah, 2018). 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 using rapid ethnographic techniques and conducting short-term case studies, triangulation of multiple data sources or methods, especially a combination of qualitative and quantitative data can be of use and is often referred to as a mixed-methods approach (Bernard, 2006; Yazan, 2015). Quantitative methods such as sensor-based monitoring or numerical surveys can aid the researcher in collecting more objective, statistically significant data that has higher generalizability to a larger sample as compared to qualitative methods. These methods 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 a deeper understanding of the 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 & Ormerod, 2000; Creswell & Creswell, 2018; Sovacool, Axsen, & Sorrell, 2018).

A non-exhaustive overview of widely used ethnographic methods and their intended purposes and limitations is shown in Table 1 (Bernard, 2006; Daae & Boks, 2015; Dicks, 2002; Sovacool et al., 2018).

1.3 Gaps in Design for Development research

Despite the growing use of a mixed-methods approach to technology design, there is a need for more empirical examples that formalize and systematize this process (Jagtap, 2018; Stanistreet et al., 2015). Studies such as these for underserved contexts exist but generally focus on evaluating the already developed technology (O'Reilly, Louis, Thomas, & 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 & Rosenthal, 1998). In addition, engineers and designers are often not formally trained to conduct ethnographic-based case studies

Table 1 Ethnographic methods

Method	*Purpose*	*Limitations*	*Procedure*	*Source*
Interviews	Collecting data related to needs and expectations of users; evaluation of design alternatives, prototypes, final design	Subject to interviewer and social desirability bias	The researcher designs a set of qualitative and/or quantitative questions that are verbally discussed with respondents in a conversational manner.	Sovacool et al. (2018)
Surveys	Collecting structured data related to needs and expectations of users; evaluation of design alternatives, final design	Subject to interviewer and social desirability bias, difficulties in capturing the 'why' of a phenomenon	The researcher designs a standardized set of qualitative and/or quantitative questions to administer to respondents within a target group.	Sovacool et al. (2018); Krumpal (2013)
Focus groups	Small groups of various stakeholders (5–8 people) to discuss issues and requirements, identify areas of (dis)agreement	Subject to interviewer bias, group responses may be different from individual	The researcher facilitates a small group discussion based on specific themes or research questions.	Daae & Boks (2015); Sovacool et al. (2018);
Participant observation	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	The researcher spends time with participants observing daily tasks/activities and behaviors. Can either be a participating observer (actively engaging in activities) or observing participant (not actively engaging).	Bernard (2006); Daae & Boks (2015); Sovacool et al. (2018);
Focal follow	Collecting time-stamped information concerning a specific sub-task	Can be time intensive, immersion difficult when outside the culture of study	The researcher spends time with the 'focal' who is performing a specified task and is required to document sub-tasks, time spent on each, and general observations	Altmann (1974)
Usability testing	Collecting quantified data related to measurable usability criteria	Sample and testing environment may not be representative of real- life scenario and population	The researcher conducts a standardized test in a controlled or uncontrolled setting to test for various quantifiable product variables	Dicks (2002)

(Mink, Diehl, & Kandachar, 2018). To account for this lack of training, more comprehensive detail is needed on data collection and methods throughout the design process to serve as empirical examples (Kujala, 2003; Rosenthal & Capper, 2006). 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.

1.4 Study goals

This study will examine the process taken to address the problem of monitoring and evaluation in the clean cooking and fuels sector. The FUEL system was assessed in terms of technical feasibility, usability, and market fit to answer the following questions: *1) How does the FUEL perform in a real-world setting? 2) What features/attributes make the FUEL system (un)usable?* and *3) How does the FUEL compare with other comparable, tools for cookstove monitoring?* This study describes the study design, methods, and analysis used to support the design, development, and testing of a fuel monitoring system. From these analyses, we will provide broader reflections and design considerations that can contribute to frameworks for integrating qualitative and quantitative methods in multi-sited contexts.

2 Review of monitoring technologies

Here, we summarize a narrative literature review of current monitoring methods in the clean cooking sector. As discussed later, these data were then used to corroborate semi-structured interview data as well as observational data.

A narrative review, in which the researcher synthesizes data on a topic or theme familiar to them, allows for in-depth insights. 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 a fairly new concept, 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. Specific search keywords within academic and non-academic sources included 'cookstoves', 'cookstove adoption', 'cookstove impact', and 'cookstove monitoring'. Search terms within these articles included 'monitoring', 'sensor', and 'challenges'.

Existing methods for monitoring cookstove performance and adoption include surveys, temperature sensors to monitor cooking activity, manual fuel measurements, and emission sensors. These tools are used by practitioners to monitor a variety of performance indicators, including stove adoption, fuel use, time spent cooking, air pollution, and impact on human health. Measurements of fuel savings with an improved stove as compared to a baseline can also be extrapolated to carbon credits, which are a financing mechanism for some NGOs.

While surveys can be used to collect a wide variety of indicators, challenges include reporting biases (Gould & Lewis, 1985; Thomas et al., 2013; Wilson et al., 2015). The use of temperature sensors, such as Berkeley Air 'Stove Use Monitors' (SUMs), Nexleaf 'Stove Trace', and SweetSense sensors, can provide more objective measurements than surveys but may result in malfunction or data loss due to high cookstove temperatures, theft, and improper training (Dickinson et al., 2015; Ruiz-Mercado et al., 2012; Simons, Beltramo, Blalock, & Levine, 2014). To measure fuel consumption, surveys are sometimes used but have been found to be subject to bias. The Kitchen Performance Test (KPT), which requires manual measurements of fuel use in households over several days, is a more commonly accepted method of monitoring fuel use but is time-intensive and error-prone (Bailis et al., 2018; Granderson, Sandhu, Vasquez, Ramirez, & Smith, 2009). Emission sensors can be difficult to transport and costly.

The shortcomings in existing tools have driven demand for more robust tools to measure and document long-term regional fuel consumption (Masera et al., 2015). Specific requirements identified in the literature include a solution that would be cost and time-effective, accurate, long-term, able to capture seasonal or other variations over time, and able to measure desired metrics.

3 Methods

The design, development, and testing of the FUEL system occurred throughout three research phases: 1) Design Requirements, 2) Product Design, and 3) Evaluation, with the goal of creating a usable solution that would adequately address needs in different geographic and monitoring contexts. While still context-dependent, 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 in a multi-site case study and roughly followed the stages of the design process. Table 2 shows the overall progression of research phases, research goals, and methods used. 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.

Table 2 Research phases, objectives, and methods

Naming Convention	*Location & Time Frame*	*Steps in Design Process*	*Methods of Analysis*	*Research Focus*	*Research Outcomes*
Phase 1: Design Requirements	Guatemala: June 2016	• Problem Definition • Collect Information (sector issues)	• Participant observation • Semi-structured interviews	What are general challenges and barriers in the clean stoves and fuels sector?	Evidence highlighting a key challenge
Phase 2: Product Design	Oregon (product design)/ Global (interviews): Jan 2017–April 2018	• Collect Information (marketability, usability) • Brainstorm/Analyze • Develop Solutions	• Semi-structured interviews (n = 50)	What are challenges practitioners face when trying to evaluate stove impact?	Evaluation and selection of design ideas
Phase 3a: Evaluation	Honduras: May 2017	• Collect Information (usability, feasibility) • Testing/Feedback • Improve	• Participant observation • Semi-structured interviews (n = 4) • Focal follow (n = 3) • FUEL monitoring (n = 4, t = 30 days)	Evaluate technical feasibility and usability of solution	Potential need for system re-design
Phase 3b: Evaluation	Uganda: August 2017	• Collect Information (usability, feasibility) • Testing/Feedback • Improve	• Participant observation • Semi-structured interviews • Focal follow (n = 2) • Surveys (n = 50) • FUEL monitoring (n = 85, t = 30 days)	Evaluate technical feasibility and usability at a larger scale in a different context (Eastern Africa)	Metric of no. of sensors fully working, potential need for system re-design
Phase 3c: Evaluation	Uganda: May 2018	• Testing/Feedback	• Surveys (n = 85)	Corroborate usability findings from Phase 3b	Understand long-term usability

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

3.1 Phase 1 – design requirements

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. The study was part of a household energy course offered through the Humanitarian Engineering Program at Oregon State University, with the objective of engaging students in the production and testing of clean energy technologies in an immersive setting (Oregon State University, n.d.). 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, manufacturing, and distribution of improved cookstoves for rural households, partnered with the university to facilitate the course. The methods used during this research phase included participant observation and semi-structured 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 adequately situated to grasp and define the problem.

3.2 Phase 2 – product design

The next phase focused on the second step of the design process: collecting additional information on user requirements and design specifications, with the goals of further defining and quantifying the magnitude of the problem, evaluating current market needs in the stove sector, and creating design concepts. Following initial brainstorming, the main challenges within the sector and the feasibility of the selected idea were assessed using semi-structured interviews with global stakeholders in the sector, either in person or through video or phone calls.

3.3 Phase 3 – evaluation

Based on the data collected during Phases 1 and 2, we chose the FUEL system from a larger set of brainstormed alternatives as the most viable design. Therefore, the primary goals of the remaining phases were to test the technical feasibility, usability, and market value of this solution in several use contexts and to identify any prominent design issues with the sensor or storage system before scaling.

3.3.1 Phase 3a – Honduras, May 2017

Honduras was chosen as a test site due to strong partnerships with StoveTeam, our previous partner in Guatemala, who runs a factory there. In addition, Honduras has been a focus region of clean stove programs, making it a representative area of study.

The selected community, El Eden, is a rural village located about 30 km north of the city of Copan Ruinas in a valley where households planted their crops on a steep mountainside and regularly navigated the terrain to plant or harvest crops and collect growingly scarce firewood. Four households from El Ede were chosen for the study by convenience sampling. 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 guide usability testing of the fuel storage system, a list of design questions and resulting design specifications were created, as seen in Table 3. The methods used to answer these questions included participant observation, semi-structured interviews, focal follow, and photography.

One specific research objective was to evaluate if the fuel holder could be adapted to store and transport fuel during collection trips, and if doing so would provide added utility and value for participants. A focal follow was conducted with four participants to study the cooking and firewood collection process as a system and understand how the FUEL could integrate into the current system with the least intrusion and highest utility.

Semi-structured interviews were also conducted with each participant to elicit feedback on FUEL usability. Thematically coded interview data were then

Table 3 FUEL system design attributes

Design Consideration	*Questions Raised*	*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?	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?	Adaptable to storage habits
Structural support	Are household roof structures available and sturdy enough to support system?	Max weight capacity, system

triangulated with quantitative usage data from the FUEL sensors to corroborate whether positive answers were associated with higher use and vice versa.

3.3.2 Phase 3b – 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 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 aims to distribute 150,000 clean stoves within 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 in 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 purchasing group to reduce sampling bias.

Training sessions were organized 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 semi-structured interviews. Interview 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 next training session at the second study site.

To inform system usability and post-processing of data, participant observation, and semi-structured interviews were integrated throughout the study. A usability survey was conducted, and data were analyzed using thematic coding for open-ended questions and quantitative analysis for Likert scale questions. 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 this context. Written observations were supplemented with time-stamped photographs.

3.3.3 Phase 3c - 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 3b. An objective of the survey was to record the current uses of the fuel holder when participants were not required to use them. Survey data were analyzed using thematic coding. A focus group of ten participants who used the FUEL less than 60% of the monitoring days as indicated by sensor data from Phase 3b was also planned, with the objective of understanding why people did not use the system and eliciting feedback on what could have been done to improve their experience.

4 Results

4.1 Phase 1, design requirements, 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. During Phase 1, Oregon State University student researchers worked with the NGO Stove Team International to quantify various impact metrics, using open-ended and Likert scale surveys to assess usability, and temperature sensors to monitor stove adoption. 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 & Strauss, 1990; Glaser & Strauss, 1967) to enable open-ended, non-prescriptive problem identification. 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.

While in Guatemala, participant observation also helped to reveal the shortcomings of current monitoring methods commonly used in the sector, which were corroborated with a narrative literature review as outlined in Section 2. It was observed that baseline surveys were prone to bias and provided inaccurate guesses of time spent collecting firewood, the amount of firewood used, and how often stoves were being used. Placement and installation of the temperature sensors were 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.

From these initial observations, we decided to implement a load cell to monitor fuel consumption. Our analysis highlighted the central importance of fuel in both the cooking process and as an indicator of multiple metrics of cookstove performance. Upon evaluation of brainstormed ideas, using a load cell to monitor fuel use was identified as the most likely to meet requirements as defined through the literature review and stakeholder interviews, 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, based on participant observation and semi-structured interview data from Phase 1. We initially hypothesized that a logging load cell could be used to determine:

H1 the frequency of fuel collection events and amount of fuel collected per event

H2 fuel consumption per cooking event

H3 duration of cooking events and number of events, with temperature as a backup measure

It was also hypothesized that the container for fuel could:

H4 connect to a load cell in tension or compression (Figure 2)

H5 double as a carrier during fuelwood collection

H6 be usable for participants with minimal added effort.

4.2 Phase 2, product design, Oregon/Global 2017–2018

On-site research included the development of the FUEL prototype for future testing, conducting stakeholder interviews to define needs and resulting design implications, and compiling a competitive analysis of similar tools. The initial prototype system included the load cell, electronics, thermocouple, and

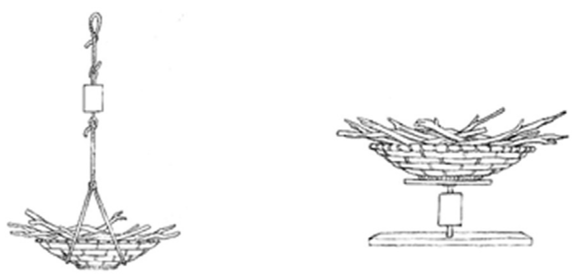

Figure 2 Initial concepts for tensile and compressive fuel storage

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, 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 flexibility for accommodating different locations and fuel types.
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 should 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 & 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 and carbon credits.

A comparison of monitoring methods, including the FUEL, in the clean cooking and fuels sector is shown in Table 4. Emission sensors are also used in cookstove M&E initiatives, but as the focus was on monitoring adoption and fuel consumption, they were not included in this analysis.

Table 4 indicates that comparable sensors are listed at a similar price point to the FUEL and have a similar battery life and lifetime. Thematic coding of interviews with NGOs, donors, and climate financing organizations and observation in Guatemala revealed similar themes uncovered in the literature, including problems with existing M&E methods and design requirements of solutions that were intuitive for field staff and easily processed data.

Table 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	Stove usage	Stove usage	Stove usage	Fuel and stove usage
Fuel usage	✓	✓				✓
Stove usage		✓	✓	✓	✓	✓
Wireless upload				✓	✓	✓
Autonomous		✓		✓	✓	✓
[h]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 h (battery), indefinitely (solar)[b]	6−18 months[d]	3 months[f]

[a] iButton Link Technology, 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.
[h] Here, we assumed 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. Price for the temperature sensor varies based on temperature rating, and duration varies based on the rate of logging.

4.3 Phase 3, Honduras, May 2017

Following the sensor design, results from Phase 3 provided insights on FUEL system sizing and usability. Photographic data sent 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 H1.

For the focal follow, 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. 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 H1. The data also indicated that H5, adapting the fuel carrier to a collection device, would be difficult because of size 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 H5 in this region.

Semi-structured interviews indicated that the participants were initially accepting of and interested in the fuel holder. During household check-in visits, participants were asked questions about what features of the system they thought could be improved 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. 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 semi-structured 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 cooking with the stove for most of the monitoring period. In comparison, the remaining three households used the holder 59%, 84%, and 100% of the days.

4.4 Phase 4a – Uganda, August 2017

Results from Phase 4a provided information on system sizing, installation, and usability via a training session, interviews, surveys, and participant observation. During the training and feedback session, several Ugandan employees of the NGO were present as translators. The lead researcher recorded observational data and question responses manually and audio-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 on 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.

During the training and semi-structured 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. Participant observation and semi-structured interview data showed that women would often chop wood into smaller pieces directly before cooking a meal, suggesting that wood might not be directly placed into the holder after collection and serving as evidence towards invalidating H1 for this study context. Participant observation of people preparing and cooking meals revealed some potential sources of uncertainty in data analysis, such as the use of fire starter and smaller kindling that might not be stored in the holder and therefore not measured by the load cell.

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 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-ended and fixed questions. Open-ended questions allowed for more freedom in responses and were used to bring up themes not already considered in the survey design, while fixed choice questions provided 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 min each to conduct. Results showed that when asked how the holder was working for them so far given a scale of ✔-, ✔, or ✔+, the options chosen were 0%, 6%, and 94%, respectively. However, 10% of households stated that they had experienced a problem with the system, 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 3.

Reported benefits, as shown in Figure 4, 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 validated H4. These data were corroborated by observations of typical wood storage habits before FUEL installation, in which several households were observed using bricks to elevate wood off the ground.

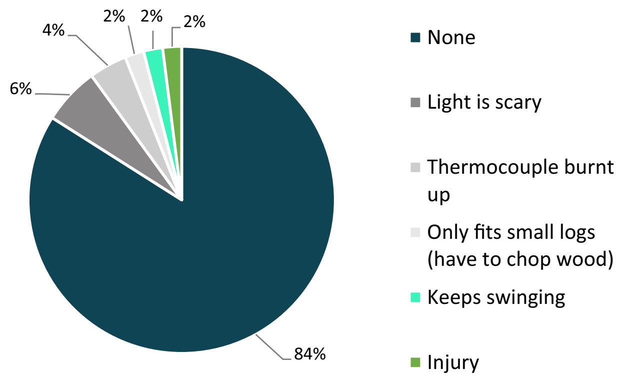

Figure 3 Perceived challenges of fuel holder. Apac, Uganda, 2017

For the focal follow of firewood collection, 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. This method yielded similar findings of 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 significantly deviated from storing in a bag and was additional evidence towards invalidating H5 in this context.

For the second focal follow, the lead researcher and two field staff from ILF sat in the kitchen during meal preparation and cooking 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. For the second focal follow of the woman using the FUEL while preparing a

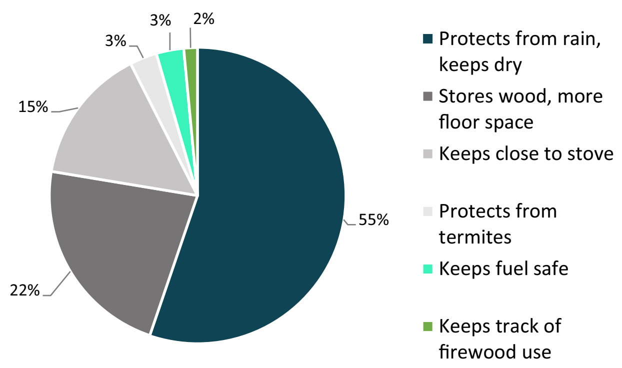

Figure 4 Perceived benefits of fuel holder. Apac, Uganda, 2017

meal, it was observed that while the user was able to add and remove wood from the holder, fuel would sometimes catch on the burlap material. Despite this observation, the participant reported that she did not have difficulty adding or removing fuel. She did inquire as to whether she had to add wood to the holder if she had chopped it while cooking and whether she could use fuel from one holder in a different stove. The focal follow also highlighted the potential difficulty of correlating weight reductions to cooking duration and indicated that temperature measurement would be necessary for accurate data on cookstove duration and system use, H3.

4.5 Phase 4b – Uganda, May 2018

Follow-up surveys conducted 8 months after the initial study were designed in Magpi, an online survey design platform that allowed local Ugandan field staff to remotely collect and transmit data to the researchers. ILF field staff from Phase 3b conducted the surveys without the lead researcher present, spending approximately 20 min with each participant. Surveys included a mix of fixed choice and open-ended questions, which were guided by the responses from the open-ended surveys administered in Phase 3b. 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. Results and implications from the follow-up survey are briefly discussed.

4.5.1 Storage content

Enumerators were asked to observe the contents stored in the holder as they conducted surveys in each household kitchen (Figure 5). 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 78% of households were still storing wood in the holder eight months after the end of the study period. Of the remaining participating households, 9%

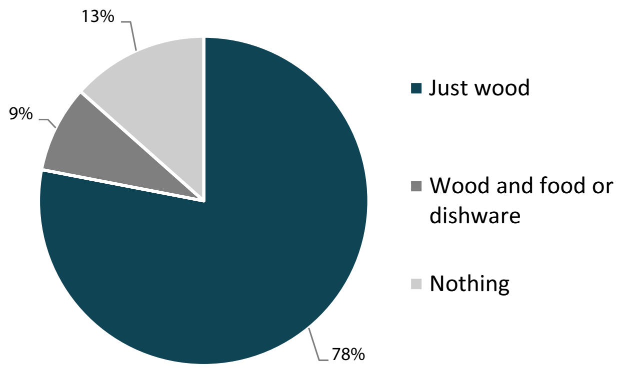

Figure 5 Observed Holder Storage Content after 8 months. Apac, Uganda, 2018

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, four 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 the use of the holder continued long after the end of the study period.

4.5.2 Perceived benefits

In response to fixed-choice questions, 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.

4.5.3 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 this task.

Sensor-based 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.

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

In summary, Table 5 shows how methods used in each phase informed validation or invalidation of each hypothesis. In the 'Evidence Towards Validation'

Table 5 Summary of methods and hypothesis (In)Validation

	Hypothesis	*Phase*	*Method(s)*	*Evidence for validation?*
Technical feasibility Load cell could be used to determine:	H1 frequency and amount of fuel collected	3a, Honduras	photographic data	X
			focal follow	X
		3b, Uganda	participant observation	X
			semi-structured interviews	X
	H2 fuel consumption per cooking event	3a, Honduras	sensor-based	✓
		3b, Uganda	sensor-based	✓
	H3 duration and quantity of daily cooking events	3b, Uganda	participant observation	✓ (with temp)
			focal follow	✓ (with temp)
Usability Fuel container would:	H4 connect to a load cell in tension or compression (tension selected)	3b, Uganda	participant observation	✓[a]
			semi-structured interviews	✓[b]
	H5 double as a carrier during fuelwood collection	3a, Honduras	focal follow	X
		3b, Uganda	focal follow	X
	H6 be usable for participants	3a, Honduras	semi-structured interviews	✓[c]
			participant observation	✓
			sensor-based	X/✓[d]
		3b, Uganda	semi-structured interviews	✓[b]
			survey	✓[e]
			participant observation	✓
			sensor-based	✓[f]
		3c, 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.

column, footnotes provide examples from our results that helped to validate ('✓') or invalidate ('X') each hypothesis.

5 Discussion

Our discussion will identify design change suggestions specific to the FUEL and overarching themes that can inform DfD frameworks, paradigms, and choice of methods. The ultimate result of this research was the development of the FUEL sensor to help address the gap in available M&E tools and provide a more comprehensive understanding of cookstove impacts.

5.1 Study-specific findings

In the context of this study, a combination of qualitative and quantitative methods elucidated several aspects of product usability. Triangulation of sensor and survey data indicated that the holder was usable for the majority of participants. 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. Observing localized tasks that were integral to the cooking and, therefore, monitoring process allowed for more targeted brainstorming, informing the idea of remotely weighing fuel. Observational data resulted in the development of an algorithm that correctly accounted for various use cases and improved system accuracy (Zhang, Zhao, & Ventrella, 2018). In terms of the competitive analysis, it was found that the cost and lifetime of FUEL were comparable to similar sensors for monitoring usage of clean cookstoves. In addition, FUEL is the only existing technology that can autonomously monitor fuel consumption.

5.2 Resulting system improvements

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

- *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 it. This problem 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.
- *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 of the logging load cell.
- *Electronics/data storage/transmission:* Based on participants' fear of the LEDs and uncertainty of whether the sensor was actually logging, an 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 deployments or removed altogether. In response to stakeholder requirements, a wireless data transmission system and analysis platform are currently under development to enable easier data transmission.

- *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 parallel studies conducted in Uganda and Burkina Faso 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, 2019).

5.3 Limitations

A previous review of ethical concerns in ethnographic design research included supporting user inclusion and consideration of the 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). Although a useful tool, ethnographic investigation still raises several ethical considerations that should be addressed.

- The positionality of the researcher can 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.
- 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. 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 broader 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.

A second limitation is the generalizability of this process to other projects. However, it is not necessary to exactly replicate the approach used for this study. The ability and necessity of using certain rapid ethnographic methods depend on the research question, as some methods are better suited for certain types of questions, and the available time and financial resources. A single study location, use of fewer methods, and/or a shorter time frame may be sufficient depending on the context. Fewer methods, study locations, or smaller sample sizes can also be justified once data saturation has been reached (Fusch & Ness, 2015). Despite these suggestions, the process of designing for contexts outside of what is familiar is often inherently time-consuming and resource intensive. Therefore, in contexts where products are locally demanded, they should ideally be locally designed.

During the follow-up surveys, several participants had inquired about the result of the FUEL data and the implications for their health. These results helped to inform the idea of integrating a feedback mechanism for participants into the system design. Further consideration for the democratization of tools and data and determining how best to share these with stakeholders is also needed (Sawicki & 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 be integrated into a household for a long time. Regardless, 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 & Smith, 2018). Further work is also needed to assess and incorporate ethics into DfD contexts.

5.4 *Triangulation*

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 & 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 et al., 2018). Over-formalized methods, which may discourage more casual, open conversations and inclusivity of participants, demand that a balance be found in systematized, "statistically significant" data and informal but richer contextual data (Gregory, 2018). Reflection of the design process also led to the identification of more general design considerations that build on preexisting theory.

5.5 *Reflections on design theory and resulting considerations*

A synthesis of data from participant observation, focal follow, and semi-structured interviews informed the 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 efficient and cost-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 semi-structured 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 induce fear. Findings of contextual and aesthetic concerns agree with earlier studies that have observed this phenomenon in similar settings and have called for more emphasis on recognizing local cultural context and meaning in design (Kujala, 2009). A combination of identifying the localized socio-cultural implications during early prototyping phases and an adequate explanation of the technology's function can help to increase user trust and willingness to adopt.

Another finding was the 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. 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 in its efficacy and lower barriers to adoption.

6 Conclusion

This paper details the design, development, and testing of a sensor system for measuring fuel consumption and cookstove use in underserved contexts, identifying appropriate tools and methods applicable through the use of a multi-site, longitudinal case study. Context-based data guided us to invent a solution that addresses business, technology, and user requirements in impact monitoring for DfD. We found that users were generally accepting of the FUEL system, as evidenced by high sensor-measured usage rates and continued use of the fuel holder post-study. Based on our ethnographic findings we suggested several design changes to further increase product efficacy, including wireless data transmission, removing the blinking LED, and adding a component to simplify the process of removing fuel from the holder. One limitation discussed is the ethical implications of conducting user-based research, especially with marginalized populations. While several methods are suggested for conducting ethical studies, such as relying on local field staff to conduct parts of the ethnographic study, further research is needed on ways to ensure that intended users are driving the solutions.

In terms of methodology, our certainty of the survey results was improved through the triangulation of ethnographic data with sensor-based data. Triangulation also 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 allowed us to more confidently rely on our sensor data for more generalizable findings across cultural, geographic, and economic contexts. Possible reasons for when sensor usage was measured to be low were contextualized using survey and participant observation data and resulted in several design changes. 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 as to why certain trends are occurring.

These case studies 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 educational material that directly addresses concerns, as well as incorporating visual or other sensory cues into technology to increase user trust. Ultimately, this case study resulted in the design and evaluation of a new tool that helps fill a gap in understanding the impacts of clean energy technologies worldwide.

Declaration of Competing Interest

The authors have a conflict of interest because they are in partnership with a company that manufactures and sells sensors like the ones in this study.

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