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DEVELOPMENT AND PILOT STUDY OF AN INTEGRATED SENSOR SYSTEM TO MEASURE FUEL CONSUMPTION AND COOKSTOVE USE

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ABSTRACT

Accurate, accessible methods for monitoring and evaluation of improved cookstoves are necessary to optimize designs, quantify impacts, and ensure programmatic success. Despite recent advances in cookstove monitoring technologies, there are no existing devices that autonomously measure fuel use in a household over time and this important metric continues to rely on in-person visits to conduct measurements by hand. To address this need, researchers at Oregon State University and Waltech Systems have developed the Fuel, Usage, and Emissions Logger (FUEL), an integrated sensor platform that quantifies fuel consumption and cookstove use by monitoring the mass of the household's fuel supply with a load cell and the cookstove body temperature with a thermocouple. Following a proof-of-concept study of five prototypes in Honduras, a pilot study of one hundred prototypes was conducted in the Apac District of northern Uganda for one month. The results were used to evaluate user engagement with the system, verify technical performance, and develop algorithms to quantify fuel consumption and stove usage over time. Due to external hardware malfunctions, 31% of the deployed FUEL sensors did not record data. However, results from the remaining 69% of sensors indicated that 82% of households used the sensor consistently for a cumulative 2188 days. Preliminary results report an average daily fuel consumption of 6.3 ± 1.9 kg across households. Detailed analysis algorithms are still under development. With higher quality external hardware, it is expected that FUEL will perform as anticipated, providing long-term, quantitative data on cookstove adoption, fuel consumption, and emissions.

INTRODUCTION

Improved fuels and cookstoves have been designed and recently disseminated in 80 million households globally. These projects seek to mitigate the harmful health and environmental impacts of traditional biomass cooking, which contribute up to 8% of anthropogenic climate change, and are attributed to 3.5 million premature deaths every year from smoke inhalation [1,2]. Despite the high number of cookstoves deployed, it is often unclear to what extent intended users ultimately adopt various improved cookstove designs or to what extent these displace traditional methods. The technical performance of improved stoves in a real-use setting is also not well characterized. Therefore, objective, affordable, and unobtrusive monitoring is needed to measure in-field performance metrics and optimize designs to increase frequently insufficient rates of user acceptance [3-8]. Some of the most important performance metrics include cookstove use frequency, stove stacking, fuel consumption, and emissions [6,9,10].

Traditionally, qualitative surveys have been used as a relatively easy and inexpensive method to measure these and explore cookstove adoption and impact. Although important, the use of only qualitative methods to assess stove performance can be subject to bias and result in higher uncertainties on the potential health and environmental impacts [11]. Therefore, researchers and project implementers have acknowledged the importance of supplementing qualitative data with quantitative monitoring and evaluation in the cookstove sector, and have called for more objective tools to better understand adoption and in-field performance [12-16].

To meet this need, several autonomous sensor-based technologies have recently been developed to monitor performance over time at the household level. These include temperature and emissions sensors that generate logs of cookstove body temperature as a proxy for use, and quantify ambient air quality or personal exposure. However, to date there is still no sensor-based technology available to directly measure one of the most important metrics of programmatic efficacy: fuel consumption. Despite the strong need to evaluate fuel consumption in real-use conditions, only a minority of stove evaluations do so because of challenges in capturing accurate and long-term data [17,18].

This paper presents research and development of the Fuel, Usage and Emissions Logger (FUEL), a novel sensor-based system designed to meet this need by logging the mass of a household's fuel supply and cookstove temperature over time to quantify fuel consumption, cookstove adoption and use, and extrapolate to emissions. This paper will discuss the use of FUEL to determine key performance metrics as compared to current monitoring methods in the sector and their limitations. It will also discuss the function, method of installation, data analysis, and preliminary use and technical performance results from a field study of 100 sensors in northern Uganda. It will highlight use of the FUEL system to aid in the goal of better understanding technical performance and adoption, while increasing the transparency and impact of improved cookstove projects.

BACKGROUND

Stakeholders at all levels in the global clean cooking sector ranging from project implementers to monitoring organizations to funding bodies are beginning to advocate for more objective quantitative measures of technical performance and adoption to prove or improve the efficacy of projects [19]. This efficacy is defined in terms of metrics that indicate the overall performance of a cookstove project and include adoption and usage rates, displacement levels of traditional methods and stove stacking, time savings, fuel consumption, and emissions reductions. These metrics are currently quantified using a variety of methods, including household surveys, the Kitchen Performance Test, and sensor-based monitoring.

Program Monitoring & Evaluation Metrics

There is presently an effort by the International Organization for Standardization (ISO) to develop international standards for clean cookstoves and clean cooking solutions through the Technical Advisory Group 285 [20]. This group is working to develop a set of comprehensive metrics and testing methods needed to evaluate cookstove performance. These metrics include cookstove adoption, displacement and stove stacking, time, fuel consumption, and emissions.

Adoption and Usage. The frequency with which users will adopt and use a cookstove over a sustained period of time is a direct function of the usability of the technology [21]. A design that does not meet a user's needs will not be regularly used and therefore not generate the intended impacts. Therefore, measuring the adoption and usage rates of improved cookstoves is critical to understanding the impact of a cookstove project. The adoption process is captured in the diffusion of innovation theory, which describes the dynamic variation in how an innovation is communicated and adopted over time [22]. For stoves and fuels, adoption has been divided into three stages; acceptance, initial use, and sustained use [6,23]. Assessing the evolution of technology adoption necessitates long-term monitoring to fully capture seasonal variability and sustained use [3,24-26]. For example, a study conducted in rural Mexico that measured clean cookstove adoption found that full saturation of sustained use was reached after 4 months [28].

Adoption is generally quantified by the timing, variety, frequency, and consistency of use over time [6,28,29]. This can be measured using cookstove temperature as a proxy for cooking events and duration, where a cookstove body temperature elevated above a specified threshold relative to ambient indicates a cooking event, or stove "on" condition. The number of events is aggregated by unit of time (per day, week, month) to measure long-term adoption.

Displacement and Stove Stacking. Stove stacking occurs when a household uses multiple devices for cooking and heating, and is more common than complete displacement of traditional cookstoves in households that have access to multiple cooking devices [30,31]. This is akin to the idea that households in higher income areas have many cooking devices in their kitchens, each designed for specialized tasks (e.g. stove, oven, coffee maker, microwave, toaster). Because households may stack multiple cooking devices for use with different cooking tasks, which can greatly reduce potential impacts, it is necessary to measure the use and performance of all cooking devices in the household to fully capture actual health and environmental impacts [33]. Displacement and stacking can be measured through survey-based methods or by monitoring the adoption and use of each device in the household.

Time. Cooking time can be broken into several subtasks, all of which contribute to the total cooking duration. These sub-tasks include firewood collection, food preparation, fire-starting, cooking or reheating food, and tending the stove during the cooking process. Multi-tasking may also occur during these sub-tasks, including caring for children or completing additional chores. With a traditional stove, women generally spend at least 5 hours each day collecting firewood, and preparing and cooking meals [34]. In addition, cooking can extend to additional tasks that require fuel, including space heating or boiling water for drinking [35]. One potential benefit of an improved stove is that it could decrease the time spent collecting firewood by reducing the amount of wood used per cooking event, shorten cooking duration, or allow for more free time to perform other tasks instead of tending the stove or cooking. Time spent on cooking tasks can be measured using surveys, controlled cooking tests [36], or the time allocation method [37], in which a researcher in the field observes and records the duration of each task. Quantitative monitoring of time spent cooking, in addition to time spent on the related activities, can provide a more accurate depiction of the process.

Fuel Consumption. A key component of the cooking process is the fuel collection and use. Fuel collection or purchase represents cost, time, and often significant effort for the user [38]. In cases of nonrenewable wood harvest, collection can also lead to environmental degradation and deforestation [39]. Improved stoves are usually designed to increase heat transfer efficiency and reduce fuel use. Therefore, directly quantifying fuel consumption can help to indicate whether this objective is being met. The type of fuel used varies based on socio-economic status and availability, but can include various wood types, charcoal, coal, biogas, and LPG. Numerous past studies have attempted to quantify fuel consumption by manually weighing fuel or using survey-based methods [39-41].

Emissions. Pollutant emissions from cooking are of interest in two regards: 1) health and 2) climate. The impact of emissions on human health is dictated by the concentration of pollutants in the air to which a human is exposed and is therefore a function of not just the cookstove but also the room, ventilation, and location of the person. Thus, measurements are taken to quantify exposure based on air quality. To measure climate impacts, the total pollutants released from combustion are of interest, and emissions are typically sampled directly as they exit the cookstove.

Household air pollution (HAP) from solid fuels accounted for an estimated 4.3 million premature deaths in 2012 [43]. To have any measurable effect on health, respirable particulate matter ($PM_{2.5}$) exposure needs to be lowered significantly [44]. The non-linear nature of the integrated exposure-response (IER) curve shows that it takes a substantial reduction in emissions (~80%) to significantly lower relative health risk [45]. Measurements of air quality can be used to calculate Disability Adjusted Life Years (DALYs), which is an estimate in the number of years of life lost due to poor health or disease-induced death and serves as a metric of health outcomes. The quantification of averted DALYs requires data about both stove usage and the health of the population. DALYs attributable to a cookstove intervention (AB_{int}) are calculated according to Equation (1) [46].

$$AB_{int} = ((PAF_{pre} - PAF_{post}) \times B \times Use_{fract} \times SFU_{fract}) \quad (1)$$

In this equation, B is the underlying disease burden, Use_{fract}, is the fraction of households consistently using the intervention cookstove, SFU_{fract} 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. 2) [45,46]. Subscripts *pre* and *post* represent PAF before and after a cookstove intervention, respectively.

$$PAF = \frac{SFU(RR-1)}{SFU(RR-1)+1} \quad (2)$$

Here, RR is relative risk for various diseases calculated using Integrated Exposure Response (IER) curves for $PM_{2.5}$ exposure [46].

This model does not account for stove stacking, which can lead to significant additional PM exposure [48]. Although fuel use measurements are not directly part of the air pollution assessment, researchers strongly recommend that fuel usage and stove stacking measurements are conducted prior to an aDALY validation to determine if the expected benefits can be achieved [49].

Clean cookstove programs have been cited as a viable method to slow climate change as well. Use of traditional cooking devices results in the release of harmful pollutants such as black carbon due to incomplete combustion [50], and solid fuels used for cooking and heating contribute an estimated 25% of black carbon emissions globally [51]. Clean cookstoves have a global potential to reduce an estimated 1 gigaton of carbon dioxide annually based on offsets of 1 to 3 tons of carbon dioxide (tCO_2) per stove [51,52].

Climate impacts of a cookstove project can be quantified in terms of tons of carbon dioxide equivalent reductions ($tCO_{2eq.}$), also known as carbon credits. Depending on the state of the voluntary trading market, carbon credits can be traded or sold for up to \$8 per ton [54] and therefore sales can be a 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 [55]. Measurements of fuel savings and cookstove adoption paired with empirical emission factors can be used to determine annual emissions reductions (ER) via Equation (3) [56].

$$ER_y = N_{stoves}\, Savings_y\, Use_{fract,y}(f_{NRB} EF_{CO_2} + EF_{non-CO_2})(1 - f_{dis}) \quad (3)$$

Here, N_{stoves} is the number of intervention stoves, f_{NRB} is the fraction of non-renewable biomass, and EF_{CO_2} and EF_{non-CO_2} are the mass of CO_2 and non-CO_2 pollutants emitted per kg or MJ of fuel combustion, respectively. The term $Use_{fract,y}$ is a measure of the annual usage rate for project cookstoves in terms of the fraction of households consistently using the intervention stove. The term f_{dis} represents the fraction of cooking processes that are still conducted using the baseline stove and is included to account for stove stacking. Finally, $Savings_y$ is fuel savings realized when completely switching from the traditional to improved cooking method, typically measured on a per-meal or daily basis and extrapolated to the entire year. This must be quantified in the field by manually weighing wood or through surveys.

Existing Monitoring & Evaluation Methods

There are several existing technologies and methods that are currently employed to measure in-field cookstove performance and adoption, including household surveys, the Kitchen Performance Test (KPT), and sensors for temperature and pollutant measurement.

Household Surveys. Household surveys are frequently used to obtain data on attributes such as household demographics, decision-making priorities, user preferences, adoption, stove stacking, and fuel use [57]. While valuable in understanding user perceptions of a given cookstove design, surveys can introduce bias into resulting analyses. One such bias is the Hawthorne effect, in which research participants act differently when they know they are being observed and will often increase uptake of the intervention technology during that period [58]. This skews observational data on metrics like adoption, stove and fuel use, and does not accurately capture typical user behavior on its own. 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 [13,58,60]. Therefore, surveys should be coupled with more objective measurements when possible to verify results.

Kitchen Performance Test. Quantitative monitoring of in-field fuel use started in the 1980s with the Kitchen Performance Test (KPT) [62]. The KPT combines qualitative survey methods with quantitative household fuel weight measurements to determine in-field fuel usage and improved stove displacement.

In the KPT, field research staff visit the sample households to weigh the fuel supply at the beginning of the testing period, then ask that no additional fuel be used or added to the supply without being weighed on a follow-up visit 2-5 days later.

The test requires field staff to visit households and manually weigh fuel supply over a defined period. While this test does provide data on household fuel consumption, there are barriers to conducting an accurate and representative test. These include biases in the surveys, user errors, seasonal variability, a lack of standardization in measurement, logistics issues, time and resource intensiveness, and the possible effects of repeated intrusion into households that consistently disrupts daily activities [41,62]. Researchers who have used the KPT have acknowledged these complications, citing the need for a less biased, less resource-intensive method that reduces the need for field worker training and provides a more accurate and long-term depiction of improved cookstove use and associated fuel savings [39–41,57,63].

Temperature Sensors. Sensor-based monitoring can reduce the Hawthorne bias of surveys and is increasingly considered essential to provide an unbiased and accurate depiction of cookstove use [30,57,12]. This type of monitoring was first introduced in the form of various autonomous temperature sensors, including SUMs (Stove Usage Monitors) and WiCS (Wireless Cookstove Sensors) [64,65]. Other temperature sensors currently on the market include StoveTrace by Nexleaf Analytics [68], Dots by Geocene [69], EXACT by Climate Solutions Consulting [70], and SweetSense temperature sensors [71]. These devices measure the temperature of a cookstove body. The temperature data are then analyzed to determine the duration and timing of cooking events, and when multiple cooking devices are used in a given kitchen, stove stacking. Relating to the terms of equations (1) and (3), these temperature measurements can be used to quantify Use_{fract}, and f_{dis}.

Some challenges with temperature sensor methods include sensor 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 cool-down time for cookstoves before and after a cooking event [30,60,65,70]. 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 [66]. Because firepower is very much location- and application- specific, accurately predicting fuel use from temperature alone is challenging.

Pollutant Measurements. Air quality and emissions sensors have been extensively used to evaluate household air pollution (HAP) in homes and total emissions from cookstoves, respectively, for at least the past 10 years. Pollutants of interest include respirable 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 (UCB-PATS), Aprovecho Indoor Air Pollution meter, various pump and filter systems, and others [73]. Larger hood systems such as the E-Pod or the Aprovecho portable emissions monitoring system (PEMS) are used to collect and measure multiple pollutants to quantify emission factors [30,72].

DESIGN OF THE FUEL SYSTEM

Current monitoring practices in the clean cookstove sector are often time and resource-intensive, may be subject to high uncertainty, and do not provide the full range of data necessary to fully understand improved cookstove adoption and performance. Most importantly, no existing technology measures fuel use over time, which is the basis from which most other metrics of interest are generated, including impacts to time, health, and environment. To meet this need, researchers at Oregon State University and Waltech Systems have developed a system to quantify cookstove usage and fuel consumption called the Fuel, Usage and Emissions Logger (FUEL) (Figures 1 [75] and 2 [76]). The sensor consists of:

- A load cell
- Onboard temperature sensor
- Port for external K-type thermocouple
- A hanging fuel holder in which to store the fuel supply, made locally with culturally appropriate materials
- An integrated power supply, analog-to-digital converter (ADC) and control module with internal clock, custom-designed by Waltech Systems.
- Two 1.5V C-batteries
- An SD card for data collection and retrieval
- Plastic housing

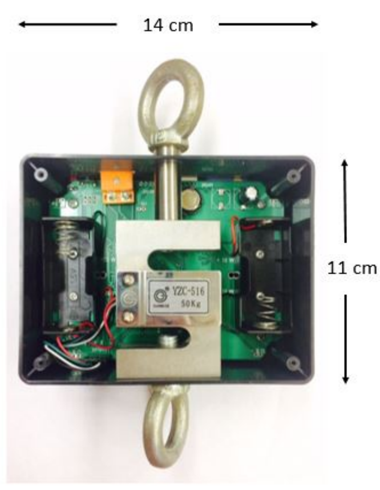

FIGURE 1. FUEL SENSOR [73]

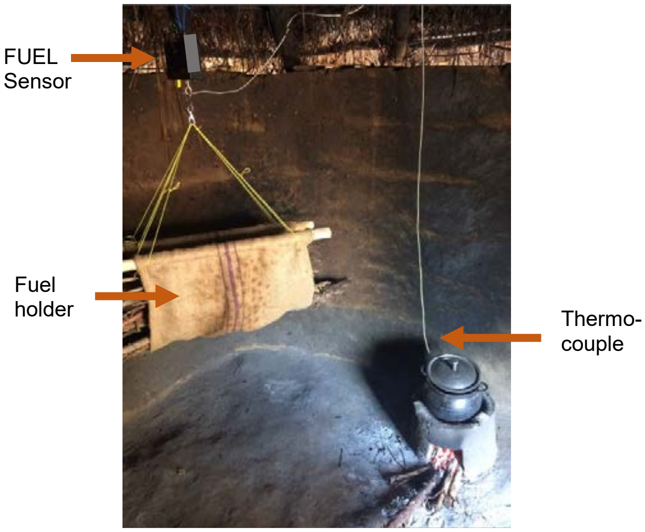

FIGURE 2. FUEL SYSTEM INSTALLED IN APAC, UGANDA [74]

This system measures and logs time-stamped data on fuel mass, cookstove temperature, and ambient temperature for durations of up to several months on a single charge. The current manufacturing cost of the sensor is $75, with a projected lifespan of 5-10 years. In practice, this system would be installed in a sample of individual kitchens, as shown in Figure 2. A household cook is asked to store all or a portion of the fuel supply in the holder and remove pieces as needed for cooking. When additional fuel is collected, it is added to the holder. Reductions in weight are integrated over a given time period to determine the total wood use during that time, whether it be a single cooking event, day, week, or month.

The thermocouple measures the temperature of the cookstove body and is used to generate a continuous temperature profile during the logging period. The temperature profile is then analyzed to determine cooking events and duration. It also serves to corroborate the weight data and correct for user error by checking that a weight reduction is accompanied by an elevated cookstove temperature. If there is an elevated temperature and no concurrent weight reduction, or vice-versa, this indicates incorrect use of the FUEL system.

The system was designed with the intention that the data from the FUEL be processed to report a number of relevant cookstove performance metrics. This includes adoption, stove stacking, time spent cooking, and fuel use. Specifically, data from the FUEL can be used to directly calculate variables of interest in equations (1) and (3), including $Savings_y$, $Usage_y$, f_{dis}, and Use_{frac}. It is expected that this robust and quantitative method can provide more accurate, transparent, and verifiable measurements to determine emissions reductions and aDALYs generated by a cookstove intervention.

METHODS

The objectives of this study were to evaluate user engagement and technical performance of the FUEL system in rural households. After a preliminary proof-of-concept study of 5 FUEL prototypes in El Eden, Honduras, a larger field study was conducted with 100 FUEL prototypes in the Apac District in northern Uganda. All research with human subjects was conducted with oversight by the Oregon State University Institutional Review Board under study number 7257.

Field Testing

In April of 2017, the first prototypes of the FUEL system were tested in 5 homes in rural Honduras with partner StoveTeam International, a non-government organization (NGO) working 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 indicated proof of concept of the existing design and were also used to inform firmware updates such as logging rate.

Following this development, in the summer of 2017, the research team partnered with International Lifeline Fund (ILF), a Washington D.C.-based NGO working in northern Uganda to manufacture and distribute inexpensive, increased-efficiency wood burning cookstoves. In this pilot study, 100 sensors were installed in 85 households in two villages in Northern Uganda. In this sample, households who owned one stove included 61 households with ILF Rural Wood Stoves (RWS), 6 with three stone fires (TSF), and 18 with locally mudded stoves (LMS). Stove stacking households included 8 with the RWS and TSF, and 6 with RWS and LMS (Figure 3). The distribution of stove types and sample size is shown in Table 1. In households that had two stoves, two sensors were used to measure stove stacking.

TABLE 1. SAMPLE SIZE AND STOVE TYPE

Stove Type	***Households***	***%***
ILF Rural Wood Stove (RWS)	47	55%
Three Stone Fire (TSF)	6	7%
Locally Mudded Stove (LMS)	18	21%
RWS and TSF	8	9%
RWS and LMS	6	7%
Total	85	

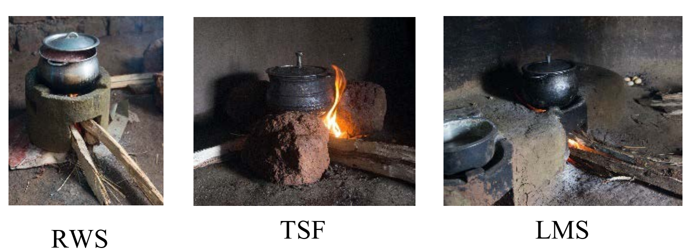

FIGURE 3. HOUSEHOLD STOVE STYPES

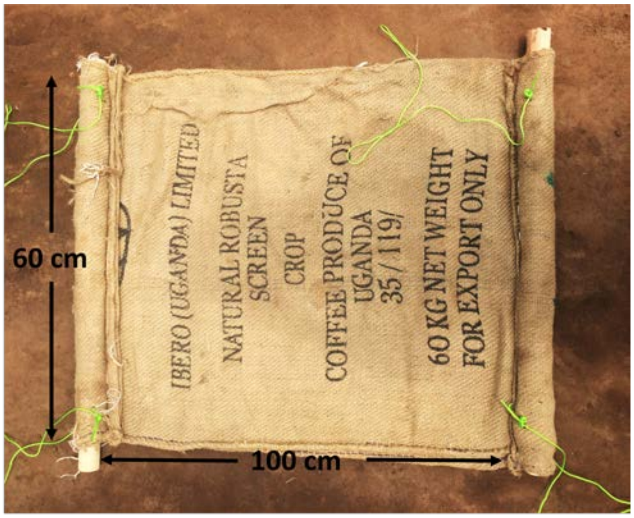

FIGURE 4. FUEL HOLDER AND DIMENSIONS [75]

The hanging baskets used to hold the fuel in this study were designed and manufactured by a local Ugandan to reduce manufacturing and transportation cost and provide an opportunity for income generation in the community (Figure 4 [77]). The holder was sized according to typical available kitchen space and produced from recycled burlap coffee sacks. The dowels were cut from wood traditionally used as supports in houses.

To measure cookstove temperature, Type K thermocouples rated at 200˚ C with 3 m extension cables were used. For data logging with the FUEL system, the sampling rate was set at every 15 seconds until a specified change in weight is detected, after which the sampling rate increased to every 3 seconds.

Installation and Data Collection

Initially, community meetings with both study villages were held to explain the purpose and correct use of the FUEL system. These meetings were also used to gain initial feedback from households on the usability of the FUEL system itself. The researchers took into consideration that storing wood in the holder was a deviation from traditional habits of storing wood on the ground, and incorporated questions regarding this habit change into both the community meeting and following household surveys. The results of these ethnographic findings will be outlined in greater detail in a future paper.

The sensor systems were installed in the households and left in place to log over a period of 30 days. Prior to installation, each household was asked about their preferred location for the system, and the sensor was then tied to a support beam of the roofing structure. A staff member would then assist in loading a portion of the household fuel supply into the holder. The thermocouple was supported by a roof beam and hung directly into the combustion chamber of each stove. A completed system installation is shown in Figure 2.

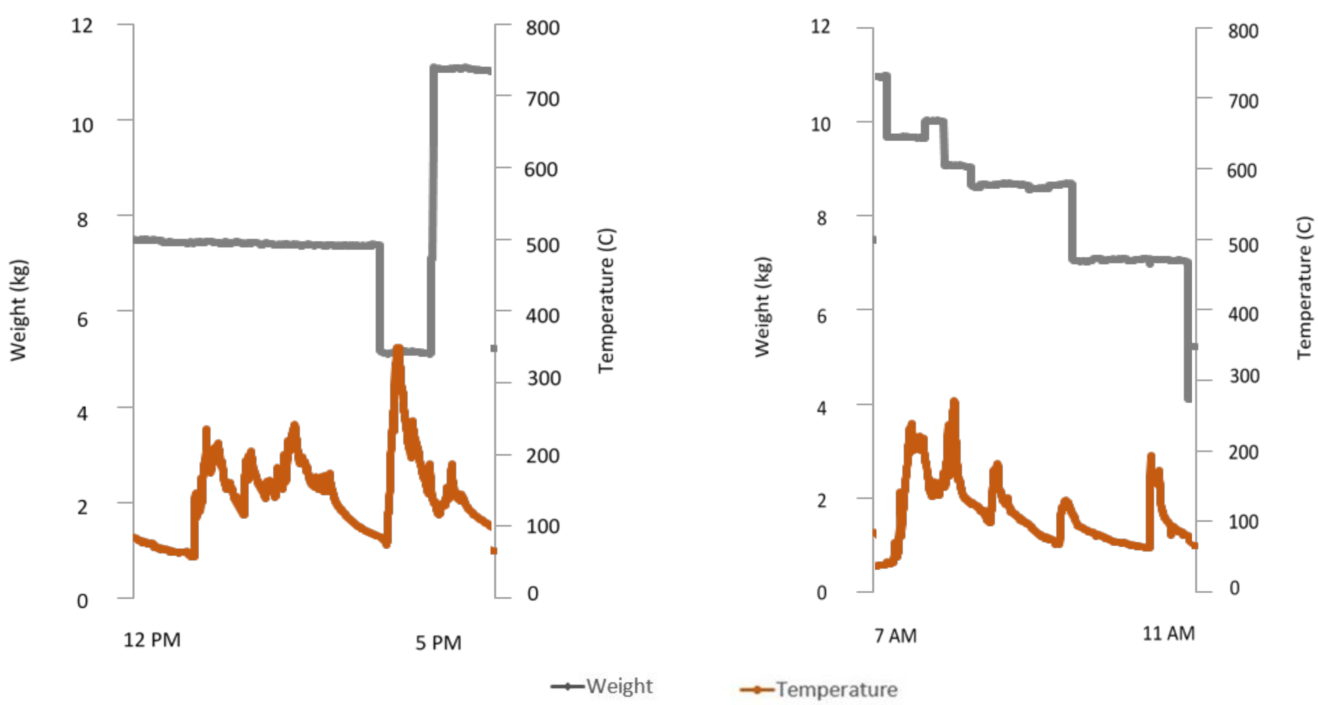

FIGURE 5. (A) HOUSEHOLD NOT USING FUEL HOLDER; (B) USING FUEL HOLDER CORRECTLY [76]

During installation, local surveyors also collected basic household demographic data, such as the number of people in the household. After 30 days, local field staff returned to collect the sensors. The fuel holders remained in the household if participants desired. The SD card files were then uploaded in comma-separated format (.csv) to a local computer and sent to researchers.

Raw Data

Raw data output from the FUEL includes time (Unix), weight (ADC), thermocouple temperature (ADC), internal sensor temperature (ADC), used as a proxy for ambient, and battery life (ADC). Because each load cell has a variable calibration curve, the sensors were individually calibrated before deployment using a 2-point calibration at 1 kg and 30 kg. Each thermocouple was calibrated with a specified corresponding sensor in ice water and boiling water. This enables the algorithm to convert the raw weight and temperature values from ADC to kg and ºC, respectively.

Algorithm Development

A primary goal of field testing of the FUEL system was to gather real-world data needed to inform development of the algorithms to convert time-stamped data on fuel weight and temperature into quantitative metrics of cookstove adoption and performance. These are reported by corroborating proper use of the system for cooking events by ensuring elevated temperatures correspond to reductions in fuel load, determining fuel consumption as an integration of the weight losses, and extrapolating to overall energy use and emissions.

Corroborating Cooking Events. Temperature data from the FUEL system are used to determine cooking events and duration, and to corroborate the weight data to correct for user error. For example, a data sample taken from a 24-hour logging period of a household in El Eden, Honduras, is shown in Figure 5 A and B [78]. In figure 5A, the household has just received the system and was using the fuel holder incorrectly, while in Figure 5B from the following morning, the household had begun to use it correctly. These graphs demonstrate how temperature data can be used to inform the algorithm and identify or correct for user error. In Figure 5A, although the temperature is increasing, indicating a cooking event, there is no change in fuel weight. This signifies that the cook has used fuel that was not stored in the holder. Therefore, it is known that not all fuel use has been accounted for and the data should be flagged. Figure 5B indicates a logging period with optimal use, in which the decreases in weight are corroborated to the presence of an elevation in temperature. Identification of these events in the algorithm allows the analysis to verify good data and flag suspect data, and alert researchers to the need for corrective action which could involve follow up with household to ensure that the system is being used consistently and correctly.

Fuel Consumption. Fuel use is calculated by integrating all of the mass reductions over a period of time. A mass reduction is identified by setting a threshold value, W_0, for the difference between two consequent data points, W_i and W_{i-1}. This

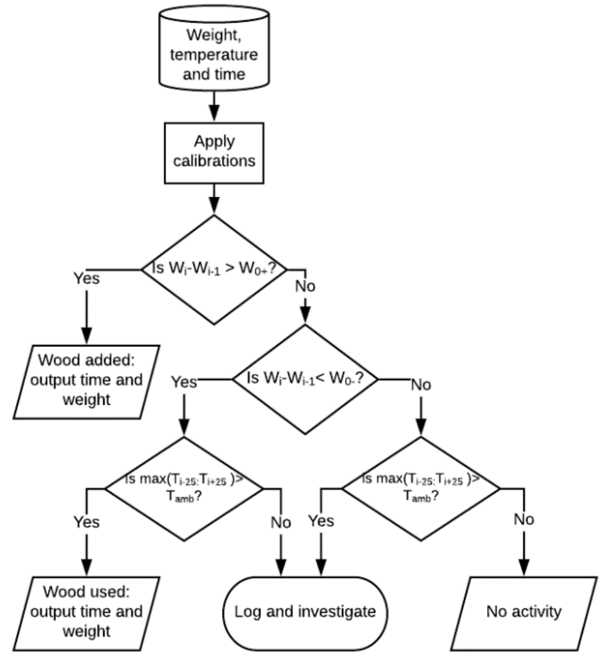

FIGURE 6. ALGORITHM TO CONVERT RAW WEIGHT DATA TO FUEL USE [77]

threshold value was set to avoid fluctuations in weight data that were noise-related. The algorithm to determine daily fuel use, corroborated with temperature, is shown in Figure 6 [79]. The difference between each discrete weight value, W_i, is taken and compared to a positive and negative threshold value. If the weight difference is negative, past a specified threshold value, it is then corroborated with the temperature, T_i, to verify an actual cooking event. Otherwise, it will require manual interpretation to determine why there was a change in weight but not temperature, or vice-versa. This will also require further investigation, corrective action, and may necessitate correlating temperature and energy flux to fuel weight [66].

Calculated Metrics. The measurements of fuel consumption and cookstove use can then be further analyzed to report energy use per person and extrapolated to emissions, carbon credits, and aDALYs generated in the household by incorporating additional variables relevant to the household, fuel supply, or cookstove performance.

When comparing fuel use between different households, it is necessary to account for differences in household sizes and ages. Normalizing across various households allows for direct comparison of fuel use per capita between households. This is accomplished with the standard adult equivalence chart that denotes the relationship between age and gender with adult equivalence [80].

Fuel moisture content can vary greatly between geographic regions or even households and is typically between 5% and 30%. It is dependent on fuel type, age and condition of the wood.

Measurements of moisture content can be taken to account for this, or the uncertainty in solid fuel weight can be applied [81].

Emission factors report the various emissions released from combustion of a known fuel type and quantity for a given cookstove design. They are determined through lab or field testing, and several databases exist for previously measured emission factors [72,75–77]. The relevant emission factors can then be used to calculate pollutants for a given stove and fuel quantity (Equation 4).

$$pollutant_k = EF_k \times m_{fuel} \tag{4}$$

Here k represents any emission species, such as carbon monoxide, methane, black carbon, or the like. In this equation the emission factors would be in g/kg and fuel consumption measured in mass of fuel over the time period of interest.

RESULTS AND DISCUSSION

The objective of the pilot study was to evaluate the performance of the FUEL system from both a practical and a technical standpoint.

Practical Evaluation

From a practical standpoint, preliminary qualitative data from community meetings and household surveys suggest that the system was usable for households, and that storing fuel in the holder was not an issue. Interviews revealed the weighing of wood was intuitive to users as the concept of the scale was well understood from purchasing food items at the market. Additionally, the elevation of the fuel in the holder was viewed as a positive attribute for Ugandan cooks. Observation corroborates these findings, as households often elevated their wood supply on rocks to keep it off the ground and away from moisture and termites, so the fuel holder was not seen as obtrusive to many of the participants. This indicates 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.

The roofing structure in each kitchen consisted of individual, sturdy branches from which the FUEL sensor could be hung directly. This enabled a streamlined installation process that eliminated the need for additional hardware, such as support beams. The holder was designed to minimize intrusiveness in the kitchen, and allowed for ample cooking space. Participants also indicated the desired placement and height of the holder, which increased usability.

Including walking time between households, installation of the FUEL system took two staff members approximately 15 minutes per household on average. 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.

Technical Evaluation

From the 100 sensors installed in Apac, Uganda, a total of 10,923,476 data points were logged over 53,928 hours. An example of raw data from a full successful logging period is shown in Figure 7, where black is fuel weight and light grey is temperature.

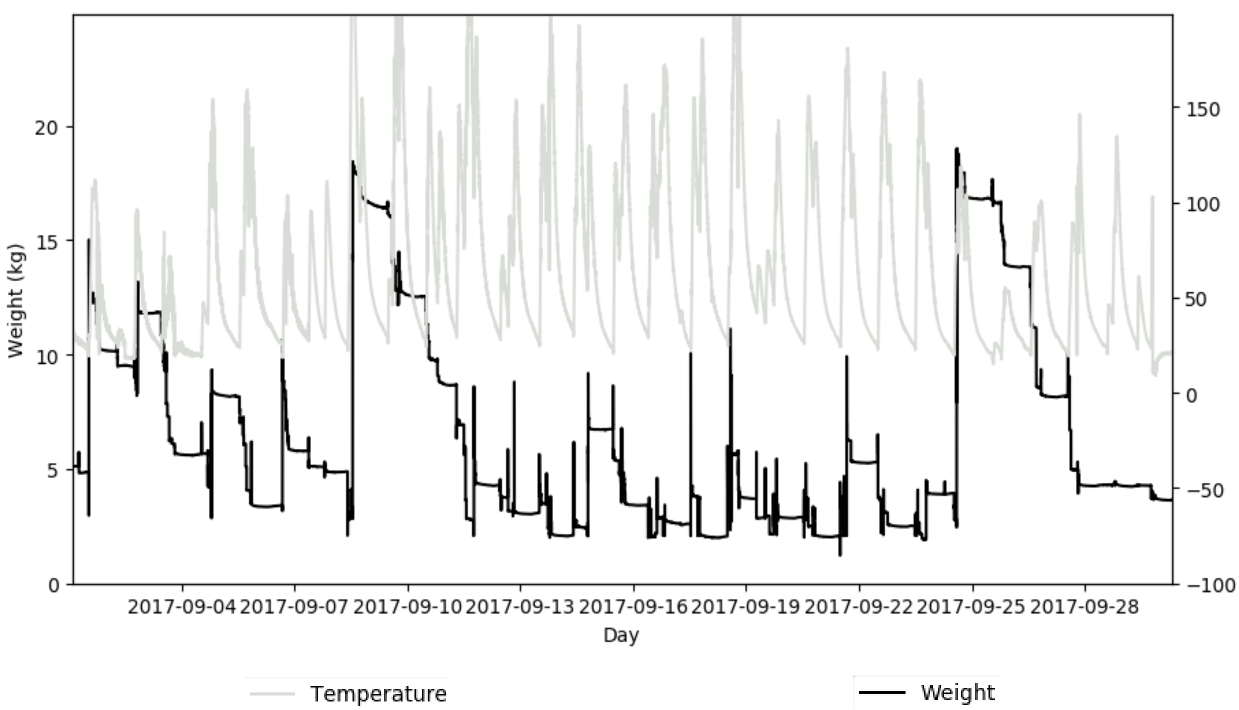

FIGURE 7. TEMPERATURE AND WEIGHT VS TIME FOR 30 DAYS

FUEL Performance. A breakdown of overall sensor use and functionality is shown in Figure 8. Some of the sensors did not log data for the entire monitoring period due to various prototype hardware failures. Of the 100 sensors, 11 did not initiate logging due to SD card failure. Another 18 stopped logging after a short period, 1 logged indiscernible non-linear data, and 1 SD card was removed from a household. The terminated logging could have occurred from coin cell battery discharge, the 1.5 V batteries becoming dislodged from the holder, or faulty SD cards. These data points were therefore not included in the analysis. These issues can be resolved by replacing the original SD cards with higher quality ones and creating tighter battery connections.

Of the remaining 69 working sensors, 82% showed consistent use of the fuel holder by the user over the entire logging period. Here, consistent use was defined as use of the FUEL system at least one time per day with at least 1 kg of wood used for over 60% of the days measured.

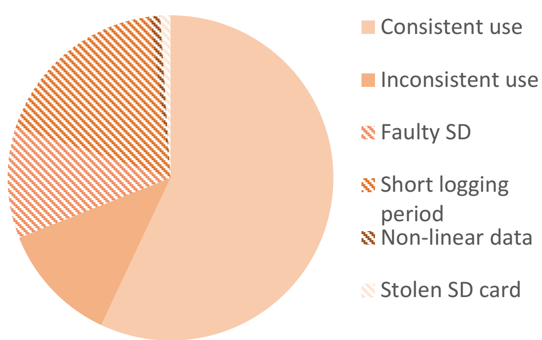

FIGURE 8. FUEL PERFORMANCE IN APAC, UGANDA

Single Household Fuel Consumption. A 26-day sample of daily fuel use for a household of 4 people in Apac, Uganda is shown in Figure 9. The average daily fuel consumption was 2.5 kg fuel with a standard deviation of 1.95 kg. The variability in fuel consumption data may be representative of days when food for one meal is reheated, which was prevalent in this region. Other sources of variability could be identified through further observation of cooking in the study village. This high variation between days can indicate the importance of monitoring fuel use over a longer period of days than the 3-5 that is typically used in the KPT.

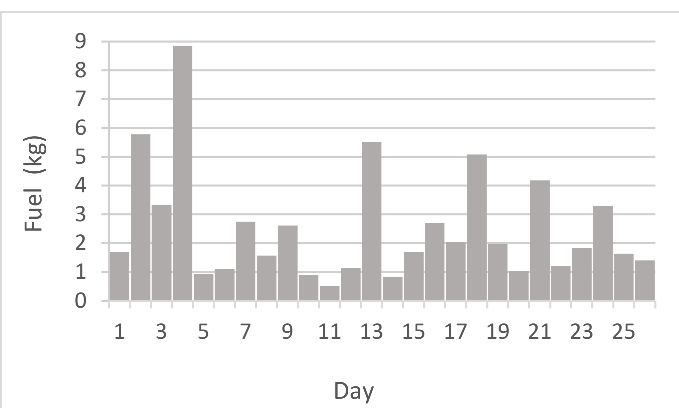

FIGURE 9. DAILY FUEL USE FOR HOUSEHOLD IN APAC, UGANDA

Stove Stacking. A 29-day sample of daily fuel use for a household that in Apac, Uganda that stove stacks with the LMS and RWS is shown in Figure 10. The average daily fuel consumption was 7.1 kg fuel for the LMS, and 5.5 kg fuel for the RWS. This preliminary result demonstrates that the FUEL can be used to measure stove stacking using two sensors.

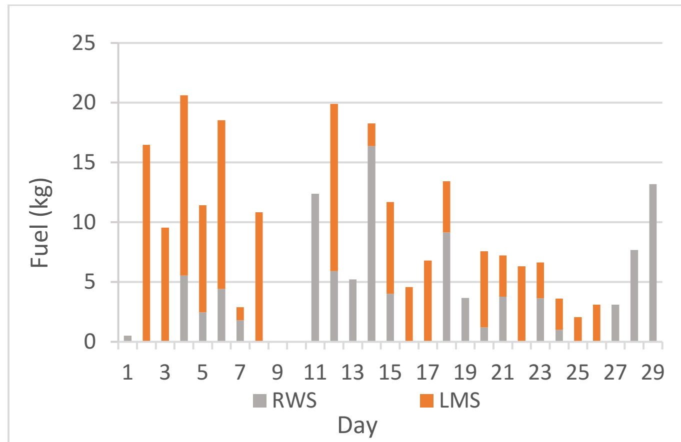

FIGURE 10. DAILY FUEL USE, STOVE STACKING, IN APAC, UGANDA

Average Community Fuel Consumption. A distribution frequency of average daily fuel at the village level is shown in Figure 11. Households used an average of 6.3±1.9 kg of fuel per day across all stove types. The FUEL system can be used to estimate a community's average fuel use, and total consumption over a given period.

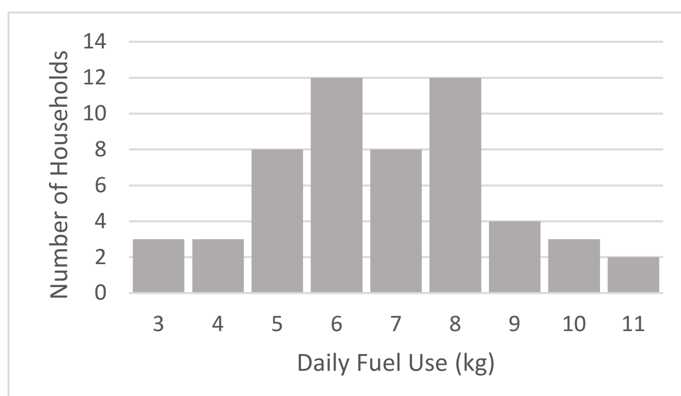

FIGURE 11. DISTRIBUTION OF AVERAGE DAILY COMMUNITY FUEL CONSUMPTION, IN APAC, UGANDA

Additional Metrics. Cooking events and duration, emissions, carbon credits and aDALYs were not calculated in this analysis, but this would be done using the fuel consumption and stove usage data from the FUEL system. Cooking events and duration would be calculated using elevated temperature data as a proxy for use. Emissions would be calculated using the rate of fuel consumption per day, week, or month and the measured emission factor, as referenced in Equation 4. Carbon credits would be calculated using temperature as a proxy to determine $Use_{fract,y}$ and fuel consumption would be used to determine $Savings_y$, as referenced in Equation 3. aDALYs would be calculated using temperature as a proxy to determine Use_{fract}, as referenced in Equation 1.

Human-Technology Interface. The data showed that rather than storing their fuel in the holder consistently, some households chose to place their fuel supply for a meal in the holder for a short amount of time just to record the data, and then removed the entire portion immediately to cook with it. This action resulted in near-instantaneous, linear spikes in data that were originally attributed to noise caused by unintentional interaction with the system. As it is challenging to discern noise from this type of intentional human activity, future work will involve designing a robust algorithm to account for this. This finding highlights the value in accounting for user context in system design.

External Hardware. High thermocouple failure occurred because the selected thermocouples were not were not rated for a high enough temperature to withstand direct placement in the combustion chamber. This can be mitigated in the future by using higher temperature-rated thermocouples or attaching the thermocouples to the outer cookstove body near the pot supports. This situation also underscores the balance between maintaining an accessible cost of the sensor system and ensuring equipment durability, as thermocouples with higher temperature ratings are higher cost.

The process of using SD cards to organize and store data was cumbersome. At the end of the logging period, a staff member manually collected each card and individually upload the data files to a computer. The files were then aggregated and transferred to researchers via email. This challenge will be mitigated in future studies through incorporation of wireless data transmission to eliminate the need for SD cards entirely.

CONCLUSIONS AND FUTURE WORK

Overall, the preliminary results from this study show that the FUEL system can be used to measure long-term fuel and cookstove use. Future work will include following up with previous users in Apac, Uganda, to gain feedback on use of the system over the entirety of the logging period and implement a second monitoring period with upgraded sensors. These upgrades will include higher quality SD cards and thermocouples to more accurately assess performance. In addition, the algorithms will be further developed to corroborate fuel use with temperature, and temperature with cooking duration. Upon completion of this development phase, a validation study to compare FUEL measurements to the KPT is planned.

The long-term goal is to make this technology available and usable for cookstove programs and researchers, so practitioners can more easily measure long-term fuel consumption and cookstove adoption. The researchers are currently investigating the integration wireless temperature sensors to replace the thermocouple, integration of sensors to directly measure emissions, and wireless data transmission to replace SD cards.

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