Measuring Usage and Adoption of Improved Cookstoves in Ugandan Households using Quantitative and Qualitative Methods

Prithiviraj Sundararaman, Amit Gandhi, Daniel Frey
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA
psundara@mit.edu

Acuku Helen Ekolu, Betty Ikalany
TEWDI-Uganda
Soroti, Uganda

Megha Hegde, Kendra Leith, Daniel Sweeney
D-Lab
Massachusetts Institute of Technology
Cambridge, MA, USA

***Abstract*— Improved Cook Stoves (ICSs) present a range of benefits such as decreased fuel consumption and improved air quality. However, in order for these benefits to be realized a household must adopt and consistently use the ICS. This paper documents the first phase of a stove adoption study conducted in Soroti, Uganda with a locally manufactured Tier 2 efficiency cookstove, tested under IWA 11. A market-based approach was used to disseminate ICSs in the local community to a group of 40 participant households. Study participants were divided into three groups non-users, new users and existing users. Initial field interviews were conducted with all participants to understand their perceptions of the stove and reported usage patterns. The most common reason cited for purchasing the stove by new users was fuel savings. Additionally, 130 days of usage was collected using a custom made Stove Use Monitor (SUM). The SUMs indicate that existing users consistently use the ICS. New users exhibit low and inconsistent usage during the initial 35 days of owning the ICS, but within approximately 75 days' increase usage and follow same pattern as the existing user group.**

Keywords— Improved Cookstoves; Adoption; Stove Use Monitor; Uganda

I. INTRODUCTION

The recent United Nations Sustainable Development Goals lay out a course of action to end poverty, promote prosperity and well-being for all, protect the environment and address climate change. Access to modern energy technology and services has been identified as a key enabler of these development goals. The UN Sustainable Energy for All Initiative (SE4All) provides a framework, the "energy ladder" which defines different tiers of modern energy access. Climbing the energy ladder on a household level involves shifting from candles and kerosene to solar and grid-connected electric lighting, as well as changing from traditional, inefficient to efficient, clean forms of cooking and heating.

While grid extension and affordable solar powered lanterns and home systems have enabled a growth in the access to electric lighting, the majority of households in low-income countries continue to rely on inefficient solid-fueled devices for cooking and heating. In addition to the significant time and financial burdens of these practices, households are exposed to harmful emissions, which according to the World Health Organization result in 4.3 million deaths per year. Modern cooking technologies such as electric induction and liquefied petroleum gas, and high-performance solid fueled stoves remain unaffordable for many households in developing countries. Donor-based stove programs have been effective at achieving stove dissemination in high numbers, however sustained adoption has been shown to be low. In order to achieve adequate adoption of high-performing stoves, it is important that designers and manufacturers prioritize affordability, usability and aspirational value in addition to performance.

Recent research indicates that nontraditional internationally designed cookstove technologies are sometimes adopted at low rates after introduction in a community [1]–[3]. Therefore, the health, livelihood and environmental benefits are often not realized. An approach to improving adoption might be to place more emphasis on design of product features that are valued by local customers, such as usability and fuel savings. In this case, a local producer may have an advantage in understanding customer preference, and given the right support could develop a product which combines the desired traits of a user as well as the features which offer health and environmental benefits.

The implementation partners for this work are Appropriate Energy Saving Technologies Ltd. (AEST - Soroti, Uganda) and the Teso Women's Development Initiative (TEWDI Uganda), AEST's NGO affiliate. AEST manufactures residue-derived cooking fuel and ICSs, branded as Makaa Stoves, which are sold in the peri-urban and rural communities of Soroti District, Uganda. The Makaa Stove is improved over traditional cooking methods such as a three-stone fire, offering a 30% reduction in fuel consumption and a three order of magnitude decrease in fine particulate (PM2.5) emissions. Prior research in this community by MIT D-Lab indicates that users practice a mix of indoor and outdoor cooking, and that the Makaa Stove is cost competitive with other ICSs available in the area.

The purpose of this study is to develop an understanding of user behavior, factors that affect product usage and adoption, and benefits of sustained use of improved cooking products from a community-born, market-based intervention. Additionally, as the producer of the cookstove technology being assessed, AEST will be able to leverage this information

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to further understand its customers and create products that cater to their needs.

II. Methods

A. Study design

This study uses a mixed-methods approach for collecting data on household preferences and product usage behavior. These include semi-structured interviews and remote monitoring using low-cost sensor technology. The study will span a period of approximately one year (from September 2015 to August 2016). TEWDI's involvement was beneficial to this study because of its affiliation with AEST in addition to its location, and reputation within the community. Additionally, TEWDI had access to information about purchasers of Makaa stove as well as the means to connect with them. Therefore, guidelines for participant selection were jointly established and carried out by TEWDI. The AEST Makaa stove examined in this study was purchased by users with no subsidies or prompting from the research team. As an incentive to participate in the study, users were provided with a Greenlight Planet Sun King Eco solar lantern. Efforts were made to randomize selection of participants, but limitations in the size of AEST's consumer base as well as availability of participants resulted in a convenience sample of 42 households.

The 42 participant households were divided into three groups: existing users, new users and non-users.

TABLE 1: PARTICIPANT HOUSEHOLD BREAKDOWN

User Type	Purchase Time of Makaa Stove	Group Size
Existing User	> 2 months before start of study	11
New User	<2 months before start of study	20
Non-User	N/A; do not own Makaa Stove	11

Some existing users included in this study had purchased the stove up to one or two years before the start of this study. Most of the new users included in this study had purchased the stove one or two weeks before the start of the study, but a few households had been using the stove for about one month. In the non-user group only three participant households owned an improved cookstove.

B. Household interviews

At the beginning of each interview the purpose of the study, methods and institutional review board (IRB) approvals were explained to the households, with the assistance of a translator if needed. At that time, the household representative could choose to consent and confirm their participation in the study or not. For those that consented, the researchers continued with the interview and installation of the remote monitors. To ensure that participants were comfortable with their inclusion in the study, two or three check-ins per participant household were performed within the first two weeks of the study. In addition, participants were provided with contact information for the MIT-based and TEWDI researchers should they have any questions or experience any problems. The research team strived to apply the Lean Research Principles to this study [4].

Semi-structured interviews were administered to primary cooks of all households at the beginning of the study to determine baseline user behavior, preferences, purchasing information and cooking-related aspirations. Interview questions for each of the three user groups differed slightly. For example, existing Makaa Stove users were asked about changes in their satisfaction with the stove over time, and non-users were asked about their interest in purchasing an improved stove. The interviews duration was approximately 30 minutes in length (copies of the interview forms can be obtained from the authors upon request).

C. Remote monitoring

Most cookstove usage monitoring has used stove use monitors (SUMs), which consist of the Maxim IC iButton temperature sensor and datalogger fitted with a mounting bracket to attach somewhere on the cookstove [1], [3], [6]. Due to high cost and limited data capacity of iButton sensors, this study used SUMs that were custom developed to address these limitations, the Sensen SUM. The Sensen SUM, uses an RFduino microcontroller with an internal temperature sensor and a 2000 milli-amp hour (mAH) Li-Ion battery. The SUM also includes an on-board accelerometer and micro-SD card holder. The increase in data capacity and battery life allowed for a faster sampling rate of every five minutes, thus increasing the resolution of the usage data. It was estimated that this setup would allow for approximately six months of continuous data logging with the limiting component being the battery life. A water resistant and heat resistant enclosure and sturdy mounting fixture for the Sensen SUM was designed and proved to endure most kitchen and outdoor conditions that they were exposed to.

Fig. 1. Internal Components of the Sensen SUM

Fig. 2. A Sensen SUM installed on a Makaa Stove

D. Usage Algorithm

The method used to process the data collected with the Sensen SUM draws upon existing literature and incorporates the use of neural networks for pattern recognition [3], [6]. This method of determining stove use can be adapted to new SUM datasets with minimal inputs: one training and one target set. The algorithm for identifying and calculating stove use duration involves the following steps:

1. Normalize data based on minimum and maximum temperature in dataset
2. Create training set through manual identification of stove use events
3. Train, validate, and test neural network
4. Use neural network to evaluate each set of SUM data

Normalization of the SUM data is performed first to address the variations in construction and attachment of the SUMs to the Makaa Stove as well as fuel type and ambient conditions which effect the burn characteristics. The Makaa Stove is locally manufactured by skilled artisans, therefore variation in the construction results in slight variations in the thermal characteristics of each stove. Additionally, the variations in the placement of the SUMs and mounting hardware likely influence the minimum and maximum temperature recorded by the SUMs, making direct comparison of SUM data from stove to stove difficult.

A manually predetermined subset of the raw data in an existing SUM dataset can be used as the training set (i.e. 50 days of SUM data from one user). Since there are variations in the temperature signatures that constitute a cooking event, it is favorable to include data in the training set that show heterogeneity of SUM events that should and should not be classified as stove use events. This will allow the neural network to properly distinguish between use and nonuse events since it has gained an understanding of various cases through the training set. The target set is a set of binary values corresponding to indices in the training set to indicate which regions should be classified as a stove use event. To develop the target set which is used to generate the neural network in this study, a pair of indices identifying the start and end times of cookstove use events in the training set was provided. This target must be created manually and may be informed by the use of a threshold or peak detection.

Once the training and target set have been created a neural network can be trained using various commercial software. This trained neural network can then be used to interpret the SUM data from all of the participant households to gather metrics such as number of hours of stove use in a day per user.

III. Results and Discussion

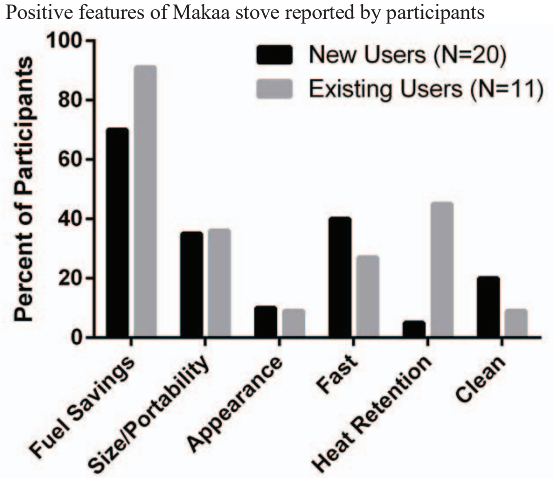
A. Household Interviews

Selected results pertaining to user preferences from the interviews with new and existing user households are presented in this section.

It is important to first note that in many cases the Makaa stove was not the only stove owned by a household. New users on average owned 2.9 stoves including the Makaa stove and existing users on average owned 2.3 stoves including the Makaa stove. The most commonly cited reasons for purchasing the Makaa stove by new users included product life, cost, portability, and energy savings. Additional stoves owned by households included one or more of the following: a three stone fire, un-improved sheet metal stove (iron sheet *sigiri*), inbuilt traditional clay stove, or other improved cookstove. From the survey it was found that of the 20 new users, nine had recently stopped using an iron sheet sigiri, citing high fuel consumption and poor durability. Other locally available improved cookstoves such as the Ugastove or Okelokuc, were also mentioned but less often than the other options presented above.

Fig. 3 and Fig. 4 show responses from participants of the positive and negative aspects of the Makaa Stove. Of the positive features reported by the participants, the most notable is fuel savings. Since a majority of the new users reported this as a positive feature it may have influenced their initial purchasing decision. Furthermore, a larger percentage of existing users also mentioned fuel savings as a positive feature indicating an increase in perceived fuel savings after purchase. As mentioned in other research studies, this data suggests that fuel savings is an important feature valued by consumers as they purchase and use an ICS [7].

Fig. 3. Positive features of Makaa stove reported by participants



Heat Retention

There is a large difference, 40%, between the new and existing users who reported heat retention as a positive feature. Due to its construction the Makaa stove has a high thermal mass resulting in high heat retention, which seems to be important to users as it likely is perceived to decrease the fuel requirement. The positive difference between the new and existing users indicates this is a probable motivator for sustained adoption of the Makaa stove.

Fast (Speed of Cooking)

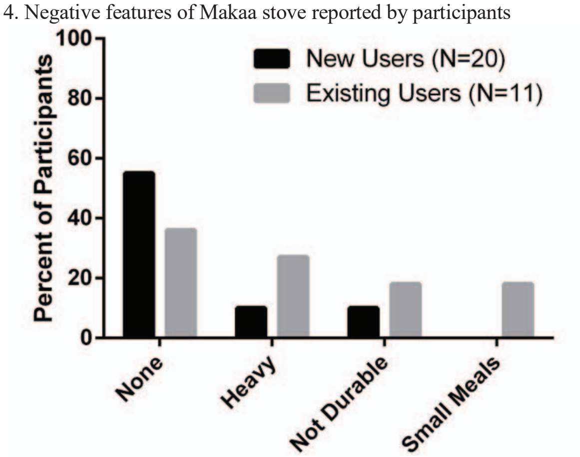
A smaller percentage of existing users as compared to new users reported the speed of cooking as a positive feature. This could mean that new users perceived the stove to be fast at the time of purchase, but after using the Makaa stove found that it did not meet their expectations. Alternatively, it could mean that over time the speed of cooking decreased due to degradations in the stove. Since this is a perceived characteristic it is difficult to attribute its meaning to either of these possible reasons. The final follow-up interviews will attempt to gather more information regarding this aspect.

Cleanliness of Stove

Despite the favorable emissions characteristics of the Makaa stove compared to traditional stoves, cleanliness of the stove in terms of both burn and emissions characteristics was among the least mentioned positive features for both groups. From observation it was found that many Makaa stove users tend to cook outdoors and may not experience the emissions from the use of a solid fueled cookstove, which may be a possible reason for its low rate of mention in the interview.

Other infrequently mentioned positive features included: strength, safety, and ease of ash collection.

Fig. 4. Negative features of Makaa stove reported by participants



Negative features reported by participants were not as prevalent as the positive features. The weight of the stove and its durability were the largest reported drawbacks. Since the existing users cited negative features of the stove more than the new users, this may indicate that the issues become more apparent with use. In particular, existing users reported that cooking small meals was difficult (designated by the "Small Meals" label). However, no new users reported this issue indicating that it may have only been encountered after sustained use of the product.

B. *Performance of Usage Detection Algorithm*

The neural network algorithm for analyzing SUM data was compared to the alternative threshold-based algorithm on a control dataset to verify its accuracy and appropriateness for this study. Fig. 5 and Fig. 6 present the two methods applied to an example stove usage event.

Fig. 5. Method 1 - Threshold based determination of stove use and duration

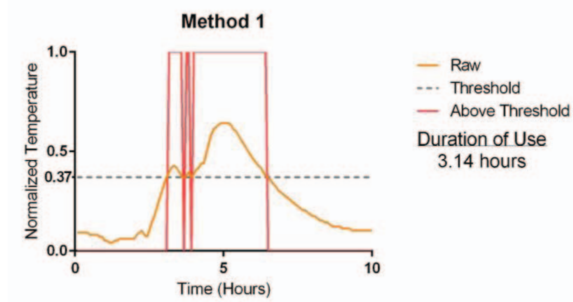
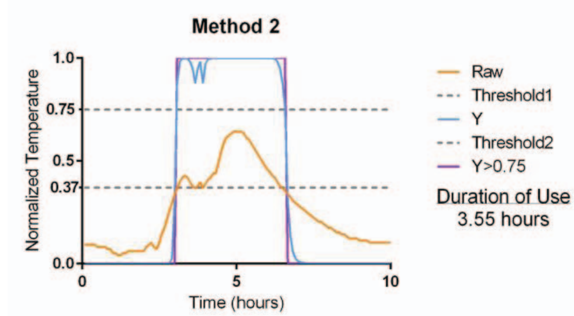


Fig. 6. Method 2 – Neural Net based determination of stove use and duration



The primary issue with threshold-based processing algorithms for processing SUM data is that they will underestimate the duration of use in the cases where the stove is used in a low heat setting or where multiple peaks are present. Although underestimation, as shown in Fig. 5, of approximately 25 minutes seems low, it is accrued over the course of a day and results in an underestimate of the average usage time. Table 2 shows the difference in results when a pure threshold based identification is used versus the neural network over the course of 75 days. Both methods are benchmarked against the true value which was manually identified and used as the testing set for the neural network.

TABLE 2: PERFORMANCE COMPARISON OF SUM PROCESSING ALGORITHMS

Algorithm	Hours in Use	Error (Hours)	Error (%)
True Value (from testing set)	362.75	-	-
Threshold Only	326.25	-36.5	11%
Neural Net	365.08	2.33	1%

C. *Stove use monitoring*

30 Sensen SUMs were deployed for an initial duration of approximately 150 days. 20 Sensen SUMs were deployed on stoves belonging to new users, and the remaining 10 Sensen SUMs were deployed on stoves belonging to existing users. Due to sensor malfunction, 9 sensors recorded partial data over the course of the deployment. The remaining 21 sensors (13 new users, 8 existing users) captured 945,000 data points totaling 3,150 days of active measurement.

Fig. 7 through Fig. 12 aggregate the duration of cookstove usage for each group. Table 3 summarizes the trends of usage and number of meals for each group which was monitored with Sensen SUMs. As expected, there is a high correlation between the number of hours of use per day and the number of meals per day.

TABLE 3: SUM 130-DAY SUMMARY OF TRENDS

User Group	Average Use (hours)	Average # meals per day	Pearson Correlation Coefficient	p-value
Existing	6.7902	1.9846	0.3912	4.19E-06
New	6.2082	1.5374	0.5352	5.40E-11

Fig. 7 and Fig. 8 presents the average and standard deviation of daily use for each participant group over the period of 130 days after the start of the study. A reason for the large standard deviation in daily usage is that timestamps were not synced across all SUMs, therefore the 24-hour usage recorded by a SUM started and installed in the morning on day one is different than that of a SUM started and installed in the evening.

Fig. 7. Existing User Daily Usage Trends

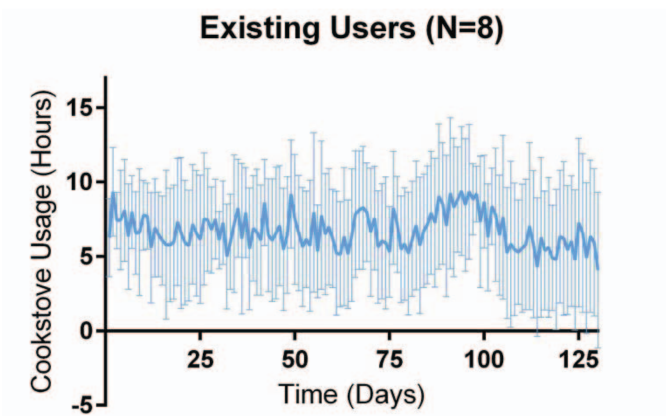


Fig. 8. New User Daily Usage Trends

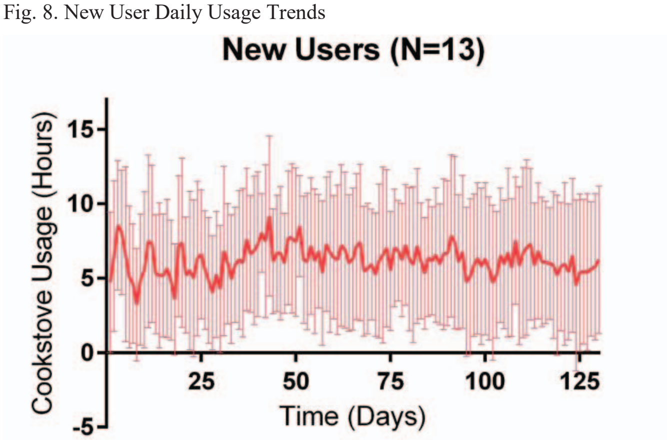


Fig. 9 presents the same data after a 5-day average was computed to address the large variations. This shows that the daily cookstove usage of the new user group begins lower than the existing user group. For the first 35 days the average usage of the new user group is 5.81 hours, while the average usage of the existing user group is 6.77 hours. At 30 days the new user group usage begins to rise. Around 40 and 50 days after the start of the study the duration of cookstove usage of the new users resembles the usage of the existing users. Between days 35 and 75 the average usage duration for the new users was 6.646 hours, and the average usage duration for the existing users was 6.637 hours.

In the existing user group, there is a large increase in usage at day 100. This spike is not present in the new user data but there is an increase in the standard deviation around the same time. This large increase in use is expected to be the result of visitors or children returning home from boarding school, which was mentioned by the participants at the time of data retrieval

In Fig. 8, at the start of the data collection we see large oscillations in usage for the new user group. For the first 25 to 30 days, usage fluctuates between 5 and 7 hours. This fluctuation is captured in the 5-day average (Fig. 9) as a standard deviation. Fig. 10 and Fig. 11 show the standard deviation in usage as a function of time. The standard deviation of the existing user group does not exhibit any temporal patterns and remains centered about 0.75 hours meaning that the pattern of their usage is more consistent. However, in the new user group the standard deviation of usage exhibits an exponential decaying behavior and settles close to the average of the standard deviation of the existing

Fig. 9. Cookstove Usage 5-day Average

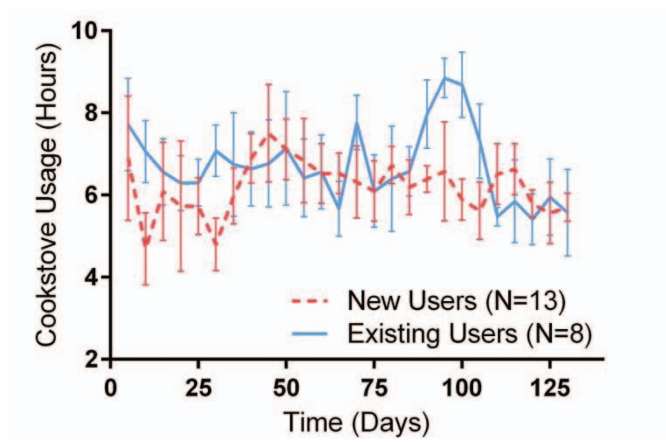


Fig. 10. Standard Deviation of Cookstove Usage versus Time – Existing Users

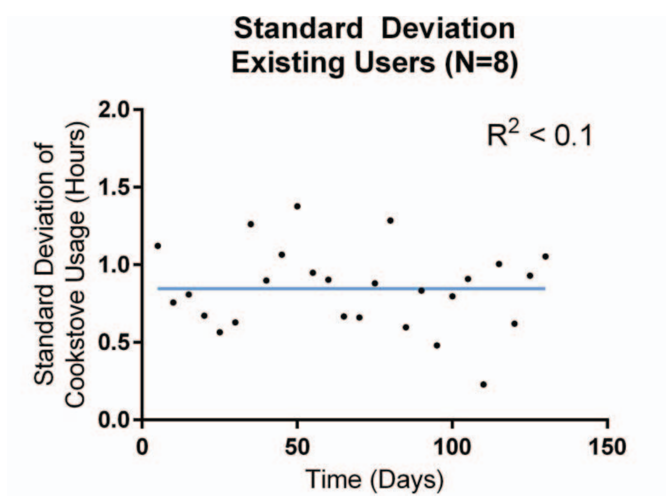
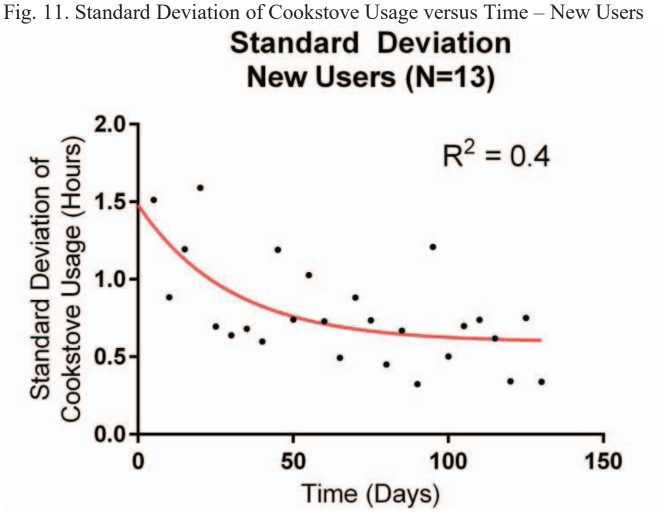


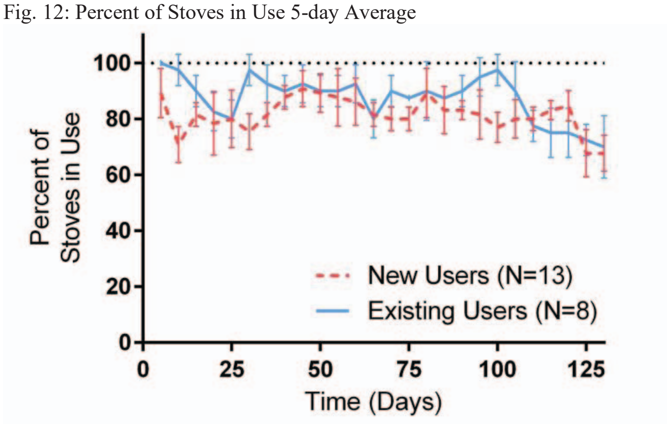
Fig. 11. Standard Deviation of Cookstove Usage versus Time – New Users



user group. The mean of the standard deviation of cookstove usage for the new user group after settling was 0.78 hours.

The duration of usage of the stove often depends on the type of meal being prepared. However, if a threhold on the duration of usage is chosen to determine if a stove was used in a given day. Then a visualization, which is not sensitive to the type or number of meals cooked in a single day, can be ascertained. This threshold was chosen to be one hour in order for a particular stove to be classified as "in use" for a given day. Similar to Fig. 9, a 5-day average of the fraction of stoves in use for each group was computed (Fig. 12).

Fig. 12: Percent of Stoves in Use 5-day Average



It is notable that in the existing user group there are frequent instances where 100 percent of the stoves in the participant group are in use. However, in the new user group those instances are much more rare. Overall, the trends for each user group appear to be similar. However, there is a departure in this similarity after about 80 days, for which no reason is currently available. The second follow-up to be conducted in August of 2016 will aim to further explain this discrepancy.

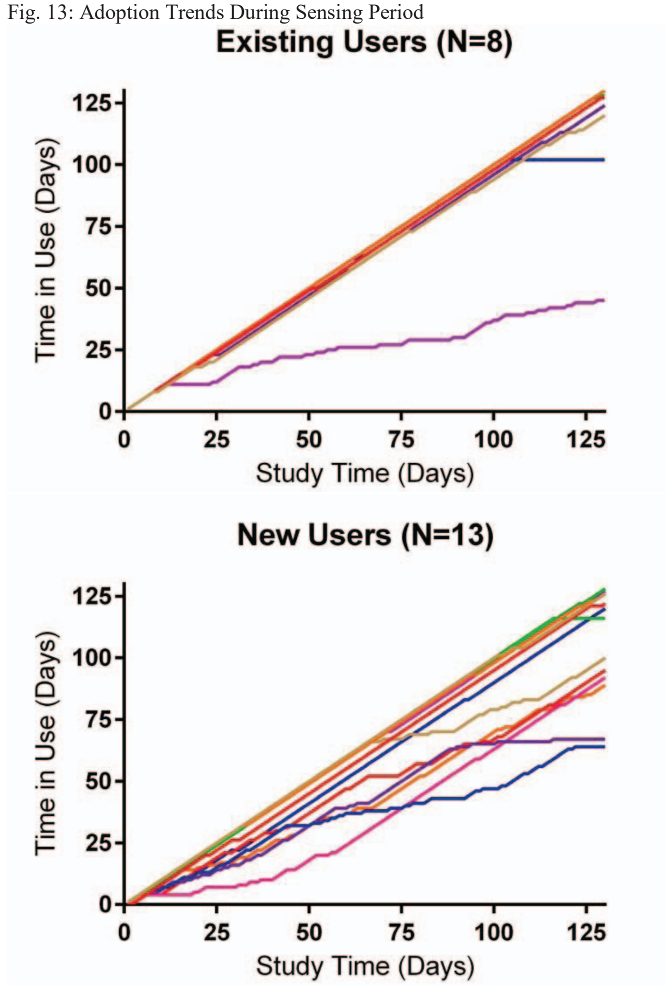
It is apparent that aside from one user, members in the existing user group are consistently using the stove. The one outlier household had mentioned in the survey that their Makaa stove was primarily used for preparing small meals and tea, which may explain the lower rate of usage. In the new user group, a larger variation in usage is present. Conclusions from visual inspection of these plots are as follows. After 130 days: five users adopted at the beginning of the study, four users adopted after ~50 days, two users did not adopt, and the remaining two users dis-adopted after 110 days of consistent use. These trends will be further expanded upon after the second round of data collection to be conducted in August of 2016.

Rogers' describes in the Diffusion of Innovations Theory the concept that an innovation permeates the marketplace in a normally distributed fashion with respect to the target consumers (Fig. 14) [8]. It is possible that the patterns evident in the adoption trends of the Makaa stove are artifacts of this theory.

D. Adoption measurement

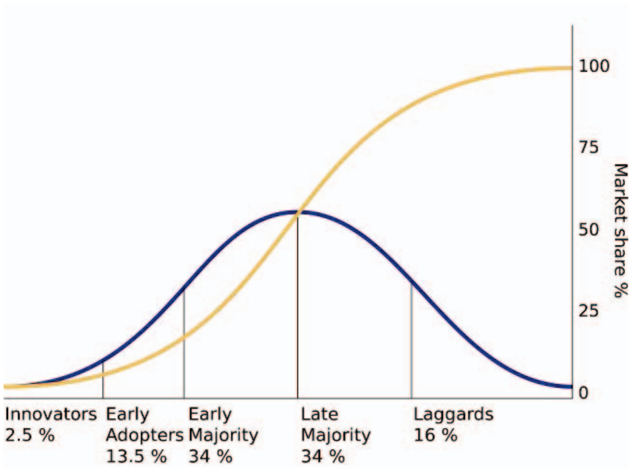
Fig. 13 shows the days that each stove is in use against the daily progression of the study.

Fig. 13: Adoption Trends During Sensing Period



The existing users may fall into the early adopter category, while the new users may represent the early majority. Therefore, their rate and patterns to reaching sustained adoption may be different. In addition, it is possible that the factors that influence adoption for the early adopters are different than the ones that would promote adoption for the early majority. As a result, it is important to continuously monitor adoption through tools such as surveys and sensors to increase the success of a product, such as improved cookstoves.

Fig. 14: Everett Rogers' Diffusion of Innovation Model [8]



IV. Conclusions

This study uses semi-structured surveys and a continuous sensor data logging platform to examine the adoption rates of an improved biomass charcoal stove. The stove in consideration is produced locally by the for-profit partner of TEWDI, Appropriate Energy Savings Technologies Uganda (AEST). Participants were separated into three groups: a non-user group, new user group and an existing user group. Trends in usage were compared and contrasted between the groups. In this study, it is apparent that sensors can be a cost effective means of gathering information about adoption rates. Additionally, when a market based intervention is combined with a locally manufactured stove and stove use monitoring sensors a high rate of adoption is observed among users. It is possible that bias may have been introduced by the presence of the sensors, which should be further explored. Nonetheless, the use of sensors in a field setting presents many benefits in understanding not only product adoption but gathering indicators of product performance. Data related to adoption may be particularly useful for NGOs seeking to implement stove programs so they may promote the use of cleaner cooking technologies. In addition, this data may also be useful for distributors and manufacturers as they would be able to learn the failure rates, time to failure, and periods of non-use related to their product. In this specific case, the manufacturer was able to provide after sales service to the users who had damaged stoves based on observation during follow-ups. This appears to be a critical parameter in ensuring adoption and sustained use of improved cook stoves. However, it should be noted that the methodology employed in this study is not the only way that improved cook stoves can be introduced into communities.

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