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Customizing Malawi-made solar electric cooking technology and business models to provide access to very low income villagers

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Executive Summary

In this project, ***Customizing Malawi-made solar electric cooking technology and business models to provide access to very low income villagers***, we explore and evaluate one of several potential paths for making off-grid solar electric cooking (OGSEC) affordable and accessible for some of the lowest income households in rural Malawi.

We design of our approach to low-income solar electric cooking access with the observation that access to OGSEC may be less expensive and more flexible if the OGSEC infrastructure and equipment can be purchased as an initially small modular system with components that can incrementally increase in capacity over a period of several months or years with new purchases. By allowing rural subsistence farming households to purchase components of an OGSEC system incrementally after harvest when cash from selling the crop harvest is available, we avoid the financing and monitoring costs of pay-as-you-go business models. Incremental purchases also enable customers to make payments when money is available without the burden or obligation of regular monthly or weekly payments that are the hallmark of the pay-as-you-go business model.

We call our new business model "pay-as-you-grow" or PayGrow for short, because customers make incremental payments as they incrementally grow their solar electric cooking system infrastructure over a period of years.

A key requirement of implementing the PayGrow business model is the ability to introduce an initial, entry-level solar system and service that can contribute to household cooking energy requirements yet be inexpensive enough to be affordable for a very low income subsistence farmer household to purchase up-front. This initial system is an entry-level OGSEC system that can then be expanded over the years with additional purchases of solar panels and larger, higher-power solar cookers over time. In this project, the entry-level system has a solar panel capacity of 150 peak watts (Wp).

In order to create this initial entry-level OGSEC system, Kachione, LLC. designed and began the pilot production of a 150Wp solar home system with insulated solar electric cooker (i.e. SHSw/ISEC) that it began distributing in May/June 2019. In the course of this study, we conducted a field test and evaluation of this system and the PayGrow business model with customers located in the Machinga District of Malawi.

We collected monitoring and evaluation data with a combination of household interviews and data loggers installed in the cookers that monitored temperature, voltage and current. We conducted cooking experiments in our workshop in Blantyre, Malawi to estimate the solar electricity requirements per kilogram of cooked food for different typical Malawian foods using the insulated solar electric cooker (ISEC) that we designed. We also developed an energy accounting model of the ISEC so we can estimate energy delivered to food and water by using ISEC high-resolution time series measurements of temperature and voltage. Detailed household consumption interviews provided us with both a picture of household spending and economics and a detailed picture of household food consumption that we used to estimate household cooking energy requirements.

Findings from the study include the following:

(1) In our service area in low-income, rural Malawi, 60% of household cooking and water heating energy use is heating water for cooking *nsima* and for bathing.

(2) A solar home systems with insulated solar electric cooker (SHSw/ISEC) can provide an extremely beneficial service to approximately 10% to 30% of rural, Malawian households who can utilize the system efficiently even during periods of very low

sunshine, but there is a large fraction of households that do not find the ISEC useful or compelling.

(3) If a household cooks all of its food with an ISEC that that has a theoretical efficiency of 50% (i.e. heat losses to the environment are approximately equal to the heat delivered to food), then the cooking and water heating electricity requirements for the household are approximately 717 Wh/capita/day, which means for the average household of 4.3 persons, this is a daily cooking energy requirement of approximately 3.1 kWh/day. Of this amount, we estimate from household interview data that 46% is used for cooking the local staple food of boiled corn meal called *nsima*, 14% is used for heating water for washing and bathing, 11% is used for beans, 9% is used for fish and eggs, 7% is used for rice, 10% is used for vegetables, and 3% of the household energy requirement is needed for cooking chicken and goat meat.

(4) As a first purchase, an affordable SHSw/ISEC provides substantially less than 1 kWh/day of cooking and heating energy: Given this energy limitation do households cook small amounts of food at high temperature or heat larger quantities of water at lower temperatures? We find that rural Malawian households universally chose the latter option: heating larger quantities of water to temperature that are very warm but not boiling hot. This water is primarily used for bathing.

(5) Key factors that affect system utilization may include: (a) whether the panels the mounted on the roof or kept indoors at night for security, (b) the daily solar resource and temperature that the water in the ISEC attains by evening, (c) the amount of work that households have to do with their farming plots, (d) the number of competing uses for solar panel electricity, and the size and quality of battery serving those uses, (e) education and orientation regarding proper system use, (f) the age of the oldest woman in the household, (g) the empowerment level of the woman of the house, and (h) incentives for good utilization.

(6) The price at which customers purchase the system (i.e. highly subsidized vs. discounted market price) does not appear to have any correlation with the level of cooker utilization.

(7) In our sample of 37 households during the low-sun, rainy season, approximately 2 out of three 3 of households utilized the ISEC in their SHSw/ISEC system. The one-third of users that did not use the ISEC, generally prioritized using the solar panel to charge batteries that they bought for other electricity uses. Thus, during times of low solar insolation, they discontinued cooker use to have enough electricity for other demands for solar electricity.

(8) Of the 2/3 of households that used the ISEC in the rainy season, about 1 out of every 10 users utilized the ISEC once per day or more, another 40% of users utilized the ISEC between twice per week and once per day, approximately 1 out of every 4 of users utilized the ISEC between once and twice per week on average, and about 1 out of every 4 users utilized the ISEC less than once per week.

(9) For all SHSw/ISEC recipients, approximately 1/3 use the system relatively well during the rainy season (i.e. more than twice per week).

(10) Because of the relatively low cost of high-resolution temperature data loggers (i.e. ~$25 each), it is possible to create an "Earn & Grow" delivery and product distribution model for HISEC products that delivers larger, more expensive SHSw/HISEC systems only to those households that utilize solar electric cooking well. We believe this solves the efficient cooker utilization problem for our customer base by delivering more expensive high efficiency cookers only to households that will use them well.

(11) Given the ability of a substantial fraction of SHSw/ISEC customers to utilize their solar electric cooking system with relatively higher efficiency and efficacy, we believe

that development of systems and activities for peer-to-peer, community-based knowledge-sharing and education with respect to solar electric cooking hold great promise in increasing solar electric cooker utilization and cost-effectiveness for the rural Malawian population at large.

Given the findings and experience gained from this project, Kachione, LLC plans on further developing affordable off-grid solar electric cooking access throughout rural Malawi and beyond through the following set of next steps:

- ***Expanding the PayGrow business model to an "Earn and Grow" model*** where customers can earn rewards for high cooker utilization efficiency. The concept behind a strongly incentivized Earn&Grow business model is that customers will be able to create "Climate mitigation earnings accounts" where customers can accumulate credits and "points" for environmentally beneficial reductions in wood consumption that they can use to help pay for future solar electricity infrastructure investments.

- ***Exploring the introduction of a smaller and cheaper entry-level SHSw/ISEC system*** that can allow customers to demonstrate their interest in solar electric cooking before upgrading to a more expensive, higher capacity SHSw/ISEC systems.

- ***Developing and field testing ISECs with PCM-based thermal batteries*** that utilize the technologies developed by MECS-supported research at California Polytechnic State University and evaluating the degree to which such improvements can increase utilization efficiencies for some customers.

- ***Designing and developing Malawi-made solar-electric pressure cookers (MM-SEPCs)*** and testing a distribution and customer training model that can empower villagers to effectively use MM-SEPCs to increase the amount of wood they can save. This includes exploring MM-SEPC designs that can also be used on wood fires where customers can save energy on the cloudiest days when the solar panel is not producing enough electricity.

- Continuing the process of ***converting Kachione, LLC customers from battery-based solar lighting and phone charging systems to super-capacitor-based solar electricity storage*** for lighting and phone charging systems so as to increase the lifetime and durability of the non-cooking component of SHSw/ISEC systems.

- ***Developing collaborations with companies and projects interested in deploying SHSw/ISEC technologies*** in other markets in Malawi or in neighbouring countries (e.g. Tanzania)

- Kachione, LLC plans on ***developing and testing an Earn&Grow group kitchen concept*** that can attain greater economies of scale and utilization efficiencies for small groups of households than can be obtained with individual SHSw/ISEC systems.

We at Kachione LLC believe that in the next 10 years, much of rural Malawi and rural Africa will have much of their cooking energy requirements "solar electrified." In this process, tens of millions of households will gain access to 100 times as much electricity as they have access to right now. This will completely transform standards of living in rural Africa.

We hope that in our work with solar electric cooking in rural Malawi will make a significant contribution to the coming clean, solar-electric cooking transformation in rural Africa.

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1. Introduction

1.1 The Problem Setting

Globally, about 1 billion people remain without access to electricity, and another 2 billion people have access to some electricity but still cook with relatively dirty fuels such as wood and charcoal.

Because Malawi is a very low income country, the proportions are even more dramatic than for the developing world in general. In Malawi, more than 80% of households operate without access to substantial amounts of electricity and between 90% and 100% percent of households cook with wood, charcoal, or some combination of the two fuels while a few households use grid electricity for relatively small amount of cooking that is done on electric hot plates.

Per-capita income in Malawi in current dollars in 2018 is $389/year on average according to World Bank data.[1] Yet a majority of people in Malawi have less than average income, and thus live off of less than $1 per day. The purchasing power of a dollar in Malawi is relatively high because the general shortage of cash in the Malawi economy means that people can purchase more with less actual cash because prices for locally produced goods and services deflate to create a local market equilibrium between the supply and demand of both goods and cash. When cash is in short supply, cash is expensive and participants in the economy have to sell more goods to get the same cash causing price deflation. This is the general state of affairs in rural villages[2] where most people operate in a subsistence economy.[3]

The actual purchasing power per capita in Malawi is $1,311 according to World Bank figures in 2018.[4] This means that on average for every $1 that a Malawian possesses, they can purchase a basket of basic consumables that typically would cost ($1,311/$389) = $3.4 on the international markets. This reflects the generalized deflated level of product and service prices in Malawi.

The deflated price levels in the Malawi economy have plusses and minuses. On the minus side, it is very hard for Malawians to purchase imported goods. This is because imported goods tend to be about three times more expensive than locally produced goods 'on average.' This makes it very challenging to bring new, imported technologies to Malawi because of their relatively high expense relative to the relatively limited local supply and availability of cash.

But on the plus side, when a project or technology saves the equivalent of $1 of cash expenses or generates $1 of cash income in the local economy, this savings or income can generate more than $3 of benefits in terms of actual consumed goods (e.g.: food, soap, housing, clothes, etc.) for the household that saves the money or earns the income.

[1] https://data.worldbank.org/indicator/NY.GDP.PCAP.CD, accessed January, 2020.
[2] In 2018 in Malawi, 83% of people living in rural areas. See: https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=MW
[3] See for example: "Traditional production in … African economies" by George Dalton, (http://web.mnstate.edu/robertsb/380/tradafrprod.pdf) for a discussion of how subsistence economies can operate in ways that are different than market economies.
[4] https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD, accessed January, 2020.

1.2 Strategy for addressing very low incomes and severely deflated prices

The generalized price deflation in Malawi indicates a very clear and somewhat obvious strategy that can be used for introducing new technologies in the face of the very low incomes: Namely developing and disseminating “Made-in-Malawi” technologies and products that are less expensive by virtue of being produced with low-priced Malawi-sourced inputs.

As an illustration, let’s compare two simple cases: one where 100% of the product is produced from imported parts and equipment, and another where only 20% of the parts and equipment are imported. Assuming all other things being equal and assuming that the price deflation of local products transfers through to the final cost, we have:

Case #1: 100% * 3.4 = 3.4 (ratio of production cost compared to ‘local’ costs)

Case #2: 80% + 3.4* 20% = 1.48 (ratio of production cost compared to ‘local’ costs)

We see that the second case with 80% local content has a cost factor that is less than half of the imported product case.

This is the cornerstone of what Kachione LLC does in partnership with Kuyere, USA. We produce much more affordable, Malawi-made solar products which are designed to minimize customer cost by maximizing Malawian value-added by minimizing imported content and cost.

1.3 Malawi-made with the Pay-as-you-Grow (PayGrow) business model provides solar electricity access for very-low-income households

What is "PayGrow"?

PayGrow stands for "Pay as you Grow" and is similar to its namesake--the PayGo business model--in that it breaks up the payment of a potentially expensive solar system into smaller payment increments that are more affordable to low income customers.

But there are two problems with the PayGo business model for Malawian subsistence farmers that are solved by a 'PayGrow' alternative. The first problem with buying solar systems with PayGo is that the business, equipment and operational overheads and expenses associated with PayGo usually make PayGo solar systems more than twice as expensive over the long term than their non-PayGo counterparts. While the second barrier to PayGo for Malawi subsistence farming households--who are a majority of households in Malawi--is that it requires regular payments to sustain system operation and access. Yet, subsistence farmers have incomes that are irregular and episodic, usually peaking in the months after a crop harvest.

PayGrow in contrast to PayGo does not use debt financing to break up solar system payments into smaller pieces, but instead breaks the physical solar system itself into smaller pieces that customers can buy as incremental system improvements and upgrades. Because each system component is modular and long-lasting, each customer in the PayGrow model incrementally grows their own, personal, customized solar system over time as they get cash from selling crops from their subsistence farming activities.

The link between solar electric cooking and PayGrow

The key link between the PayGrow business model and solar electric cooking comes from the fact that in rural Africa, more than 95% of household energy use is for cooking. This means that after solar lights and phone charging are taken care of, the next most important energy activity to convert to solar electricity is cooking. Note also that cooking energy use is more than ten times as large as other typical village energy uses. This means that when a village household is ready to upgrade from a 5-10 watt solar panel to a solar panel that is larger than 100 watts, then it is time for them to get a solar electric cooker to effectively utilize the extra energy from the larger panel.

This is exactly how Kachione, LLC uses solar electric cooking the development of PayGrow-based solar system expansion for very low income village customers. Whenever a customer gets a solar panel that is larger than 100 watts, the customer also gets a solar electric cooker. Specifically, the cooker is connected as a "dump load." This means that any solar electricity that is not used by other devices in the solar home system is used by the cooker to heat food or water.

The utilization of cookers & solar panels is the key to cost reduction

The key to maximizing PayGrow cost-effectiveness when customers get a larger solar panel is making sure that the customers utilize the solar panel efficiently and to the fullest extent possible. When the cost of a solar panel can be amortized over a larger number of utilized kilowatt hours (kWh) then the cost per kWh of electricity decreases proportionally. At the end of the day, rapidly decreasing the kWh cost of solar electricity is what is going to make significant amounts of solar electricity kWh's for cooking affordable for hundreds of millions of very-low-income rural Africans.

How a cooker utilizes a variable solar energy resource.

The key to utilizing a variable energy source is energy storage. Typically, when people think of energy storage and solar electricity, they think of batteries, but this need not be the case. If we think "out of the box" there are many different types of energy storage besides just batteries.

Four additional forms of stored energy that relevant to solar electric cooking in isolated solar home systems are: (1) thermal storage in water or food, (2) "virtual storage" in the form of behavioural response or "demand responsiveness of loads", (3) energy stored in a back-up energy source such as wood, and (4) phase-change material (PCM) that is designed as a thermal battery for a cooker. [5]

For a very-low-income, isolated, asset-limited household, the most solar electricity that they can possibly use is all of the solar electricity that is produced by their solar panel. Because it may be many years before such a household can afford to accumulate the 500 to 1000 watts of solar panels that they may need to provide for all of their cooking and hot water needs, for

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[5] For a description of an ISEC w/PCM see: Nate Christler, Matthew Weeman, Justin Unger, and Marcus Strutz, "Insulated Solar Electric Cooker with Phase Change Thermal Storage Medium." https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1542&context=mesp.
See also, for example: Murat Kenisarin and Khamid Mahkamov. "Solar energy storage using phase change materials." *Renewable and sustainable energy reviews* 11, no. 9 (2007): 1913-1965.https://www.sciencedirect.com/science/article/abs/pii/S1364032106000633

many years, such households will be able to convert only part of their cooking energy to solar electricity. They therefore require a back-up energy source to complement their solar electric cooking. For many years, wood will be that back-up source—at least in Malawi. Therefore, the key to efficient solar electric cooking for isolated households over the near-to-medium term is to use all of the solar panel electricity when it is available, and then to use wood to supply that portion of cooking energy that the solar panel simply is not big enough to provide.

This is accomplished through the use of an Insulated Solar Electric Cooker (ISEC).[6] An ISEC takes the variable input power of a solar panel and accumulates and stores the energy as heat in food or water. When the heating elements of an ISEC are produced with diodes rather than resistors, the ISEC can be efficiently operated with a direct connection to a solar panel with no need for voltage control electronics, or a battery and charge controller.[7]

When a highly insulated ISEC is used to slowly cook food, it can cook food more efficiently than regular electric cooking (similar to an electric pressure cooker (EPC)) because of decreased heat losses to the environment. When an ISEC is used to heat water, it can either directly substitute for wood that might have been used for water heating (e.g. for tea or washing), or the hot water can be used as an input to cooking over a fire as a way to decrease the wood or charcoal needed to cook a meal.

If an ISEC is going to provide concrete benefits to a household, it is essential that it be effectively used by the customer.

Figuring out how to get ISEC cookers to be effectively used in practice in a PayGrow solar electricity access model has been the key focus of this particular MECS project and study.

The Next Step? PayGrow with incentives or Earn&Grow

One thing that appears clear from our interaction with customers to date is that even relatively small discounts ($10 or $20) for solar equipment and accessories are likely to be a big incentive. In addition to motivating behaviour, incentives often act as consumer "information." For example, if customers know that they can get an incentive for using solar hot water in their cooking, they get information that using solar hot water is probably good for the environment and probably saves wood.

In the Earn&Grow variant of the PayGrow model, we plan on using incentives for good cooker utilization behaviour to help customers get discounts on future PayGrow purchases. Specifically, we plan to compensate--through discounted purchase prices--customers who utilize efficient solar electric cooking well, in direct proportion to the value that their behaviour provides to the global economy in terms of climate change mitigation.

Perhaps by crediting customers in full for the climate benefit that their solar electric cooking adoption behaviour produces, we can overcome one of the most persistent barriers that is preventing isolated, subsistence-farmer customers from adopting solar-electric cooking: lack

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[6] See: Watkins, T., P. Arroyo, R. Perry, R. Wang, O. Arriaga, M. Fleming, Christopher O'Day et al. "Insulated Solar Electric Cooking–Tomorrow's healthy affordable stoves?." *Development Engineering* 2 (2017): 47-52. https://www.sciencedirect.com/science/article/pii/S2352728516300653

[7] See: Gius, Grace, Matthew Walker, Andre Li, Nicholas J. Adams, Robert Van Buskirk, and Pete Schwartz. "Hot diodes!: Dirt cheap cooking and electricity for the global poor?." *Development Engineering* 4 (2019): 100044. https://www.sciencedirect.com/science/article/pii/S2352728519300508

of cash. AND we perhaps can substantially increase electric cooker utilization efficiencies also: a key goal of the MECS program in general.

Aims of the project

The general aim of this project “Customizing Malawi-made solar electric cooking technology and business models to provide access to very low income villagers” (MM-SEC-4-VLIC[8]), is to enable access to solar electric cooking to some of the lowest-cash-income households and communities by designing an extremely cost-effective solar electric home system with insulated solar electric cooker (SHSw/ISEC)

1.4 Developing and optimizing the SHSw/ISEC

The first specific aim of the project is to further develop and optimize the SHSw/ISEC system design by understanding how customers use the system. We want to optimize the design of our SHSw/ISEC, making it as very beneficial to the customer while minimizing the cost. To do this we need to know the details of how the different customers use the system so that we can optimize system utilization efficiency in order to minimize unit service cost.

In addition to optimizing the product design, we want to optimize the business model and delivery method and terms for getting the product to customers.

1.5 Measuring economic, social and environmental impacts and benefits of the SHSw/ISEC

The second specific aim of the project is to optimize the design of the business model by more fully understanding of the details of customer household economics and variability of behaviour between households. Our ultimate goal is to create as much NET BENEFIT to our customers as possible. To do that we need to know the details of their household economics. What do people spend money on? What do they not spend money on? What are the different ways that a SHSw/ISEC save them time, money and resources?

When we look at the collected household data and estimates of net social and environmental impacts, we will look for new ways to improve the SHSw/ISEC and the business model that implements it. These further improvements will enable us to increase net benefits that Kachione, LLC can create for its customers in its product and service delivery business.

Objectives of the project

The specific objectives of the MM-SEC-4-VLIC project are to collect data and analyse benefits, cost and performance of a baseline SHSw/ISEC design along with a potential design variant. This data and analysis is meant to enable further improvements in SHSw/ISEC design so that new variants of the system can be produced that increase economic, social, and environmental benefits for both consumers and the climate. Key to the performance evaluation of the solar electric cooker will be understanding the utilization behaviour of the users as a function of solar resource, system characteristics, and household characteristics for a reasonably large variety of rural Malawian households.

[8] This shortened abbreviation, MM-SEC-4-VLIC, means “Malawi-made solar electric cooking for very-low-income communities”

2. Methodology

The methodology we use in the MM-SEC-4-VLIC project is a benefit-cost, performance and utilization study. Specifically, the study involves both the collection of comprehensive household consumption data and minute-by-minute monitoring of the voltage and temperature of solar electric cooking pots.

2.1 Details of data collection

Household consumption data is collected with regards to weekly/daily goods and services consumption amounts and expenditures for a comprehensive set of consumption items. Data is collected for households both with and without cookers and for selected households both before and after they obtain a SHSw/ISEC.

Meanwhile households with cooking pots have the pots fitted with both voltage and temperature data loggers which record the cooker operational behaviour over the full 24 hours of day and night.

Outline of the concept: Getting solar electric cooking to compete with wood

There are four different clean cooking ideas or concepts that being evaluated in the current study. These include: (1) Can direct-use solar electricity for cooking compete with wood? (2) To what extent is it possible to utilize water and food as extremely low cost energy storage media to avoid the use of electrical batteries in the adoption of solar electric cooking methods? (3) How do users in practice stack different types of solar electricity/energy both relative to each other and relative to wood and charcoal? And (4) how well do diode-based heating elements perform for powering the cookers in actual practice in a SHSw/ISEC?

2.2 The ISEC as a “slow cooker”: low power means longer cooking times.

A low-power ISEC functions in practice as a slow cooker. Slow cookers were popular in the United States in the 1970’s and tend to operate at lower temperatures than regular cooking. Slow cookers operate at a minimum safe cooking temperature of 74 deg. C, and a normal operating temperature of 85 deg. C.[9]

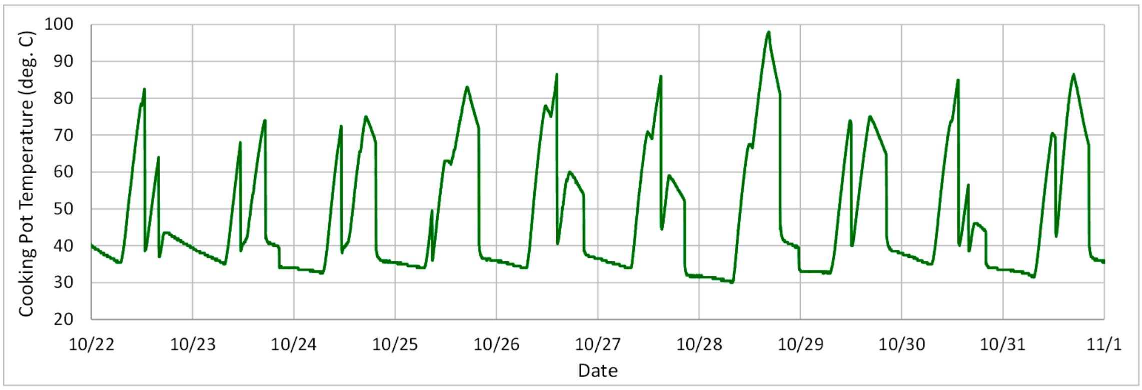

Figure 1: Temperature time series for an ISEC during the sunny season. The temperature measurement is on the side of the aluminium cooking pot, some distance (i.e. several centimetres) from the heating elements.

[9] Haws, Susan. "Using the Convenient Slow Cooker Safely." (2018).

Figure 1 illustrates the variation in temperature for an ISEC used by a high-utilization customer in the sunny season in rural Malawi. The general behaviour of the ISEC temperature is that the contents of the ISEC heat up in the morning, and then if hot water is drawn from the ISEC and replaced with hot water at lunch time, then there is a large drop in temperature and the contents heat up again in the afternoon. If only a small amount of water is drawn from the ISEC during lunch, then the contents keep heating until late afternoon. Then when the sun sets, the contents start cooling down until hot water is drawn from the ISEC in the evening and replaced with cool water that then begins heating the following morning.

Generally, customers used the ISEC for heating water rather than for cooking food.

Note that since the input power of the ISEC is less than 150 watts, and because there is somewhat limited insulation to avoid making the cooker extremely bulky, the peak temperatures for this particular design of the ISEC in the sunny season is between 80 and 100 deg. C when the ISEC has been heating for most of the day. These peak temperatures correspond well to the standard operating temperature of commercial slow cookers.

2.3 The extreme affordability of direct-use solar panel electricity

We make solar electricity for cooking extremely affordable if we can use the electricity directly out of the solar panel. In bulk shipments, the cost of solar panels in Malawi can be below $0.40/watt. If each watt of peak panel capacity can produce approximately 1 kWh/year (i.e. about three hours per day on average), then the cost of that is electricity over 10 years is only $0.04/kWh. We estimate that a kWh of electricity for cooking is equivalent to between one and two kilograms of wood. This is because electricity can be used at 5 to 10 times the efficiency of wood for cooking. With the energy content of electricity at 3.6 MJ/kWh, this is equivalent to 3.6 x 5 = 18 MJ of wood at 5X efficiency. And 18 MJ is approximately the energy content of one kilogram of wood. In rural Malawi, the market value of a kilogram of wood is approximately $0.09/kg, so that direct-use solar electricity for cooking can be cost-competitive with wood when it costs approximately $0.09/kWh or less.

2.4 The lowest cost energy storage medium: water and food

When we can use water and food itself as the energy storage media, then because there is no incremental cost to the water (which is used in the cooking anyways), the cost of the storage media is effectively the insulation required to keep the heat retained in the water. By using an insulated cooker, the cost of energy storage is simply the cost of the insulated container that is required to help retain the heat in the cooker. Because this cost can be just a few dollars in Malawi, the cost of energy storage in an insulated container is very inexpensive.

But the key question is: to what extent will Malawian villagers actually use an ISEC and how will an ISEC perform in practice in actual customer households?

2.5 Cheap and robust, locally produced, cookers with diode-based heaters with voltage control

The use of diode-based heating elements is what allows the solar electric cooker in the SHSw/ISEC to be Malawi-made. The key reasons to have a Malawi-made cooker is to lower cooker cost and so that most of the money that is invested in the cooker itself can be recirculated in the local economy and contribute to economic growth in low-income communities.

The diode-based heating elements are very inexpensive, costing only a few dollars in parts, and allow for voltage control in the heating element without the necessity of additional electronics. Other cooker parts are sourced from the local market. Lids for the cookers are made locally from scrap metal, and insulation covers for the cookers are made in local tailor shops from cloth that is imported to the country as very low cost used clothes.

Assumptions made

There are a series of key assumptions that underpin the MM-SEC-4-VLIC project. These assumptions include:

- For the typical very-low-income household, full access to solar electric cooking is likely to take many years of incremental investments
- The first step to solar electric cooking access is access to solar electric hot water
- Many households will be willing to "fuel stack" by using solar electric cooking outputs as inputs to cooking activities that are not yet solar electrified.

We discuss each of these assumptions in turn.

2.6 Full access to solar electric cooking access will likely take many years of investment for most very-low-income households

Because of the extremely low cash incomes of tens of millions of rural African households—i.e. less than $1/day/capita—millions of households can afford to invest less than $100/year in household energy infrastructure annually. Typically, even under the best circumstances, such a small investment will provide less than 100 peak watts of new solar system infrastructure. This amount of new solar infrastructure—if dedicated to cooking—would likely provide between 0.2 and 0.4 kWh/day of new cooking capacity per year.

Studies indicate a useful energy cooking requirement of between 0.18 to 0.37 kWh per meal per capita is typically what is needed for cooking that is typical of Africa.[10] If a typical Malawi family of 5 people that eats 2.5 meals per day, this translates into a household useful cooking energy requirement of 2.7 to 5.6 kWh/day. It is therefore likely that it will take a typical very-low-income household 5 to 10 years to acquire the infrastructure to satisfy a majority of its cooking energy requirements. Though it is likely that with increases in cooking process efficiency, this can be accelerated somewhat.

2.7 Solar electric hot water as the first step in access to full solar electric cooking

Water is ubiquitous, is extremely inexpensive, has a relatively high specific heat capacity and is used as an input into a tremendous variety of cooking processes and food recipes. For these reasons, we focus our solar electric cooking access efforts initially on providing access to solar electric hot water. It is assumed that this hot water is either used directly (e.g. for tea or bathing), or indirectly as an input in to cooking dishes. In either case the solar electric hot water can provide wood and charcoal savings by the diminishing need of fuel

[10] See: Batchelor, S. Solar electric cooking in Africa in 2020. A synthesis of the possibilities. Evidence on Demand, UK (2015) v + 44 pp. [DOI: 10.12774/eod_cr.december2015.batchelors]

energy for cooking and water heating. Alternatively, the use of solar-electric hot water increases the standards of living of the customer household by allowing households to use more hot water. We note that the assumption that customers will find solar electric hot water useful and interesting may not be true for a large number of households which may live in hot areas where hot water for bathing and washing is not needed, or who may find the utilization of hot water from a solar electric cooker inconvenient and unnecessary.

But in our efforts, we assume that many—if not most—very-low-income households will appreciate and understand their household financial constraints and will be willing to use solar electric hot water as their entre into more expensive and interesting forms of solar electric cooking.

2.8 Fuel stacking as a key tool in incrementally improving solar electric cooking access

Fuel stacking behaviours will be a key tool in providing incremental solar electric cooking access to very-low-income households in a way which can be affordable and feasible. But fuel stacking may require extra time, interest and incentive to overcome the extra inconvenience of fuel stacking procedures and to motivate the changes in behaviour. When households have tight time constraints—as most households do—then the behaviour changes and time requirements of incorporating solar electric hot water fuel stacking may not be feasible for many households. Whether or not solar electric hot water can be effectively incorporated into a household's cooking and water heating activities will depend to a large extent on the degree to which households perceive the benefits of solar electric hot water.

A concrete measurement of household interest, participation and utilization of solar electric hot water is a key focus of this project.

3. Implementation

The work conducted

3.1 Technology approach and equipment

The MM-SEC-4-VLIC project uses diode-based heating elements in insulated solar electric cookers to provide water heating and cooking for village customers.

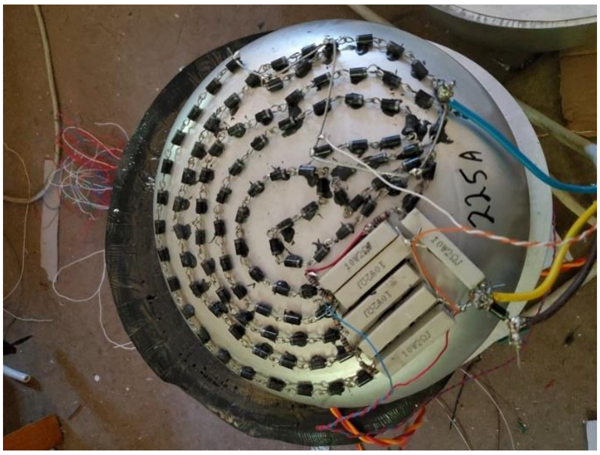

Figure 2: Heating elements and voltage data collection leads attached to inner pot of an ISEC.

Figure 2 illustrates the assembly of the parallel diode-based heating elements for ISEC cooking pot. The diode-resistor strings are hooked up in parallel, and glued to the bottom of the pot with a high temperature epoxy that is rated to approximately 300 deg. C. For the research, a thermocouple is added to the exterior of the inner pot, and voltage leads are added for measuring the voltage across the heating element, and the parallel resistors (for current). The heating element is then covered in a cement/sand mortar which is allowed to set.

Figure 3: Nested pot assembly with outer cloth insulation cover.

The inner pot is then nested in two outer aluminium pots. Between the inner pot and the second pot is just air, while between the second pot and the third pot is insulation (shredded clothing). Then used clothes purchased in the local market are custom-sewn by local tailors into an insulating cloth covering that keeps the heat contained within the cooker during cooking.

3.2 How the idea was generated

The insulated solar electric cooking concept has been under development by Professor Pete Schwartz at the California Polytechnic State University since 2015.[11] In December 2017, Dr. Robert Van Buskirk who works with Kachione, LLC and the social enterprise Kuyere!,[12] contacted Prof. Schwartz regarding his solar electric cooking research. At that time, Kuyere! had been using diode-strings as very inexpensive over-voltage regulators for battery packs in its inexpensive, Malawi-made solar systems.

It was quickly recognized that diode heating elements could provide both heat for ISEC-based cooking and voltage regulation for inexpensive, scaled-up solar systems. It was further realized that such diode-based ISEC cookers could be used as the cornerstone of a larger strategy to provide very inexpensive solar electricity throughout rural Africa because of increases in utilization efficiencies for solar panel capacity that can be obtained with SHSw/ISEC systems, and the fact that diode-based designs allow for very simple, inexpensive and robust designs for Africa-made ISEC systems.

An SHSw/ISEC system can create very high utilization efficiencies for its solar panel because of the fact that the ISEC can act as a “dump load” that takes any electricity output from the solar panel that may not be used for other loads in the system. The ISEC then stores this energy as useful heat in cooked foot and/or hot water. This useful hot water and food energy is then available for a household’s daily cooking and cleaning activities. Because cooking and hot water demand for rural African households tends to be more than 10 times the demand of other energy uses, households should be able to fully utilize a majority of useful energy output of the solar panel in the ISEC because household total cooking and hot water energy demand exceeds the total output capacity of the solar panel, even on sunny days. For the SHSw/ISEC system, the lack of an electro-chemical battery, combined with very high utilization efficiencies of the solar panel lead to the potential for very low per-kWh solar electricity costs for a rural African household using the SHSw/ISEC system.

These technical developments are documented in some detail in the following publications:

Van Buskirk, Robert, and Peter Schwartz. "Solar electricity access for rural Africans at less than $0.02/kWh by 2030." (2019). https://www.researchgate.net/publication/331262290_Solar_electricity_access_for_rural_Africans_at_less_than_002kWh_by_2030

Van Buskirk, Robert. “Can efficiency be sufficient for African cooking?” May 2019 ECEEE 2019 Summer Study 3–8 June 2019At: Belambra Presqu'île de Giens, France, May 2019. https://www.researchgate.net/publication/333681214_Can_efficiency_be_sufficient_for_African_cooking, and

Gius, Grace, Matthew Walker, Andre Li, Nicholas J. Adams, Robert Van Buskirk, and Pete Schwartz. "Hot diodes!: Dirt cheap cooking and electricity for the global poor?." Development Engineering 4 (2019): 100044. https://www.sciencedirect.com/science/article/pii/S2352728519300508

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[11] See: http://sharedcurriculum.peteschwartz.net/solar-electric-cooking/, or more generally https://duckduckgo.com/?q=%22Schwartz%22+insulated+solar+electric+cooking

[12] See: https://kuyere.org/about/

3.3 Production, installation and data collection activities

From June to September of 2019, Kachione LLC produced and distributed 65 SHSw/ISEC systems to customers throughout the Machinga District of Malawi. Some customers received the systems as part of promotional discount lotteries at a promotional price of $30 each, while later in the distribution process, systems were provided at a discount price of $70 each. Generally the households who received access to the SHSw/ISEC at discount prices were selected from the 3000 solar lights and phone charging SHS system customers who wanted to upgrade to a system with larger solar panels.

In September, after signing of the project contract and securing of a small project financing loan, the project purchased a suite of materials and equipment including diodes and other electronic parts, more than 120 data loggers (40 temperature and 80 voltage) for ISEC monitoring, 90 150W solar panels (at a total cost of less than $6K), and 1000 kg of phase change material (at a cost of less than $3000 for upgrading the ISECs to ISECs with thermal batteries[13]).

In October, a first round of field monitoring activities was implemented which tested household interview data collection and data logger data collection with ISECs outfitted with data loggers.

In November, the data loggers arrived in Malawi, and 20 ISECs were built equipped with data loggers and deployed to the field.

In December, an additional 20 ISECs with data loggers were built and deployed to the field bringing the total number of households monitored in the main study to 40.

In January, additional data downloads of ISEC operation were undertaken, and selected households were upgraded to highly insulated solar electric cookers (HISECs).

The project findings

3.4 Customer cooking and hot water energy requirements

Figure 4 illustrates the estimated daily per-capita food and hot water energy requirements.

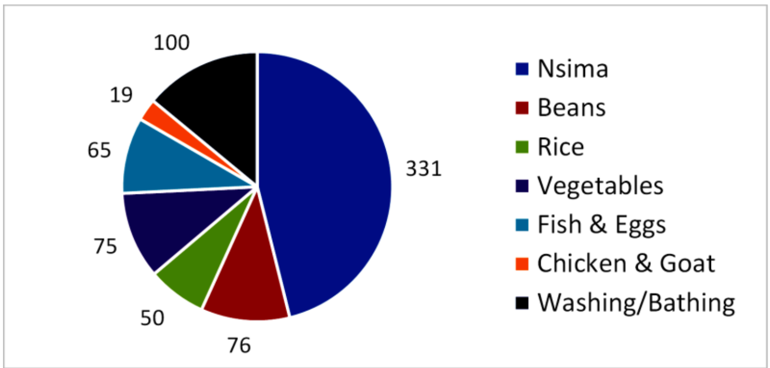


Figure 4: Estimated daily watt-hour per-capita food and hot water electric energy requirements for rural households in the Machinga District of Malawi

[13] See the MECS-financed project at California Polytechnic State University. See: https://digitalcommons.calpoly.edu/mesp/494/ and https://www.youtube.com/watch?v=vK-XyyHJaX4

We estimate that the total per-capita electrical energy requirement for food and hot water for our study households to be 717 Wh/capita/day. Assuming three meals per day, this corresponds to 0.24 kWh per meal per capita which is consistent with the 0.18 to 0.37 kWh per meal per capita estimated from other studies.[14]

The daily food cooking and hot water energy requirements illustrated in figure 4 are estimated for a typical electrical cooker assuming that a moderately insulated ISEC is used. The energy requirements are estimated from the daily per-capita food consumption obtained from household surveys which are then converted into energy requirements using cooking energy intensity measurements and experiments conducted in the Kachione, LLC workshop in Blantyre.

For details of the energy requirement estimation methods and data see Appendix B of this report.

3.5 How do customers adjust to small solar energy supplies? With small food volumes or larger volumes and a low temperature rise?

A key challenge of using no-battery solar electric cookers with high solar panel utilization efficiency is that the amount of food that the cooker can cook will vary from day to day as a function of sunshine.

So for a small, no-battery solar electric cooker, what is the best way of adjusting to the variable, day-to-day cooking capacity of the system?

Before going to the field, the project conducted a series of cooking tests at its workshop in Blantyre, and recorded both the amount of *nsima* cooked, and the amount of time needed to cook the *nsima*.

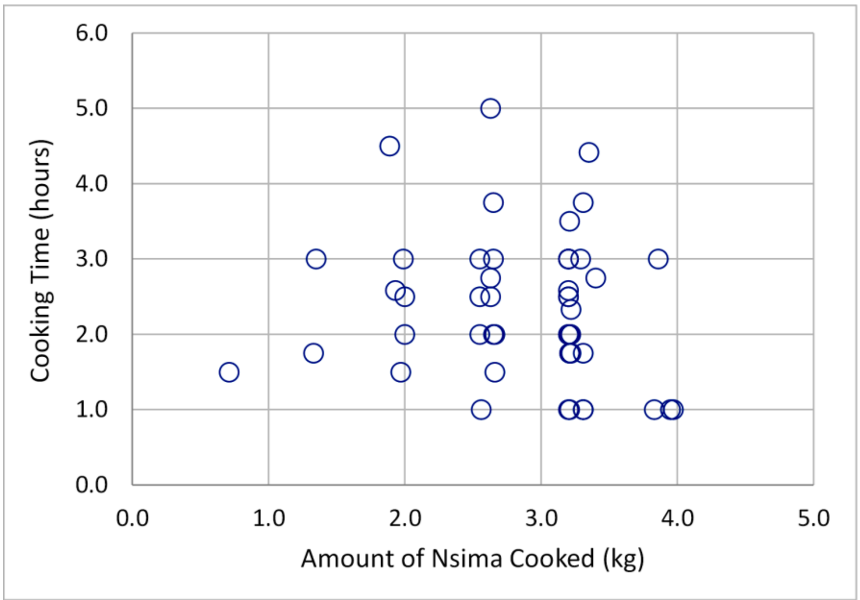


Figure 5: Cooking time vs. amount of *nsima* cooked for a series of cooking tests in a 600W solar electric ISEC cooker.

We see from the cooking tests, that a 600W ISEC can regularly cook between 2 and 4 kilograms of *nsima* per day and that the cooking time ranges generally from 1 to 4 hours with

[14] See: Batchelor, S. Solar electric cooking in Africa in 2020. A synthesis of the possibilities. Evidence on Demand, UK (2015) v + 44 pp. [DOI: 10.12774/eod_cr.december2015.batchelors]

little or no correlation with the amount of food cooked, but with a highly variable cooking time that depends on the amount of sunshine.

For affordability reasons, the SHSw/ISEC system distributed in this project was 150Wp rather than 600Wp. Given such a small system will households choose to cook a very small amount of nsima (i.e. ¼ as much as in the workshop experiments, 0.5 to 1 kg per cooking session), or will they use the cooker to heat water, and then use the hot water for cooking?

What we found universally, is that customers used the lower power SHSw/ISEC to heat water that was then used for cooking or bathing, instead of cooking food in the ISEC.

Next, we describe the details of the ISEC utilization for hot and warm water production in the household.

3.6 Distribution of SHS system utilization frequency for the ISEC customer population during the rainy season

Our key project finding consists of the distribution of ISEC utilization frequencies during the rainy season for the customer population of Kachione, LLC. The utilization distribution function is shown in figure 3 below for the 2 out of 3 customer households that were observed to utilize the ISEC in a SHSw/ISEC system during the rainy season.

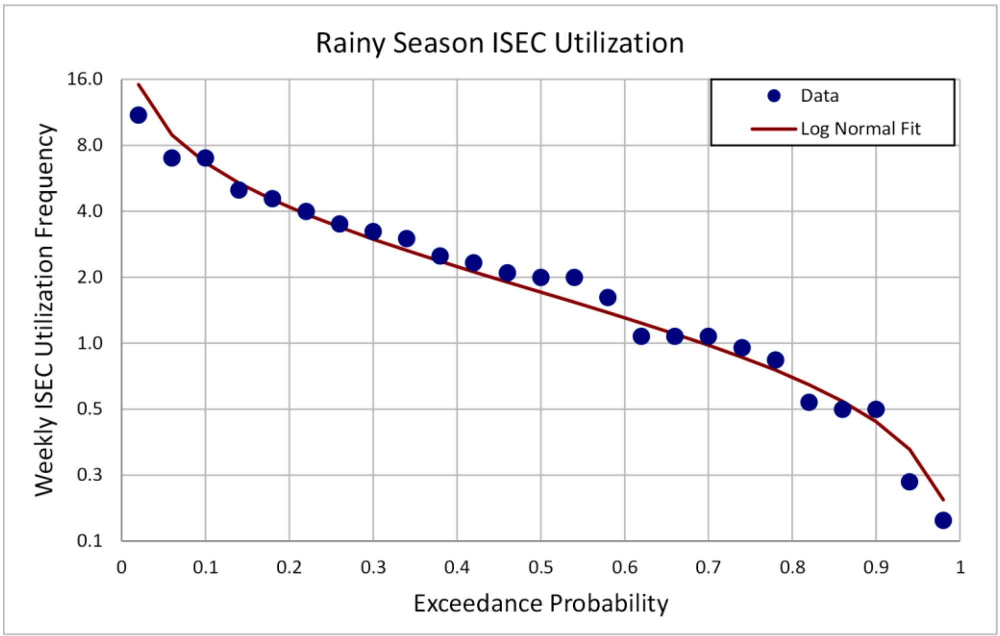


Figure 6: Weekly utilization frequency (uses per week) of the ISEC in a SHSw/ISEC system during the rainy season in the Machinga District of Malawi. Utilization frequency fits a log-normal distribution with a median use of 1.7 times per week, and a standard deviation in the natural log of the utilization of 1.06.

What figure 6 illustrates is that for the customers that use the ISEC, approximately 10% use it more than once per day (i.e. more than 7 times per week), about half of customers use it more than twice per week during the rainy season, and approximately 25% of customer use it less than once per week during the rainy season. The rainy season in Malawi extends from November through March. During the coming sunny season, Kachione, LLC will measure how the utilization frequency of the ISEC changes as the cooking energy provided by the ISEC increases and customers can obtain a greater benefit from using the ISEC.

3.7 A dozen specific findings from the project will help Kachione, LLC rapidly advance the distribution SHSw/ISEC systems and the PayGrow business model in rural Malawi

We have 10 specific findings from our study that are relevant to advancing SHSw/ISEC and the PayGrow business model for solar energy access in very low income rural Malawian villages. These findings include:

1. An ISEC can provide relatively large relative benefits to between 10 and 20 percent of households even during the rainy season through provision of hot water for cooking and bathing.
2. By far, the most prevalent use of hot water in our area of operation is for bathing.
3. The ISEC users with very high utilization rates also use hot water as an input into wood-based cooking in order to reduce wood use.
4. Anecdotally, we observed 7 distinct factors can potentially affect ISEC utilization rates that may warrant further investigation.
5. For the 2/3 of households that utilize the ISEC in the rainy season, the distribution of utilization rates is approximately log-normally distributed with a median utilization of 1.7 times per week and a standard deviation in the log of 1.06.
6. The vast majority of households (~90%) will not provide clothes or materials to help insulate the ISEC even if instructed to do so.
7. It is better to mount solar panels on the roof rather than take the solar panel out each day, except for the 15% to 30% of households where security issues (theft) or roof shading prevent and effect roof-mounting of the solar panels. In addition, a majority of households are hesitant to pay the extra $10 cost of a roof mounting for cost reasons.
8. The potential wood savings of a low-insulation ISEC is 0.1 to 0.5 kg of wood for every kWh of solar panel output at moderately high utilization rates.
9. The potential consumption income benefits of a SHSw/ISEC are 0.2% to 2% of monthly household expenditures for a low-insulation ISEC with a 150W solar panel mounted on the roof for a low-income household.
10. Larger savings may be attainable using a highly-insulated solar electric cooker (HISEC) that has approximately 10 cm. of additional insulation around the nested cooking pots.

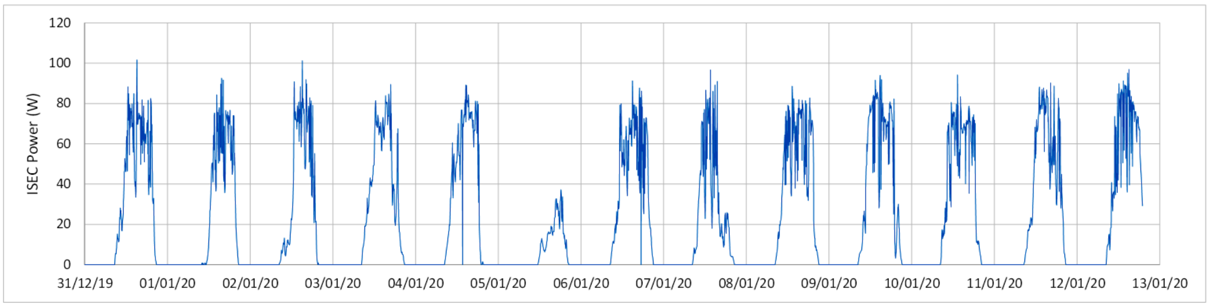
3.8 Using the detailed ISEC monitoring data, we can obtain a field estimate of the maximum solar panel utilization efficiency in a SHSw/ISEC in a Malawi village

Maximum solar panel output utilization efficiency for the maximum utilization case can be approximately estimated from data collected from the best-performing SHSw/ISEC customers as follows:

- Estimate maximum potential solar panel output from current times an estimate of the peak power voltage
- Compare peak potential solar panel output to actual power delivered to the ISEC (current times ISEC voltage)
- Conduct a heat balance calculation of ISEC contents by finding the best-fit parameters of a heat-balance model for ISEC temperature.

- From the heat balance model estimate the energy content of the hot water drawn from the ISEC. This is the energy service output
- Calculate the ratio of energy service output to total maximum potential solar panel output to provide an estimate of the total solar panel utilization efficiency.

Figure 7 shows the detailed data logger monitoring data for the household in the field sample that obtained the highest level of ISEC utilization frequency (i.e. 11 times per week). The monitoring data show the ISEC current, ISEC voltage, and ISEC temperature during a fairly cloudy and rainy time period.



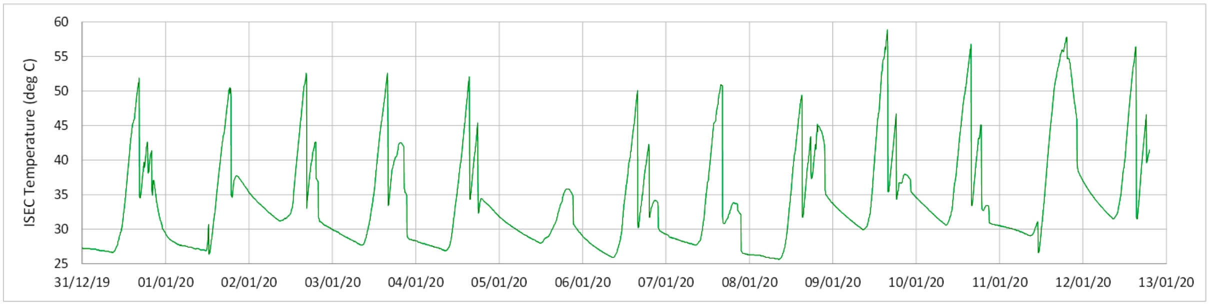


Figure 7: ISEC input power and temperature for a very high utilization household. Note how in this particular household, hot water is drawn from the ISEC more than once per day on average.

Using a heat-balance modelling of ISEC operation with the data in Figure 7, it is estimated that a total of 3.4 kWh of useful energy in the form of hot water is drawn from the ISEC during the 13 day monitoring period, with a total energy input to the ISEC of 6.8 kWh. This indicates that on average, 50% of input energy to the ISEC was lost to the environment. These energy losses can be decreased through the use of an ISEC design with higher levels of insulation. In this case, power was typically delivered to the ISEC at 15 to 16 volts rather than at the peak power voltage of 18 volts of the solar panel. The maximum potential power output of the panel is estimated at approximately 8 kWh during this 13 day period, indicating that a total of about 42% of the total solar panel output capacity was utilized as heat energy in water that was drawn from the ISEC.

For households that utilize the ISEC less frequently, we expect the utilization efficiencies to be lower in proportion to the lower utilization frequency.

3.9 Estimating potential wood savings for SHSw/ISEC users with high utilization efficiencies

Given the total solar panel utilization efficiency of the highest efficiency customers described above, we can now estimate the wood savings for a SHSw/ISEC system using this data and some simple assumptions.

First, we note that the project collected stated wood use from households participating in the study. The median per-capita wood consumption was 0.89 kg/day which at 18 MJ/kg of wood corresponds to 16 MJ/capita/day of wood energy use. Our estimate of 717 kWh/capita/day of cooking electricity requirement corresponds to 2.6 MJ/capita/day of electrical energy use which implies that on an energy basis ISEC cooking is six times more efficient that wood-based cooking.

We therefore make the following assumptions for estimating wood savings for high utilization SHSw/ISEC customers:

- Total solar panel utilization efficiency can potentially range from 10% to 50%
- Daily potential energy output for a 150 watt solar panel can range from 600 Wh/day in the rainy season to 1000 Wh/day in the sunny season, with an annual average potential output of 800 Wh/day
- The wood fuel that is displaced by the ISEC delivers 16% of its energy content to water and food in a three-stone fire and the wood has an energy content of 18 megajoules (MJ) per kg.

With these assumptions, the SHSw/ISEC will save between 80 to 400 Wh/day on average for high utilization households which corresponds to 0.29 to 1.44 MJ/day delivered to the water/food. If wood use is 16% efficient, this corresponds to 1.8 MJ to 9 MJ/day of wood which corresponds to 0.1 to 0.5 kg/wood per day or 3 to 15 kg/month. At a wood cost of $0.09/kg, this corresponds to a savings $0.27 to $1.35 per month. For lower income households that earn less than $70/month of cash income, this corresponds to a savings of more than 0.4% to 2% of household cash income.

Over five years, the wood savings can correspond to total financial savings of $16 to $80 for a total physical wood savings of 0.18 to 0.91 metric tons of wood depending on details of the SHSw/ISEC utilization efficiency. This corresponds to approximately 1.2 to 6 kg of wood savings over five years for every Wp of solar panel capacity for a reasonably well-utilized SHSw/ISEC.

3.10 Comments on cooker durability and reliability

Of the 65 SHSw/ISEC that were distributed to customers in this project approximately 7 cookers failed in the course of six months. Given that a fraction of households did not use the cooker very much, this represents a failure rate for utilized cookers in the range of 10% to 20% in six months.

There are two key failure modes that we have observed for the cookers: (1) Corrosion arising from condensed water seeping between the nested pots, and (2) Burning of the diodes in the heating element.

We believe that with improvements in design and construction methods it should be possible to get failure rates for the cooker below 10% per year.

There are two solutions to the corrosion problem. One is the design better seals between the nested pots. This can be done by simply adding a glue/sealer between the pots before they are covered with aluminium tape during assembly.

The second solution is to corrosion-proof the wiring of the heating element by coating the wires with high temperature epoxy to help prevent moisture that may get between the nested pots from getting to the wires.

There are three solutions to diode burn-out failures. One solution to add additional parallel diode heating elements, this decreases the current per heating element and lowers the temperature of the diodes.

The second solution to diode burn-out failures is to use more material and more careful assembly when attaching the diodes to the pot so that the heat transfer from the diode to the pot is improved and the diode sustains a lower temperature for a given heating power. This is the approach used by the MECS-supported ISEC research group at California Polytechnic State University (http://sharedcurriculum.peteschwartz.net/solar-electric-cooking/)

A third solution is to add temperature shut-off switches to the heating elements to help control the maximum temperature. For the ISEC's used in this study, because each heating element had an average of only 30 watts, and because the cooking pot only rarely, if ever, exceeded 100 degrees C, we did not add temperature control switches to the heating elements. We have tested temperature control switches located near the diode heating elements and we have verified that they can add a further level of over-temperature protection for the diodes to help prevent diode burn-out if this measure becomes necessary in the future.

Limitations of the innovation/approach/design/system

Four key limitations to the technologies and methods for household solar electric cooking access described in this study include:

(1) Malawi-based production of solar cooking equipment has high labour-intensity and the need for low-cost expert supervision and quality control (at least initially);
(2) It can be difficult and expensive to develop long-term customer relationships with a disbursed rural population of low-income households;
(3) It is challenging to attain financial sustainability and high levels of service quality with low-margin production and distribution of solar technology; and
(4) Compared to more conventional cooking technologies and systems, technologies customized for low-income customers may be less attractive to higher-income customers who may have the income and resources to pay profitable prices for more convenient solar electric cooking technologies.

With respect to study data and results, we note that most of the study was conducted during the height of the rainy season in Malawi, when solar resource availability is at its lowest. Several aspects of our results will be different during the sunny season. Some factors will lead to enhanced performance during the sunny season, while other factors will lead to diminished performance.

Factors that are likely to enhance performance and utilization during the sunny season include:

(1) The greater solar resource increases solar panel output on average.
(2) The more reliable availability of hotter water and greater cooking energy can motivate increased utilization.
(3) Greater consistency and reliability of operation may motivate more consistent cooker utilization.
(4) A plentiful supply of solar electricity for other household uses may increase ability and motivation to use a greater portion of available solar panel electricity output for cooking and water heating.

Factors that may diminish performance during the sunny season include:

(1) Higher operating temperatures lead to greater heat losses, and lower efficiency at the cooker.
(2) Dust accumulation can decrease panel performance.
(3) Higher panel temperatures can decrease panel efficiency.
(4) Because the sunny season is winter in Malawi (which is south of the equator), there can be fewer sunshine hours during sunny days.
(5) A potential over-supply of heating energy may lead to lower utilization of the heating energy that is available.
(6) Higher ambient temperatures may decrease the motivation to use hot water available for bathing.

4. Practical applications of the concept to the national cooking energy system (including costs)

4.1 Distributing SHSw/ISEC systems preferentially to high-utilization very-low-income customers

The most important practical result from our study comes from the fact that the top 1/3 of customers that utilize the ISEC the most effectively, obtain 5 to 10 times more cooking benefit on average than the 2/3 of customers that use the ISEC least effectively.

It is therefore very important to target, develop, and nurture high utilization customers in the distribution of SHSw/ISEC systems to very low income communities in Malawi. This is the most consequential and impactful result from our study.

We also note, that at scale, SHSw/ISEC systems retail cost approximately $1 per peak watt (Wp) of system capacity. This cost is very affordable for very-low-income households.

4.2 Crediting customers for the environmental benefits of behaviours that lead to high SHSw/ISEC utilization

A second important and consequential result of the study is that for high utilization customers, the wood savings impact of the SHSw/ISEC is likely to be in the range of 1.2 to 6 kg of wood savings for every peak watt (Wp) of solar panel capacity over a period of five years.

Figure 8 illustrates how—depending on the total environmental and climate mitigation value of the wood savings—this may lead to economically efficient and justifiable subsidies of solar panel costs in such SHSw/ISEC systems.

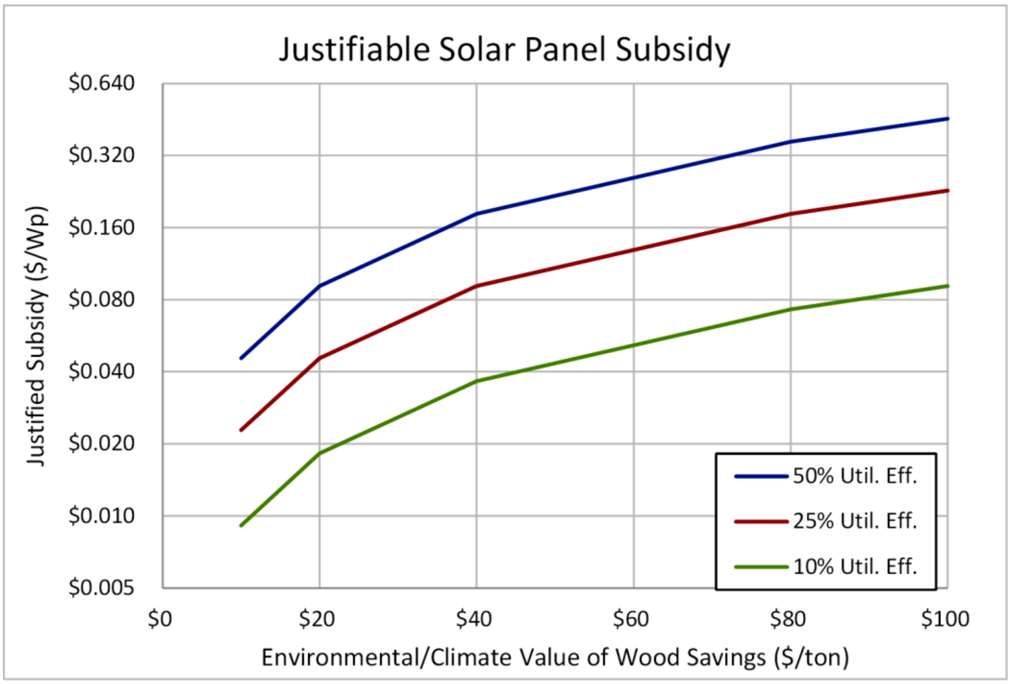


Figure 8: Justifiable solar panel subsidy as a function of the environmental and climate mitigation value of wood savings and the utilization efficiency of the solar panel in a SHSw/ISEC system. Since the wholesale cost of solar panels in Malawi can be as low as $0.40/Wp, then for high values of utilization efficiency and environmental wood savings values, a large fractional subsidy of imported solar panel costs can be justified in some cases.

Such environmental value crediting can potentially pay up to 100% of the incremental cost of solar panel capacity expansions for such systems if the cooker utilization efficiency and the environmental value of wood savings are high enough.

While the environmental greenhouse gas emissions accounting can get very complicated, note that since the social (damage) cost of CO_2 in the atmosphere is approximately $45/ton, and since burning one ton of wood emits 1.8 tons of CO_2, then the environmental value of wood savings can in some cases be as high as 1.8 x $45 = $81/ton. For this—albeit over-simplified case—it is possible to justify a nearly 100% subsidy of the SHSw/ISEC solar panel cost when utilization efficiencies of the solar panel are approach 50% in a SHSw/ISEC system.

4.3 Innovations for further increases SHSw/ISEC benefit/cost ratios

We can further increase the benefit/cost performance of the SHSw/ISEC by developing innovations to the current SHSw/ISEC approach, including the following:

- Initially delivering a SHSw/ISEC system with a smaller solar panel and upgrading the system only after it is confirmed that the customer will utilize the system well.
- Adding Malawi-made pressuring cooking technologies to the SHSw/ISEC system to increase the wood and charcoal use displaced by the system.
- Organizing a group-kitchen style of SHSw/ISEC that has better economies of scale and higher utilization efficiencies than an individual household SHSw/ISEC.
- Providing an "Earn & Grow" incentive for high levels of cooker utilization where customers earn discounts and credits on future system and solar panel purchases based on estimates of wood savings rates from cooker temperature monitoring.
- Increased customer education using a peer-to-peer training model where "power users" explain to their neighbours how to us the SHSw/ISEC with high levels of effectiveness.
- Adding a phase change material (PCM) thermal battery to the ISEC and testing if the improved utility of energy storage and faster cooking increases utilization rates and potential wood savings.

5. Next steps

5.1 Include the costs, time and resources required for next steps of development/implementation

Because organizing in low-income Africa is a largely unpredictable and uncertain enterprise, Kachione, LLC and its partner Kuyere! (https://kuyere.org/) will be taking a multi-pronged approach to further development and distribution of SHSw/ISEC systems that includes the following component activities:

- ***Expanding the PayGrow business model to an "Earn and Grow" model*** where customers can earn rewards for high cooker utilization efficiency. The concept of a strongly incentivized Earn&Grow business model is that customers get a "Climate mitigation earnings accounts" where customers can accumulate credits and "points" for environmentally beneficial reductions in wood consumption.
- ***Exploring the introduction of a smaller and cheaper entry-level SHSw/ISEC system*** that can allow customers to demonstrate their interest in solar electric cooking before upgrading to a more expensive, higher capacity SHSw/ISEC systems.
- ***Developing and field testing ISECs with PCM-based thermal batteries*** that utilize the technologies developed by MECS-supported research at California Polytechnic State University and evaluating the degree to which such improvements can increase utilization efficiencies for some customers.
- ***Designing and developing Malawi-made solar-electric pressure cookers (MM-SEPCs)*** and testing a distribution and customer training model that can empower villagers to effectively use MM-SEPCs to increase the amount of wood they can save. This includes exploring MM-SEPC designs that can also be used on wood fires where they can save energy on cloudy days. This activity also includes collecting the data and developing the models that can allow estimation of MM-SEPC efficiency and wood savings impacts.
- Continuing the process of ***converting Kachione, LLC customers from battery-based solar lighting and phone charging systems*** to super-capacitor-based solar lighting and phone charging systems so as to increase the lifetime and durability of the non-cooking component of SHSw/ISEC systems.
- ***Developing collaborations with companies and projects interested in deploying SHSw/ISEC technologies*** in other markets in Malawi or in neighbouring countries (e.g. Tanzania)
- Kachione, LLC plans on ***developing and testing an Earn&Grow group kitchen concept*** that can attain greater economies of scale and utilization efficiencies for small groups of households than can be obtained with individual SHSw/ISEC systems.

In terms of costs, simple deployment of SHSw/ISEC systems has a net cost of approximately $100 per household at the moment while field testing new ideas, collecting data, analysing data and documenting results costs roughly $500 per household. The number of households involved in deployment activities vs. innovation, research and development activities will depend on the amount of funding obtained for each type of activity over the coming months.

5.2 Note any funding planning to apply for such as EU, Innovate UK etc.

Kachione, LLC submitted an application to MECS-ECO to develop its SHSw/MM-SEPC system and start training customers in MM-SEPC utilization.

5.3 Note any partnership developments, new investors engaging with etc.

We have a partnership in active development with Africa Power, Ltd, and their Mwanza, Tanzania development efforts. We are also in the process of marketing the battery-free SHSw/ISEC concept to clean energy policy-makers in West Africa.

Dissemination Plan

5.4 *Discuss the dissemination measure done already – provide link for where on the internet the report is published by you, what journals you have plans to publish, conferences attending to publicise the research etc.*

Our dissemination strategy and plan include the following:

- ***Upgrade the design of our systems and business model and disseminate to existing customer base***. A new and improved SHSw/ISEC using a soon-to-be-developed Earn&Grow business model to our network of 3000 customers distributed throughout more than 100 villages in rural Malawi.
- ***Write and expanded version of the project report and distribute it*** on researchgate.net and academia.edu.
- ***Cooperatively collaborate with other MECS-supported teams*** to spread knowledge of our findings and to spread our technology and business model to new sectors in Africa and new countries.
- ***Collaborate with energy justice researchers to submit a paper to Nature Energy.*** Specifically, we hope to submit a paper entitled: “A new, justice-based business model for solar electrification in rural Sub-Saharan Africa.”
- ***Promote the strategy of battery-free off-grid solar home systems with solar electric cooking*** to policy circles and policy-organizations throughout Africa and beyond as the most affordable and cost-efficient means of providing substantial solar electricity access to low-income rural African communities.

6. Conclusion

For low income households in rural Malawi with per-capita incomes of $1/day or less in dollars that are not adjusted for purchasing power. Meanwhile, approximately 60% of the daily household cooking and hot water energy requirements of 3.1 kWh/day are for either heating water for washing or heating water for use in cooking the staple food, *nsima*.

An affordable, entry-level, 150 watt-peak solar home system with insulated solar electric cooker (SHSw/ISEC) can provide a variable amount of water heating of 0.5 kWh/day or more if the ISEC is utilized at a relatively high level of efficiency. Approximately 1/3 of customers in rural Malawi appear to be disposed and willing to utilize such systems at high levels of efficiency.

This creates the possibility of creating a pay-as-you-grow (PayGrow) business model for increasing levels of solar electricity access for very low income households in rural Africa. It will take several years of accumulating incrementally larger amounts of solar system capacity to reach system sizes that can provide a large fraction of a household electric cooking energy requirements of 3 kWh/day or more. But households in rural Malawi have demonstrated an ability to efficiently fuel stack and use solar electricity for creating hot water that is then input into water-intensive cooking processes or used for bathing. We at Kachione, LLC believe that this provides a sufficient foundation for expanding the PayGrow business model further and using it as a means of disseminating many thousands of highly affordable off-grid solar electric cooking systems in rural Malawi over the coming years.

7. Appendices

Appendix A: Characterization of household consumption and income

	# People	Per Capita Consumption and Spending					Total HH
Index	in HH	Cash Spndng	Self Prod	Tot Consump.	Invest. Spndr	% SelfPrd	Consump./day
1	4	$0.95	$0.52	$1.47	$0.04	35.3%	$5.87
2	5	$0.84	$0.29	$1.14	$0.07	25.9%	$5.69
3	3	$0.82	$0.27	$1.10	$0.11	24.9%	$3.29
4	4	$0.51	$0.32	$0.83	$0.00	38.8%	$3.33
5	4	$0.52	$0.28	$0.80	$0.00	35.3%	$3.20
7	4	$0.83	$0.18	$1.01	$0.04	18.1%	$4.04
8	2	$0.87	$0.60	$1.47	$0.35	41.0%	$2.94
9	4	$0.60	$0.05	$0.65	$0.00	7.6%	$2.61
10	4	$0.91	$0.25	$1.16	$0.00	21.4%	$4.65
11	5	$0.85	$0.00	$0.85	$0.23	0.0%	$4.27
12	4	$1.32	$0.64	$1.96	$0.01	32.9%	$7.85
13	4	$1.56	$0.46	$2.02	$0.07	22.8%	$8.07
14	6	$0.32	$0.22	$0.54	$1.54	40.9%	$3.22
15	6	$0.48	$0.21	$0.69	$0.62	30.7%	$4.17
16	6	$0.39	$0.03	$0.41	$0.16	6.4%	$2.49
17	6	$0.29	$0.23	$0.52	$0.47	44.7%	$3.14
18	6	$0.43	$0.04	$0.47	$0.48	8.1%	$2.83
19	3	$0.64	$0.17	$0.81	$0.79	20.8%	$2.42
20	4	$0.61	$0.04	$0.65	$0.48	6.2%	$2.58
21	5	$0.35	$0.02	$0.37	$0.24	6.1%	$1.87
22	3	$0.60	$0.09	$0.69	$0.61	13.7%	$2.08
23	3	$0.43	$0.59	$1.02	$0.00	58.1%	$3.06
24	5	$0.56	$0.00	$0.56	$0.38	0.0%	$2.78
25	5	$0.58	$0.01	$0.59	$0.00	1.5%	$2.96
26	4	$0.74	$0.07	$0.80	$0.85	8.5%	$3.22
27	3	$0.37	$0.16	$0.53	$0.00	29.9%	$1.60
28	5	$0.20	$0.29	$0.48	$0.27	59.2%	$2.42
Avgs	4.33	$0.65	$0.22	$0.87	$0.29	23.7%	$3.58

Table A-1: Consumption income for a sample of study households. Per-capita income is broken down into cash spending and non-cash self-production. Fertilizer, farm labour and house construction expenses are classified as investment spending.

Table A-1 shows the income characteristics of the households participating in the study for which fairly complete, good quality consumption and spending data was gathered.

Average household size was 4.3 persons, with an average household consumption income of $3.58 per day, meaning that per-capita consumption spending is less than $1 per day. Most spending and consumption is for food.

Item	Avg. Spend
Corn	$0.839
Beans	$0.141
Rice	$0.448
Cooking Oil	$0.122
Sugar	$0.143
Salt	$0.024
Onions	$0.025
Tomatoes	$0.224
Vegetables	$0.189
Milk	$0.011
Eggs	$0.082
Fish	$0.271
Chicken	$0.113
Goat	$0.139
Battery	$0.004
Candles	$0.005
Phone Credits	$0.243
Phone Charging	$0.002
Soap	$0.080
Meds/Hosptl	$0.105
Transport	$0.058
Building Mat.	$0.171
Water	$0.007
Farm Labour	$0.138
Fertilizer	$1.021
Bicycle Repair	$0.047
Other	$0.023
Wood/Charcoal	$0.159
Total	$4.834

Table A-2 provides detail on the average households spending on individual items. The biggest expenditure for subsistence farming households is investments in fertilizer for growing crops. The next biggest consumption item is corn, which usually is not explicitly purchased with cash but is usually self-produced by most households.

Rice is another high consumption item, and is often self-produced, as are vegetables.

Most households purchase food protein, cooking oil, sugar, soap, and goat meat from the market. Most households raise their own chickens. Battery, candle, and phone charging expenditures are essentially zero because households get these services from their solar systems.

Wood and charcoal consumption appears to be a few percent of household total spending and is about $0.159/day which is about 4.4% of total non-investment consumption and spending of $3.58/day. Note that fertilizer, farm labour and building materials are not included in consumption spending because they are investments in self-production.

Survey responses indicated that the local market price for wood of approximately $0.05 per kilogram. The household consumption of $0.159 per household per day corresponds to about 3.2 kilograms per household per day. The energy content of 3.2 kilograms of wood is approximately equivalent to the energy content of about 14 kWh. Considering that the conversion of wood energy content to energy in food is more than 5 times less efficient than converting electricity to food energy, this is roughly consistent with our estimate of and electric cooking energy requirement of 3.1 kWh/day per household.

Table A-2: Average household daily spending and/or consumption value for households in the study.

Appendix B: Estimation of household cooking energy requirements from survey data

Item	Spndg Per Cap	Price/kg	kg/Unit	Price per	Unit	Dry weight kg/cap/day	Wet weight kg/cap/day	Wh/kg	Wh/cap/day
Corn	142.5	388.0	50.0	19400	bag	0.367	2.204	150	330.5
Beans	24.0	566.7	1.0	567	kg	0.042	0.254	300	76.2
Rice	76.0	677.8	1.0	678	kg	0.112	0.336	150	50.5
Cooking Oil	20.7	964.7	0.9	820	liter	0.021	0.021	150	3.2
Sugar	24.2	1255.6	0.5	628	liter	0.019	0.019	150	2.9
Salt	4.0	906.3	0.2	181	liter	0.004	0.004	150	0.7
Onions	4.2	500.0	0.1	50	ea	0.008	0.025	150	3.8
Tomatoes	38.0	481.5	0.15	72	ea	0.079	0.237	150	35.5
Vegetables	32.1	250.0	0.2	50	bunch	0.128	0.385	150	57.7
Eggs	13.9	1666.7	0.060	100	ea	0.008	0.017	150	2.5
Fish	45.9	1500.0	0.2	300	pile	0.031	0.153	300	45.9
Chicken	19.2	3928.6	0.7	2750	ea	0.005	0.010	300	2.9
Goat	23.7	2185.7	1.0	2186	kg	0.011	0.022	300	6.5

Table B-1: Calculation of cooking energy requirements from household consumption survey data. All prices are in the local Malawi currency, Malawi Kwacha (MWK).

Table B-1 illustrates the calculation of household cooking energy requirements from household consumption survey data.

The household survey provides average per-capita daily spending on different food items and average prices for the food items. The different food items come in different units, and by converting those units into equivalent kilograms we get prices in units of currency (MWK) per kilogram. This allows us to translate daily average spending into daily kilograms of food consumption for different foods.

Our workshop experiments provided data that strongly indicated that foods break down into more energy intensive foods and less energy intensive food. More energy intensive foods appear to require approximately 300 watt-hours of energy per wet kilogram of food cooked. Less energy intensive foods require about half this amount or 150 watt-hours of electrical energy per kilogram of food cooked.

We calculate the wet kilograms of food from the dry kilograms of food by multiplying by the appropriate ratio that represents the amount of water that is typically used to cook the food. For beans and corn meal, we use the ratio of 6:1 to convert from dry to wet kilograms. For rice and other foods, we use the ratio 3:1. In the future, we will conduct more experiments in order to estimate these wet-to-dry weight ratios more precisely.

Given daily per capita dry-weight consumption, energy intensity, and wet-to-dry weight ratio the calculation is a simple multiplication of factors, and the result is provided in the right hand column of table B-1. These different food items are then combined into different food groups to provide the results presented in the main report.