Empowering Efficiency, Phase II: Refining an affordable Solar Home System with eCooking for rural Malawi.

Final Project Report

Empowering Efficiency, Phase II: Refining an affordable Solar Home System with eCooking for rural Malawi

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Executive Summary

This report, ***Empowering Efficiency, Phase II: Refining an affordable Solar Home System with eCooking for rural Malawi***, describes the results of a 1.5-year project (2023 – 2024) to make off-grid solar electric cooking systems (OGSECS) more affordable and accessible for some of the lowest income households in rural Malawi.

This project was financed by a continuation grant for the Empowering Efficiency project from the Modern Energy Cooking Services programme (https://mecs.org.uk/) and implemented by the Malawi social enterprise, Kachione LLC (KLLC).

The results and learnings from the first phase of the project are documented in the report: *Empowering Efficiency: Distributing off-grid solar electric cooking systems using women-lead organizing in rural Malawi*.[1] The first phase of the project established the beginnings of a highly cost-efficient village-based network of solar shops operated by local women's groups. In addition, the first phase of the project developed an initial low-cost OGSECS design without battery and began the process of designing and testing a high-power, long-lasting cooking system battery based on lithium titanate (LTO) battery chemistry.

In phase II of the project, KLLC pursued the following five areas of expansion and improvement

(1) Distribution system expansion
(2) Cost-efficiency improvements
(3) Improved cooking system efficiency & performance
(4) LTO solar-electric cooker battery improvement and testing
(5) Development and refinement of a Results-Based Financing (RBF) business model

The phase II project made progress in all five areas:

(1) The distribution system expanded from 5 to 15 village shops
(2) The cost per unit of OGSECS cooking power output decreased by 50%
(3) The efficiency of system capacity utilization anecdotally increased to as high as (A) 1.5 watts-hours/day of cooking power delivered for every 1Wp of solar panel capacity and (B) 1.5 watts-hours/day of battery utilization per watt-hour of battery capacity.
(4) LTO battery design and assembly processes were improved with a production run of 80 batteries in June/July 2024. KLLC is now preparing for a production run of 500 Malawi-assembled LTO batteries to be completed by April 2025; and
(5) Extensive data was taken regarding cooking energy intensity (i.e. kWh used per kg of cooked food) in OGSECS for most Malawian dishes. In addition, a household socio-economic benefit/impact study was conducted to estimate per-kWh environmental and socio-economic benefits of rural household OGSECS use.

At the end of the phase II project, KLLC now has the capability to sell more than 20 OGSECS's per week through a network of 15 village shops. The price that customers are willing to pay is between $100 and $150 for a ~700Wp system composed of imported materials[2] that cost between $150 and $200 to import in bulk volumes (i.e. by the container load). KLLC also now has the capacity to assemble 20V, 200Wh, 600Wp LTO batteries with built-in data collection at a cost of approximately $100 per battery. It is currently unknown what the rural customer willingness to pay for LTO batteries is, and the extent to which such batteries are likely to increase off-grid cooking electricity use in practice.

The OGSECS currently being distributed by KLLC can provide between 1 and 2 kWh/day of off-grid, daytime cooking which can produce between 4 and 10 kilograms of cooked food.

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[1] https://www.researchgate.net/publication/369266881_Empowering_Efficiency_Distributing_off-grid_solar_electric_cooking_systems_using_women-_lead_organizing_in_rural_Malawi

[2] Imported materials include two solar panels of approximately 350Wp each, a 600Wp maximum power point tracking (MPPT) controller, and a 24V DC electricity pressure cooker (DC-EPC).

Each kWh of cooking saves the energy equivalent of approximately 2 kg of wood fuel. Most rural customers use relatively small amounts of charcoal for cooking (i.e. about 25% of the time). It is currently unknown to what extent the average OGSECS customer will use the cooking system to its full potential.

The key learnings of the phase II project are as follows:

- **The most important benefits and performance feature**: The OGSECS benefits that customers value most are saving time and money, and the system can most effectively save time by cooking faster. Once the capital investment is made to buy the system, the buyer's need for wood and charcoal is reduced thus saving money.
- **Minimum cooking system capacity**: A 350Wp OGSECS does not reliably save cooking time even when it has a 200Wh battery, while a 700Wp battery-free OGSECS does reliably save cooking time: i.e., about 2 hours per day on sunny days.
- **Solar panel size determines daily cooking capacity**: OGSECS cooking speed and daily cooking capacity is most reliably correlated with solar panel size, with a 700Wp OGSECS being able to provide 1kWh per day of cooking on average which produces about 5 kg of food.
- **What customers cook**: OGSECS customers typically cook about five dishes per day in total for their household: two pots of nsima (ground maize cooked with water), one dish of a root starch (e.g. potato or cassava), a vegetable dish, and a protein dish (fish, soy pieces, eggs or meat). A 700Wp OGSECS can cook about half of this total.
- **Household cooking energy requirements**: It is estimated that a typical household of five people will cook a total of 12.5 kg of food per day which will require 2.5 kWh/day to cook. On a sunny day a 700Wp OGSECS can provide up to 1.5 kWh of cooking energy.
- **Cost and willingness to pay for an off-grid cooking system**: A 700Wp battery-free OGSECS costs about $250 to supply to low-income rural Malawi customers who are willing to pay about $145 for the system (at the official exchange rate).
- **Last-mile sales network**: It is fairly straight forward to maintain and grow a network of rural women-run solar shops at a cost of less than $100/month per shop if there are discounted solar products (i.e. solar lights, solar pumps and solar cooking systems) for the shops to sell and if the women can earn a 10% to 20% commission on the products that they sell.
- **Financial model for scaling distribution**: It should be possible to efficiently scale the KLLC model for distributing OGSECS if an impact-oriented Grantor can be found that can pay $0.20 per kWh of verified cooking services delivered to rural Malawians, and if a Lender can be found to provide equipment import loans that are secured by the collateral value of the grant contract. This arrangement is similar to a Clean Impact Bond (Stritzke et al., 2023).
- **Quantified cooking system benefit values**: The total monetized value of the benefit that the cooking services provide is estimated at $0.731/kWh, with 74% of the benefit accruing as women's time savings, 15% of the benefit accruing as decreased cooking fuel expenditure, 6% of the benefit accruing as health improvement and 6% of the benefit accruing as climate change mitigation.
- **Off-grid solar electric cooking is less expensive than liquid petroleum gas (LPG)**: The equivalent fuel cost of LPG-based cooking in Malawi corresponds to $0.275/kWh which can be more than twice the cost of cooking services provided by a well-utilized OGSECS. This implies that if Malawi's rural households transition to clean cooking with OGSECS that are utilized well, this could save the country hundreds of millions of dollars per year in decreased fuel import and distribution expenses over the long-term compared to an LPG-based clean cooking transition.

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1. Introduction

The Problem Setting

The problem setting for this report on phase II of the Empowering Efficiency project is largely the same as the problem setting for the first phase of the project:

Globally, about 1 billion people remain without access to substantial quantities of 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 fraction of the population without clean energy access is 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, agricultural residues, charcoal, or some combination of the three fuels. As of 2022, about 22%[3] of households in Malawi's four largest cities (Lilongwe, Blantyre, Mzuzu and Zomba) used electricity for cooking, and about 6% use LPG (US AID/UK AID, 2022). Only 18% of Malawi's population lives in urban areas.

Per-capita income in Malawi in current dollars in 2023 is $693/year on average according to World Bank data.[4] Yet most people in Malawi have less than average income. In addition, much income earned by rural Malawians is not in the form of cash but in the form of goods (i.e. crop harvests) and services (e.g. free housing) that are consumed without being purchased with cash. Thus, most Malawians live off of less than $1 per day per capita cash spending when one looks at the actual cash income that households can earn in local currency compared to foreign exchange rates. Because of declining exchange rates, such local currency income tends to have a declining purchasing power when it comes to purchasing imported technology.

In surveys that we have conducted with a non-random sample of customers for this study, the average household non-farm cash expenditure for rural customers is less than $70/month for a household of more than 5 people.

Aims of Phase II of the Efficient Empowerment project

The aim, or long-term outcome that we seek in the Efficient Empowerment project is to provide access to relatively large amounts of solar electricity to rural Malawian households. These aims have not changed since the first phase of the project. Specifically, we wish to make Tier 3[5] electricity access available and affordable to the vast majority or rural Malawian households, consistent with the objectives of Sustainable Development Goal #7 (SDG7)[6] including access to Tier 4-5 clean cooking.[7] This will allow rural Malawians to not only have

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[3] From https://pdf.usaid.gov/pdf_docs/PA0211C8.pdf: "71.8% were connected to the grid at midline, only 30.2% of those HHs reported using electricity for cooking" and 71.8% x 30.2% = 21.7%

[4] https://data.worldbank.org/indicator/NY.GDP.PCAP.CD, accessed September 2024.

[5] See: https://mtfenergyaccess.esmap.org/methodology/electricity, accessed September 2024

[6] https://www.unep.org/topics/sustainable-development-goals/why-do-sustainable-development-goals-matter/goal-7-affordable, accessed Octobert 2024

[7] https://mtfenergyaccess.esmap.org/methodology/cooking, accessed September 2024

access to lights and other electronics, but also enough electricity to cook most of their food with off-grid solar electricity.

We pursue these aims by pursuing the following five component goals:

1) Put women in control of the resources that determine solar electricity access for their household
2) Operationalize improvements in appliance efficiency that include both behaviour (i.e. utilization efficiency) and system efficiency effects
3) Advance innovation to radically reduce the life-cycle cost of electric cooking appliances for the lowest income households in Africa
4) Deploy both inexpensive battery-free solar systems and more expensive, but affordable solar systems with 10-year-lifetime batteries, where the core element of the solar system serves primarily the needs of gendered labour (i.e. for cooking).
5) Create a business model based on the concept of “economically efficient subsidies” where donation and aid revenues are channelled into targeted subsidies that efficiently deliver full benefit value to low-income women for their efficient climate-change-mitigating and socioeconomic-welfare-increasing actions

To accomplish such ambitious aims at scale will take many years and millions of dollars of aid investment. But an objective of the present project is to show in what ways the attainment of such aims may be technically and economically efficient, feasible and practical.

Objectives of the Phase II project

The objectives or short-term outcomes that we have sought to accomplish in the Phase II project in support of our longer-term aims are as follows:

1) To sustainably expand the network of village solar shops run by local women’s groups that are distributing solar pumps and solar cooker systems.
2) To improve the cooking system parts procurement so that the cost of imported parts per unit capacity decreases by more than 20%.
3) To improve the design and utilization of the cooking system so that the efficiency of system utilization can be maximized.
4) To refine the design and production process for Malawi-assembled LTO cooker batteries that are long-lasting, affordable, and able to record high-resolution operational data. And to test the use of battery data for estimating and evaluating off-grid solar electric cooking system (OGSECS) impacts; and
5) To estimate the benefits of OGSECS use for rural households in order to evaluate under what circumstances economically efficient results-based subsidies are feasible. The goal of “economically efficient” subsidies is to finance the difference between what customers are able to pay for an OGSECS and the cost of procuring, selling and delivering OGSECS to rural customers.

2. Cooking system design improvement

Adding a Maximum Power Point Tracking (MPPT) controller

During most of 2022, the first phase of the Efficient Empowerment project was pursuing a strategy in direct-DC solar (DDS) cooking system design where system efficiency was maximized by matching the power supply characteristics of the solar panel with the load characteristics of the DC electric pressure cooker (EPC).[8]

Near the end of 2022, the project began experimenting with MPPT controllers in a DDS cooking system design. The key advantage of using an MPPT is that the solar panel characteristics do not have to match the characteristics of the DC EPC load and the MPPT can adjust the voltage and current to the load to provide power from the solar panel at maximum efficiency. This conversion/matching efficiency of the MPPT is typically around 90%.

Initial selection of solar panel size

In 2021, the Efficient Empowerment project team published a paper—*How to make solar electric cooking cheaper than wood-based cooking*[9]–that analysed in detail the cost structure of off-grid solar-electric cooking. This previous study provided calculations of system cost and efficiency when the system is used once or twice per day.

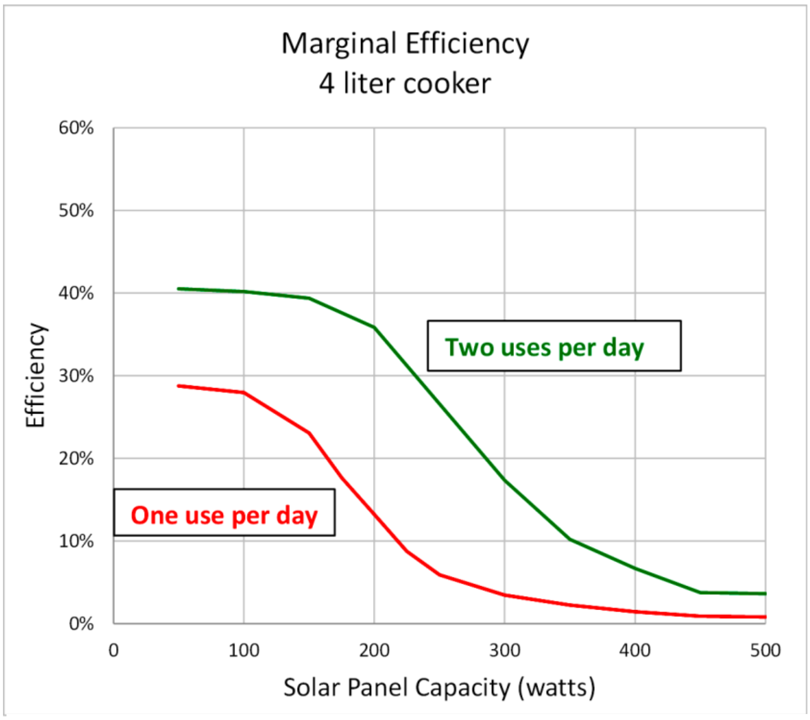

Figure 1:Marginal efficiency vs. solar panel capacity for a DDS cooker and water heater for two different use cases. In the more efficient use case water is drawn from the cooker twice per day at noon and 5PM, and in the less efficient use case water is drawn once per day at 4PM. (from [Van Buskirk, et.al, 2021])

Figure 1 shows how the marginal efficiency of utilization of a direct-DC solar cooking system varies as a function of solar panel capacity and whether the cooker is used once or twice per day. These initial calculations indicate that if a 4-liter cooker is used once per day, a solar panel of 250 watts should suffice, whereas if a cooker is used twice per day, a 350-watt solar panel should be sufficient.

Thus, at the beginning of the Phase II project, the initial OGSECS design had a solar panel of approximately 350 watt-peak capacity, which is connected to a MPPT

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[8] See for example: https://mecs.org.uk/blog/an-off-grid-solar-photovoltaic-electric-pressure-cooker-system-that-costs-only-200-in-malawi/

[9] https://www.mdpi.com/1996-1073/14/14/4293

voltage converter that powers a 5-liter 24V DC EPC. Specifically, the EPC used in this project is the eWant DC EPC which was reviewed and evaluated by the MECS program in 2021.[10]

The manufacturer accommodated a modification to the DC EPC, and provided a “Low Power” button that turned off one of two parallel heating elements in the cooker when the button was turned on. This means that the cooker has two power settings: (1) A “High Power” setting where the cooker heating element has a resistance of $R = 1.1$ ohms and a heating power of about 500 watts at 24V, and (2) a “Low Power” setting where the cooker heating element has a resistance of $R = 2.2$ ohms and a heating power of approximately 250 watts at 24V. We also note that the cooker operates well at a wide range of voltages, i.e. approximately $V = 10V$ to 26V. We note that the heating power of the cooker is $P = V^2/R$. Thus, the cooker can operate at power levels ranging from 50 watts to more than 500 watts.

Testing variations in cooking system design

Figure 2 shows the KLLC workshop set-up for testing the cooking performance of the initial OGSECS design.

Figure 2: Testing set-up for evaluating the cooking performance of the initial design of an off-grid DDS solar electric cooking system with a DC-EPC.

The initial workshop system consisted of a 370-watt or 355-watt solar panel, a 400-watt MPPT set at a target voltage of 20 volts, a power meter with cumulative energy measurement, and a 5-liter, 24V eWant DC EPC. The cooking protocol was to cook one or two dishes per day where for each dish at the beginning of the test, the initial energy, weight of the initial ingredients, initial time, and added water is measured, and where at the end of

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[10] See: https://mecs.org.uk/wp-content/uploads/2021/08/eWant-24V-DC-5-litre-cooker.pdf

the test, the final weight and final energy is measured. These tests were conducted from mid-February 2024 through the end of August 2024 and data for a total or more than 1500 cooked dishes was collected.

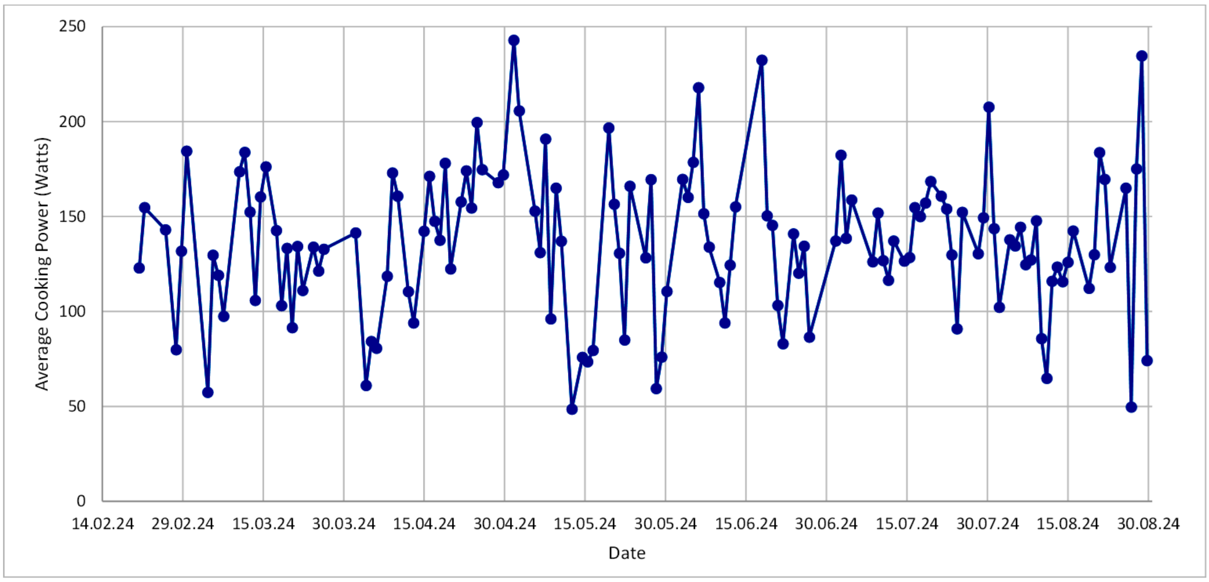

Figure 3: Average cooking power for the workshop cooking tests. Cooking power varies with the daily solar resource, ranging from as low as 50 watts to above 200 watts for DDS cooking systems that have an average solar panel capacity of approximately 350 watts.

Figure 3 provides the average cooking power in watts as a function of the day of the test. Each cooking station has an energy meter and the average cooking power is the energy difference during the cooking event divided by the time elapsed during the cooking event. Figure 3 illustrates the average power for all cooking events observed on any particular day. The primary cause of the variability of the cooking power is how the solar resource varies from day to day for more vs. less cloudy days.

System cooking power determines daily cooking capacity

Figure 4 illustrates how the daily average energy use per dish varies with the average cooking power for that day for the Blantyre workshop cooking tests. The fact that energy use per dish varies with cooking illustrates how the cooks in the Blantyre workshop often adjusted the size of the dish cooked as a function of the power that was available for cooking.

Though the protocol encouraged the cooking of more than one dish per day, typically cooks in the Blantyre workshop cooked only one dish per day per utilized system.

The data indicates that when the cooking power is between 100 and 150 watts, then the measured daily cooking use is about 0.5 kWh. Meanwhile, extrapolating the regression line, the practical cooking capacity of the system should be about 1 kWh/day when the cooking power is between 250 and 300 watts.

This is the key result of the performance analysis of the Phase II project: OGSECS daily cooking capacity is proportional to the cooking power typically delivered to cooker during use. Thus, any design change that increases average cooking power while cooking is likely to create a proportional increase in the average daily cooking capacity of the OGSECS.

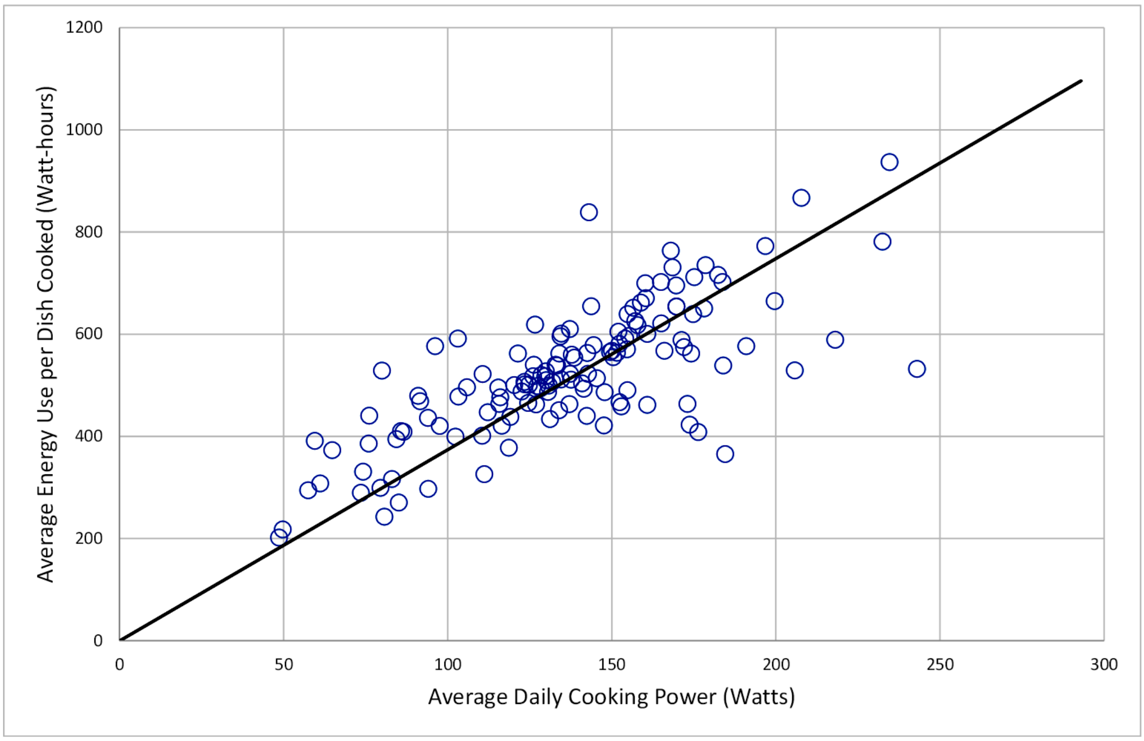

Figure 4: Energy use per dish vs. average cooking power for Blantyre workshop cooking tests.

In addition to the Blantyre workshop cooking tests, similar tests were replicated in some of village solar shops (described in the next section). As illustrated in Figures 5 and 6, the cooking energy use per dish was different in the village shop tests compared to the Blantyre workshop tests. In the village shop tests the energy use per dish was observed to be roughly constant in the village shop tests while dishes per cooker per day often varied.

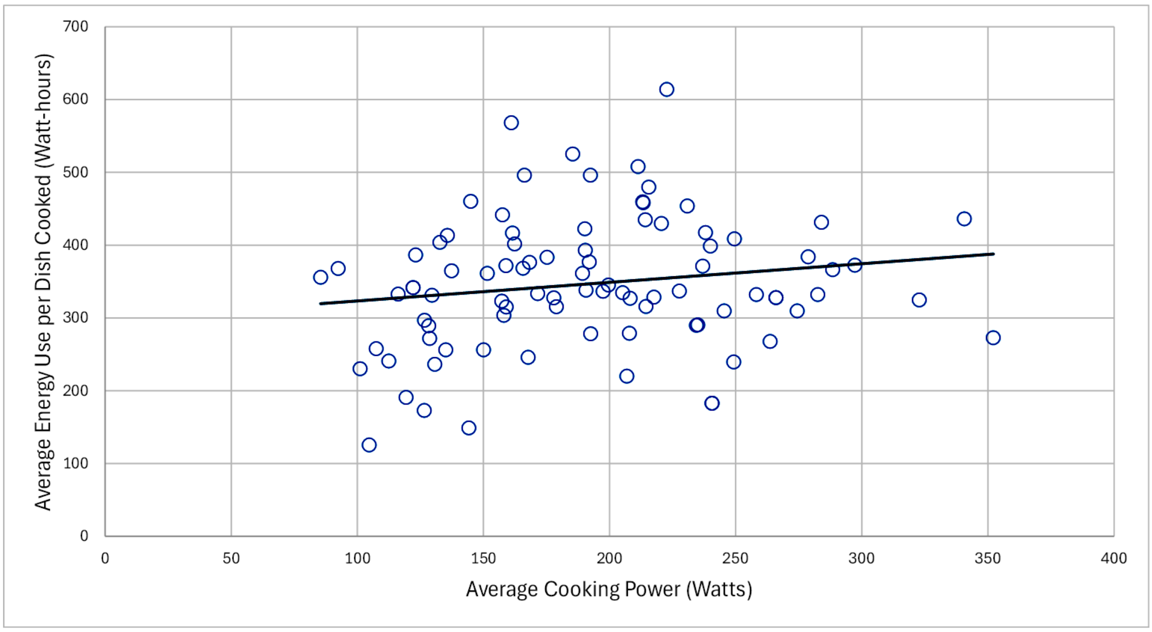

Figure 5: Energy use per dish vs. average cooking power for village shop cooking tests

In the Blantyre workshop the workers tended to cook one dish per cooking system per day. In the village shop tests, the women's collective that collected the most data often cooked many dishes per day per cooking system. The village shops had much fewer cooking systems available than the Blantyre workshop and were paid per dish for data collection.

Thus, the women's groups could best maximize their data collection income by maximizing the number dishes that they cooked per system.

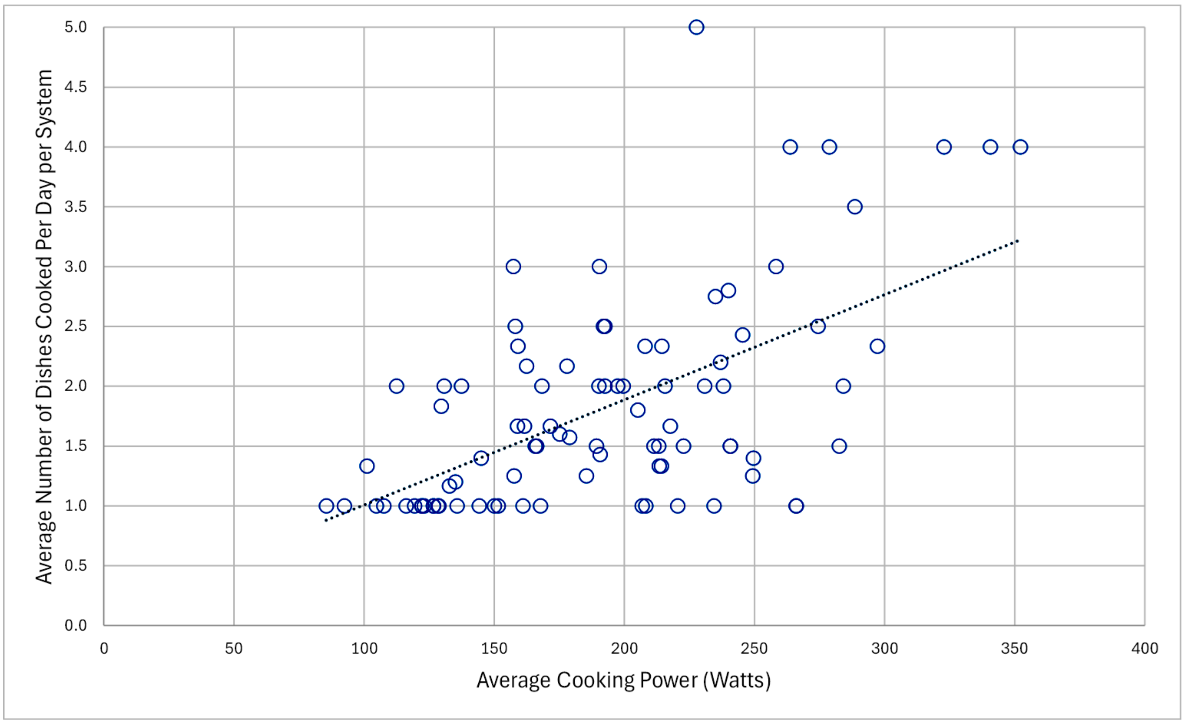

Figure 6: Number of dishes per cooker per day per system in village shop cooking tests as a function of daily average cooking power of OGSECS systems in use during that day.

But in terms of cooking capacity, it does not matter if someone cooks one large dish or multiple smaller dishes, the total amount of food cooked by the OGSECS in a day is roughly proportional to the total daily energy output of the cooking system.

Figure 7 illustrates that the average cooking energy use per day per system in the village shop cooking tests which follows a regression that is similar to the regression line calculated from Blantyre workshop cooking data in Figure 4.

The village shop regression line indicates that an OGSECS that provides 150 watts of cooking power can deliver on average 0.5 kWh/day of cooking, while an OGSECS that provides 300 watts of cooking power can deliver 1.0 kWh/day of cooking services on average. This is approximately in agreement with the Blantyre workshop OGSECS daily cooking capacity result shown in Figure 4.

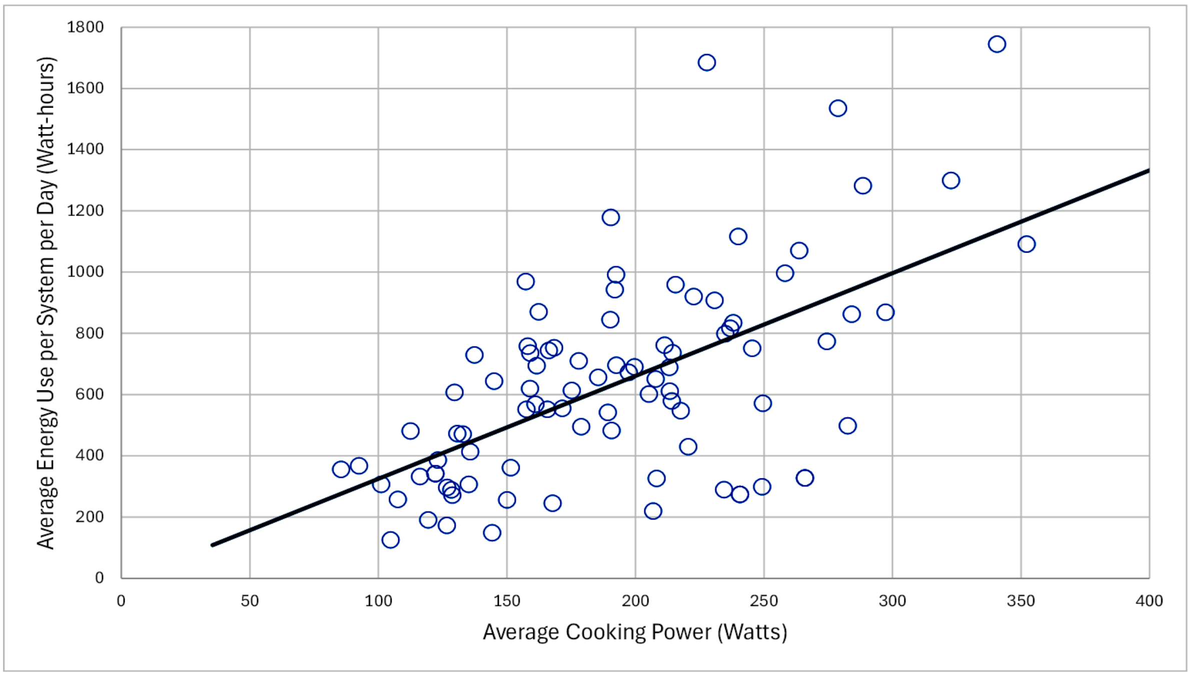

Figure 7: Average daily cooking energy use per system as a function of the average daily cooking power for the village shop tests.

3. Evolution and optimization of village shop network

In the first phase of the Efficient Empowerment project, KLLC established five village solar shops run by local women's groups. For the phase II project that began in early 2023 KLCC planned to establish at least an additional five shops.

As illustrated in Figure 8, KLLC implemented a net change of 9 additional shops in 2023, and a net of 5 additional shops so far in 2024 for a current total of 19 shops in its current sales network.

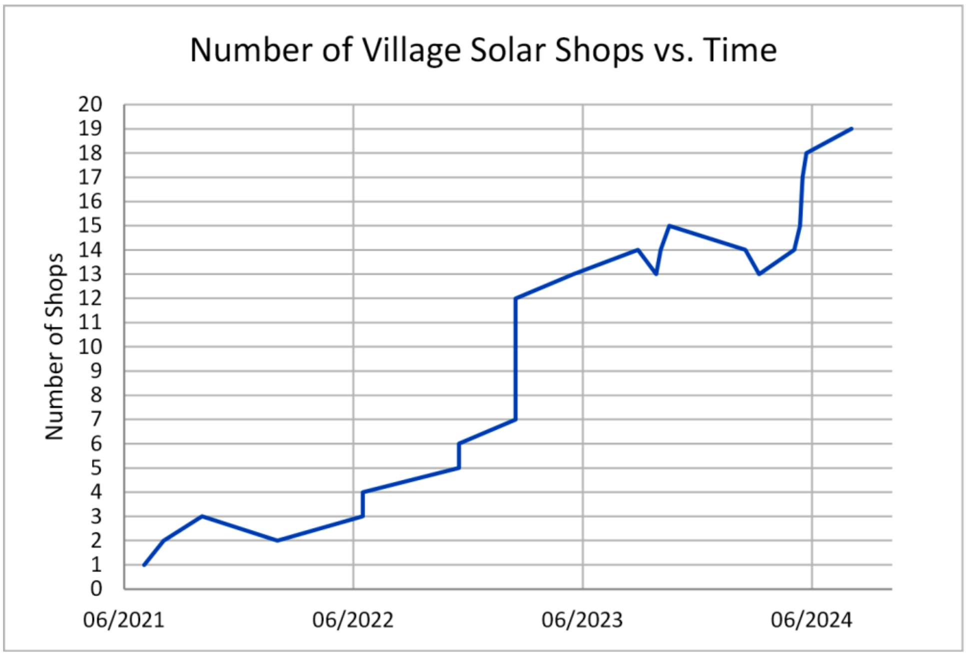

Figure 8: Evolution of the village solar shop network over time.

In Malawi, there is a "sales season" for solar products that impacts the timing of shop establishment. The sales season extends from about harvest time in April/May through the end of the dry season in November/December. This means most new shops are established near the beginning of the sales season from March through June.

In addition to selling solar cooking systems through the village shops network, KLLC also sells solar pumping systems. The solar pumping systems are subsidized by US donors. Solar pumps are much easier to sell than solar cooking systems because of the relatively large income that they can generate for rural Malawian farmers during the dry season. Before selling solar pumps in a particular area, KLLC requires a community to establish a solar shop run and operated by a local women's group. Because of the interest in buying and selling solar pumps, KLLC presently receives regular requests for opening new village shops throughout the year and throughout all regions of Malawi.

Whenever KLLC supports the opening of a new village shop, it also provides an inventory of solar cooking equipment and lends each shop demonstration solar cooking systems that the local women's group can use to cook for themselves and use for demonstrating solar electric cooking to the surrounding community. Each village shop has its own "personality" with some shops very enthusiastically adopting and promoting solar cookers and other shops maintaining a focus on selling solar pumping systems.

Occasionally a village shop will lose interest in solar system sales, or the shop may experience other management or operational issues. When such problems persist for a period of several months, the shop agreement is terminated, and other new shops are opened.

The solar products distributed by KLLC are subsidized by philanthropic donations from the US and by grant funding for innovation research from the Modern Energy Cooking Services (MECS) programme. Both US donors and MECS want to see maximum benefits for rural Malawians from the limited donation and grant funds that they provide. The last mile distribution that KLLC uses is designed to deliver maximum donation/grant cost efficiency and maximum rural Malawian benefits. How is this done?

Willingness to pay for big-ticket solar items in rural Malawi

The first thing to consider in designing the KLLC distribution system is the nature of the rural Malawian market for big-ticket solar items like solar pumps and solar cooking systems. Such big-ticket items are major investments by households that primarily engage in subsistence farming. The availability of money for investment is very seasonal, and rational purchase decisions evaluate the purchase in terms of return on investment. Because rural farmers have many farming investments that can pay back handsomely within the next growing season, typically such households require their solar investments to also pay back within a year. Yet many big-ticket solar items last many years and are priced as investments that can pay back over several years.

If the prices of solar items in the larger market in Malawi—which includes richer urban customers—reflect investments with a pay-back time of 2 to 3 years and if the rural village market is willing to pay prices that have to pay back in just one year, then the prices that village households are willing to pay for solar investments is going to be 1/2 to 1/3 of the price in the larger Malawi market for the same item with the same annual investment benefit.

This “theory” of the lower rural willingness to pay for big-ticket solar items appears to match KLLC’s general observation that village sales of solar items can occur at a substantial rate when such items are priced about half of their typical price in urban markets.

Even though rural customers are often willing to pay about half-price for big-ticket solar products, they will often claim that they have “no money” to pay and that such solar items should be 100% subsidized. It is difficult, therefore, to estimate maximum willingness to pay from surveys and questionnaires alone. To reveal the actual willingness to pay, KLLC uses “purchase competition” in the organization of its distribution system to reveal the actual optimum willingness to pay and to minimize product subsidies.

Optimizing price and subsidy for the solar cooking system

Given that the KLLC solar products are subsidized, the optimization problem that the distribution system needs to solve is how to distribute solar products to rural customers at optimum price and minimum subsidy given the existing subsidy budget. KLLC uses the law of supply and demand to help optimize prices, minimize subsidies and distribute a maximum of solar products to rural villagers.

If the subsidy is too low and the price is too high, then the sales rate is too low, and at the end of the sales season, there is unsold inventory. This is non-optimal, because there are unserved households that could have been served with the products that remain in inventory. Thus, the potential benefits of the solar system distribution are not maximized in this case.

If the subsidy is too high and the price is too low, then all of the inventory is sold before the end of the sale season, which means that the price could have been higher, the subsidy per product could have been lower, and the subsidy budget could have enabled the acquisition, sale and impact of more products. Thus again, households that could have been served are not served, and the price and subsidy are not optimized.

The solution to this optimization problem is to start the sales season at a fairly low product price, and then to gradually raise the price to adjust the sales rate during the sales season to gradually slow it down to the optimum level. The price increases are adjusted such that at the end of the sales season, all inventory is sold, with a price that is the maximum price that allows the sale of all of the inventory.

And in the case where the initial product price is too high, KLLC may find that the initial sales rate of the product is too slow during the beginning of the sales season. Therefore, to move enough inventory over the course of the sales season, KLLC lowers the price of the product to increase the sales rate to move the appropriate amount of inventory over the course of the sales season.

During the 2024 sales season, KLLC found that the 700Wp OGSECS was much more desirable to customers compared to the 350Wp OGSECS that was tested in the Blantyre workshop at the beginning of 2024. For the 700Wp OGSECS system, KLLC tested retail prices of 100,000 MWK (about $58), 250,000 MWK (about $145) and 380,000 MWK (about $220) during July and August. The result that was observed was that the 250,000 MWK price produced the best sales rate. As the end of August 2024, the 250,000 MWK price has led to a sales rate of approximately 20 OGSECS’s per week with the current village shop network. This sales rate will likely increase gradually over the course of the sales season.

4. Development of the LTO "forever battery"[11]

In the 2021 study, *How to make solar electric cooking cheaper than wood-based cooking,*[12] the team on the current project analysed the impact that long-lasting, high-power batteries can have on cooking system performance. The study found that the addition of a battery could increase the efficiency of utilization of the system solar panel and increase the reliability of energy availability for cooking events. But the cost of the extra electricity provided by the LTO battery was estimated to be about twice as costly as the cooking electricity provided by a battery-free cooking system.

Why adding an LTO battery to an OGSECS is cost-effective

Despite providing electricity that is more expensive than battery-free electricity, the addition of an LTO battery can be cost-effective because it can provide nighttime electricity that has an extremely high per-kWh value to rural Malawian customers.

Night-time off-grid electricity is provided by lead-acid batteries in rural Malawi. These batteries cost approximately $0.2 per watt hour (Wh) of capacity and have a cycle life of 500 cycles. Thus, the per-kWh cost of the currently available lead-acid off-grid battery electricity is approximately $0.4/kWh.[13] The addition of solar panels and associated electronics increases the typical levelized cost of off-grid nighttime solar electricity in rural Malawi to more than $1/kWh.

In contrast, the LTO "forever battery" being developed by KLLC is profitable at a retail price of less than $1 per Wh and has an estimated cycle life of greater than 10,000 cycles (Hall et al., 2018). By adding a battery to an existing cooking system, the cost of the additional nighttime electricity supply derives only from the cost of the battery. Thus, when an LTO battery is added to a battery-free, daytime OGSECS, it is more cost-effective than the alternative of buying a separate, small solar system for nighttime electricity. And in addition, the battery-enabled OGSECS can be more efficient and reliable than the battery-free OGSECS.

The high value of the nighttime electricity facilitated with the LTO battery is reflected in the anecdotal observation of a very high level of customer interest in the batteries. Customers are justifiably sceptical that the LTO batteries will last their expected 10-to-20-year lifetime and are hesitant to pay full price. But after customers get a few years of experience with the battery, and if KLLC provides the appropriate warrantees, this scepticism is likely to mitigate substantially, and profitable, full-price sales of LTO batteries for small electronic loads is likely to be feasible.

Design and assembly of the LTO battery

The KLLC LTO battery consists of an assembly of 5 or 8 LTO cells connected to battery management system (BMS) electronics that control the on/off state of separate charging input and load output ports. The 5-cell battery has an operating voltage of 10V to 13V, and the 8-cell battery has an operating voltage of 16V to 21V. Each battery cell has a capacity of

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[11] See: https://mecs.org.uk/recording-of-the-webinar-making-a-10-year-lifetime-solar-ecooking-battery-for-rural-africa/ for a webinar that provides additional detail regarding the KLLC LTO battery.

[12] https://www.mdpi.com/1996-1073/14/14/4293

[13] Because 1Wh of capacity cycled 500 times supplies 0.5 kWh of battery electricity.

10 amp-hours and, as of the date of this report, an individual battery cell costs less than $3.50 when purchased in bulk in China.

Figure 9 is a picture of the BMS controller board, which is operated by a programmable microprocessor that monitors the voltage of each battery cell along with the battery temperature and input and output current. The screw terminals on the board are the positive and negative connections for separate charging and discharging ports. The microprocessor can also output data to an SD card that can record as many gigabytes of data as may be necessary for long-term high-resolution operational monitoring.

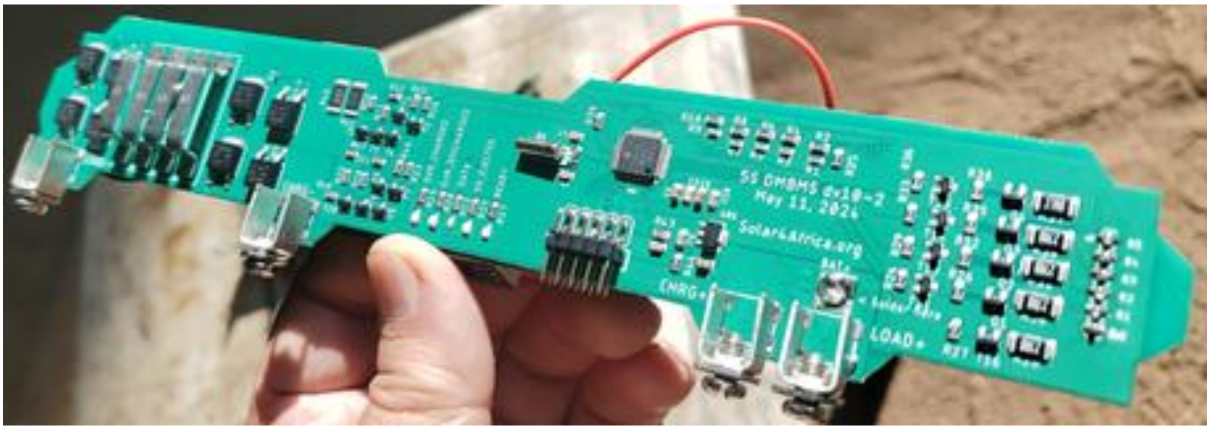


Figure 9: BMS controller board.

The battery cells are connected in series by spot-welding a pouch cell positive tab with the negative tab of the next pouch cell and covering the tabs in insulation tape. A sensor wire is also connected to each pair of cell tabs. Positive and negative power wires are also connected to the BMS board, and a voltage display is added. When the assembled cells are fully connected to the BMS board, the microprocessor is programmed, a battery label is added, and the assembled battery is placed in a flexible silicone mold into which clear epoxy is poured. After the epoxy sets, the battery is ready for use.

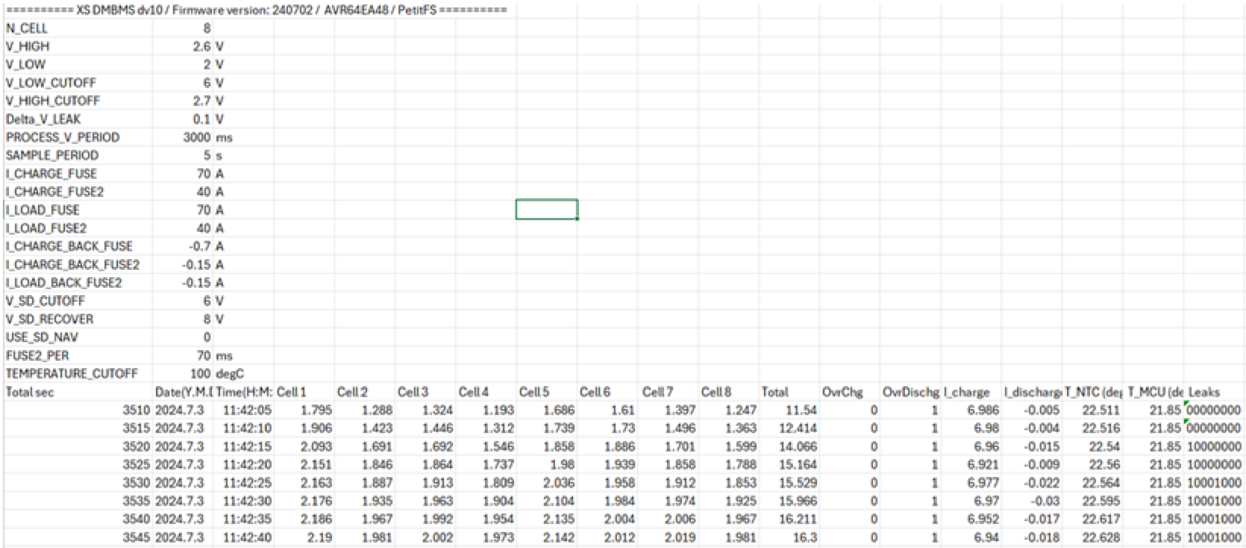
Figure 10: Assembled batteries being encapsulated in clear epoxy.

During June through August 2024, between 40 and 50 batteries of each type (i.e. 5-cell or 8-cell) were assembled. Initially several batteries were deployed at the Blantyre workshop. Initial testing led to minor, but important modifications to the BMS programming.

Subsequently about 30 test batteries were deployed at the households of approximately 30 test customers.

Operation and performance of the LTO battery

Figure 11 shows the file header for the operational data file that is recorded on an SD chip that can be connected to the LTO battery. This data includes the voltage of each battery cell, the on/off state of the charging and discharging ports, the current on each port, two internal temperature measurements (one near the power electronics and another near the microprocessor chip), and an indicator of which cells are leaking current to help cell balancing.



========== XS DMBMS dv10 / Firmware version: 240702 / AVR64EA48 / PetitFS ==========

N_CELL	8	
V_HIGH	2.6	V
V_LOW	2	V
V_LOW_CUTOFF	6	V
V_HIGH_CUTOFF	2.7	V
Delta_V_LEAK	0.1	V
PROCESS_V_PERIOD	3000	ms
SAMPLE_PERIOD	5	s
I_CHARGE_FUSE	70	A
I_CHARGE_FUSE2	40	A
I_LOAD_FUSE	70	A
I_LOAD_FUSE2	40	A
I_CHARGE_BACK_FUSE	-0.7	A
I_CHARGE_BACK_FUSE2	-0.15	A
I_LOAD_BACK_FUSE2	-0.15	A
V_SD_CUTOFF	6	V
V_SD_RECOVER	8	V
USE_SD_NAV	0	
FUSE2_PER	70	ms
TEMPERATURE_CUTOFF	100	degC

Total sec	Date(Y.M.	Time(H:M:	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Total	OvrChg	OvrDischg	I_charge	I_discharg	T_NTC (de	T_MCU (de	Leaks
3510	2024.7.3	11:42:05	1.795	1.288	1.324	1.193	1.686	1.61	1.397	1.247	11.54	0	1	6.986	-0.005	22.511	21.85	00000000
3515	2024.7.3	11:42:10	1.906	1.423	1.446	1.312	1.739	1.73	1.496	1.363	12.414	0	1	6.98	-0.004	22.516	21.85	00000000
3520	2024.7.3	11:42:15	2.093	1.691	1.692	1.546	1.858	1.886	1.701	1.599	14.066	0	1	6.96	-0.015	22.54	21.85	10000000
3525	2024.7.3	11:42:20	2.151	1.846	1.864	1.737	1.98	1.939	1.858	1.788	15.164	0	1	6.921	-0.009	22.56	21.85	10000000
3530	2024.7.3	11:42:25	2.163	1.887	1.913	1.809	2.036	1.958	1.912	1.853	15.529	0	1	6.977	-0.022	22.564	21.85	10001000
3535	2024.7.3	11:42:30	2.176	1.935	1.963	1.904	2.104	1.984	1.974	1.925	15.966	0	1	6.97	-0.03	22.595	21.85	10001000
3540	2024.7.3	11:42:35	2.186	1.967	1.992	1.954	2.135	2.004	2.006	1.967	16.211	0	1	6.952	-0.017	22.617	21.85	10001000
3545	2024.7.3	11:42:40	2.19	1.981	2.002	1.973	2.142	2.012	2.019	1.981	16.3	0	1	6.94	-0.018	22.628	21.85	10001000

Figure 11: File header for the data file that is recorded on the SD card of the LTO battery.

The BMS has a range of operating parameters that can be adjusted in the microprocessor software. These include the high and low operating voltages of the battery cells, the data sampling period, the magnitude of both the fast and slow fuses for the input and the output ports, the size of the back-current fuse for the input and output ports, the battery voltages above which the SD card data collection can occur, the time period of the slow fuse and the internal temperature above which charging and discharging of the battery is turned off.

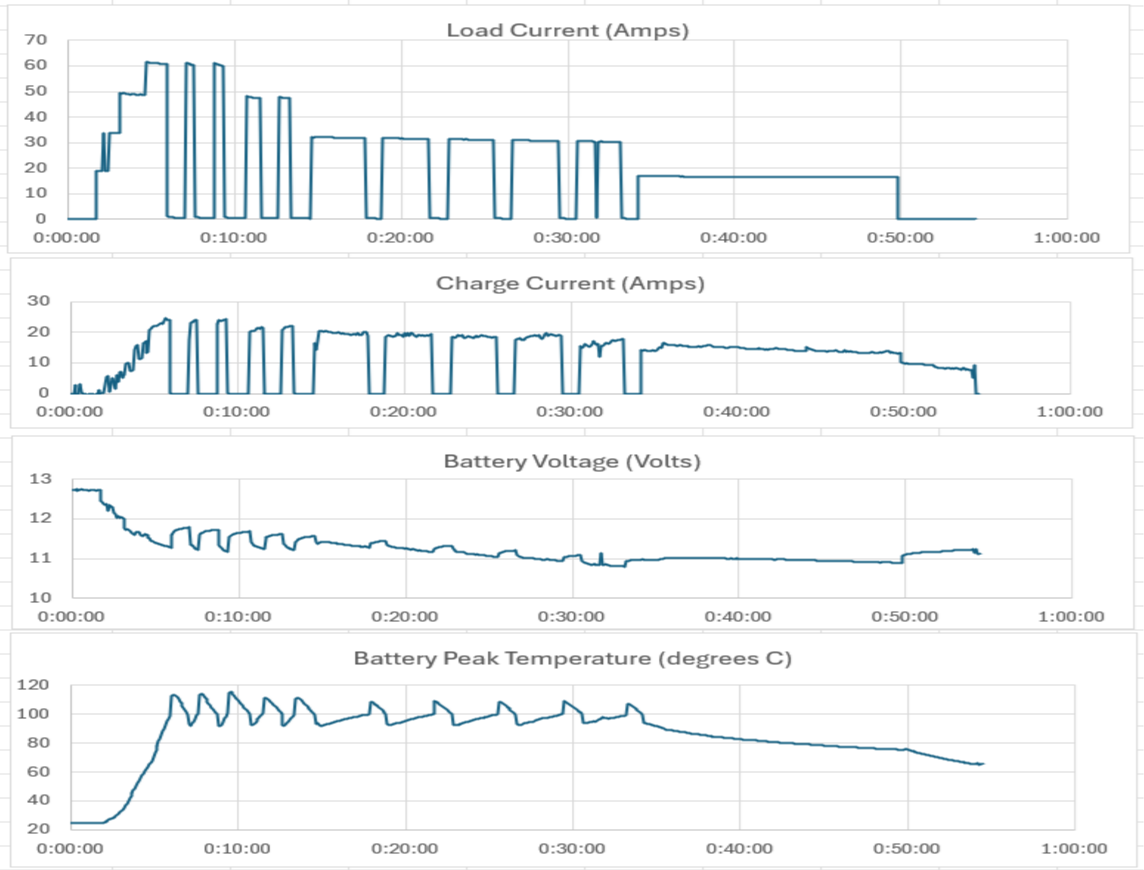


Figure 12: Battery current, voltage and temperature during a high current test.

Figure 12 shows a sample of operational data for a 5-cell, 12V, 10Ah LTO battery during a high current test. We note that even though the capacity of the battery is only 10Ah, the battery has no problem sustaining approximately 20 amps of current flow. Above 20 amps, enough heat is generated in the battery to trigger the overheating protection in the battery's software. Currently the LTO batteries have a software-enabled fuse that is set at 30 amps because our current cooking loads are approximately 20 amps. Thus, under normal operating conditions the over-temperature protection is rarely—if ever—triggered.

Alternatively, the battery can be built to sustain loads higher than 30 amps by encasing the battery electronics in more thermally conductive epoxy that will more efficiently conduct heat from the power electronics.

Note that a lead-acid battery which costs $0.2/Wh in the Malawi market has a maximum discharge rate of 0.3C, which means that the battery can supply only 0.3 watts of output power per Wh of capacity. Thus, the cost per unit power output of the lead-acid battery is $0.2/0.3 = $0.67/W.

In comparison, our LTO battery can discharge at greater than 20 amps or 2C, and thus in terms of peak output power the cost of the LTO is less than $1.0/2 = $0.5/W. For an LTO battery, a small battery can deliver a large power throughput if the power input is available from a source like a solar panel.

Thus, in those off-grid solar applications where customers are over-sizing lead-acid batteries to serve a short-duration high peak current output, a smaller capacity version of our LTO battery can deliver the same peak current at lower cost with the added advantage that the KLLC LTO battery is designed to last 10 or more years rather than one or two years like a lead-acid battery.

One might argue that using lithium iron phosphate (LiFePO4) battery chemistry would be more cost effective than using LTO battery chemistry. But LiFePO4 batteries cannot charge and discharge as fast as LTO, thus a larger capacity battery is needed for the same power throughput. We also note that the actual cost of the LTO battery cells is only $0.20/Wh when purchased in bulk, while the cost of similar LiFePO4 pouch cells are approximately $0.12/Wh. This $0.08/Wh savings from using LiFePO4 is minor because 75% of the total battery delivered cost includes parts transport, assembly, distribution, marketing and the addition of data logging features when the battery is customized for small-scale OGSECS applications in rural Malawi.

Perhaps using LiFePO4 battery chemistry instead of LTO battery chemistry could save as much as 10% to 20% on customized battery costs for a battery of the same energy storage capacity. But considering that customized LTO batteries have greater power throughput and should last more than twice as long as LiFePO4 batteries, customized LTO batteries are more cost-effective over the long term for small-scale OGSECS applications in Malawi than customized LiFePO4 batteries would be.

5. Cooking energy use data collection & analysis

In order to characterize the benefits of an off-grid solar electric cooking system, it is important to know what dishes it can cook, how fast it cooks those dishes, and how much energy is used when the different dishes are cooked.

Cooking energy use data serves multiple purposes:

1. Cooking energy requirements determine how much food can be cooked in an OGSECS of a given daily energy output capacity.
2. The types and amount of food that can be cooked by an OGSECS determines how much traditional fuel and time the OGSECS saves for a household that would otherwise cook with traditional fuels.
3. Wood and charcoal fuel savings estimates for OGSECS-based cooking can help determine the deforestation and climate change mitigation benefits that might accrue from OGSECS usage.

To address these multiple purposes, four varieties of cooking energy use data were collected: (1) Blantyre workshop cooking tests on a total of 15 OGSECS cooking stations, (2) Cooking tests in village solar shops, (3) Data recorded on small kitchen scales by households that volunteered to have “research cooking systems” at a highly discounted price, and (4) Data records from newly assembled lithium titanate (LTO) “forever batteries” powering cookers that record voltages and battery input/output current at high time resolution.

The energy requirement for cooking Malawian dishes

Figure 13 shows the relationship between the mass of food cooked and the energy used per cooked dish. Note that the data is very noisy, as many factors can affect the energy used in cooking any individual dish.

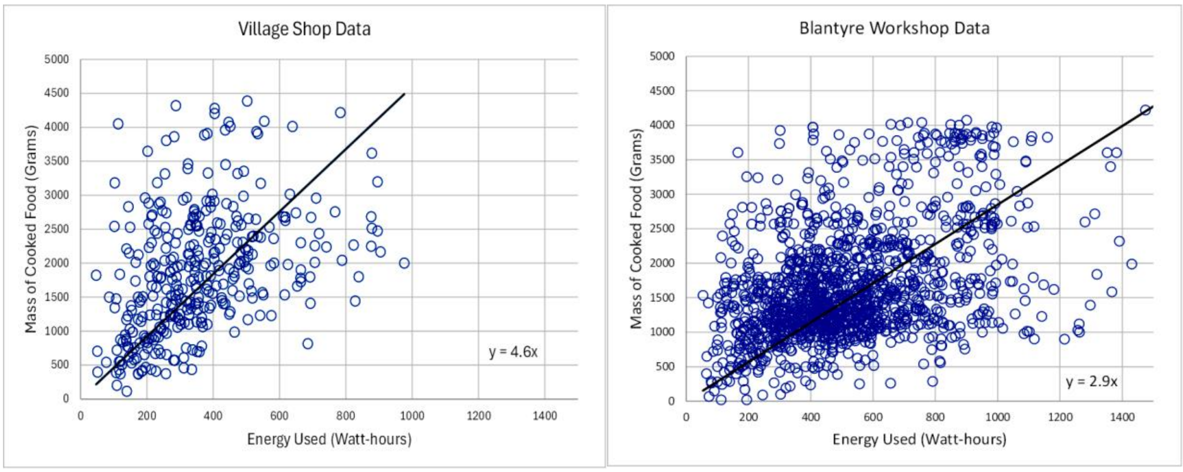


Figure 13: Cooking productivity results using energy use data from individual dishes cooked. Data is provided from village shop and Blantyre workshop tests. This data indicates that the village shop cooking is more efficient than the cooking in the Blantyre workshop as on average more food is cooked for a given amount of energy input. Regression lines are constrained to pass through the origin.

Note that the village shop tests appear to cook more food per unit energy used. Looking at the average time per dish cooked, we can see some reasons why this may be so. In the village shop tests, the average dish cooking time is 1.0 hours with an average cooking power of 190 watts. Meanwhile for the Blantyre workshop data, the average cooking time is 4.1 hours with an average cooking power of 137 watts.

In the village shop data collection, the women's collective was very motivated to cook efficiently and as quickly as possible because data collection compensation was proportional to the number of dishes cooked per day. This means that minimizing the cooking time per dish helped increase the number of dishes cooked per day, and consequently increased compensation. Efficiently stopping the cooking process as soon as the dish is done saves both time and energy for each dish. On cloudy days when the cooking power of the OGSECS was not strong, sometimes the women in the collective would not cook at all and do other, non-shop work instead.

In contrast, at the Blantyre workshop, the cooking tests were performed as part of the regular daily work routine. Workers tended to start the tests after arriving to work between 8am and 9am, and then finish the tests before lunch break shortly after noon. Cooking tests were performed on both cloudy and sunny days and on lower-capacity OGSECS systems, so the average cooking power tended to be lower than the village shop tests. Typically, only one dish was cooked per day per system, so there was no need to finish the cooking quickly.

The differences in routine and incentives between the two sets of cooking tests, appears to have led to differences in cooking behaviour that decreased cooking efficiency in the Blantyre workshop more than 30% relative to the cooking activity in the village shop.

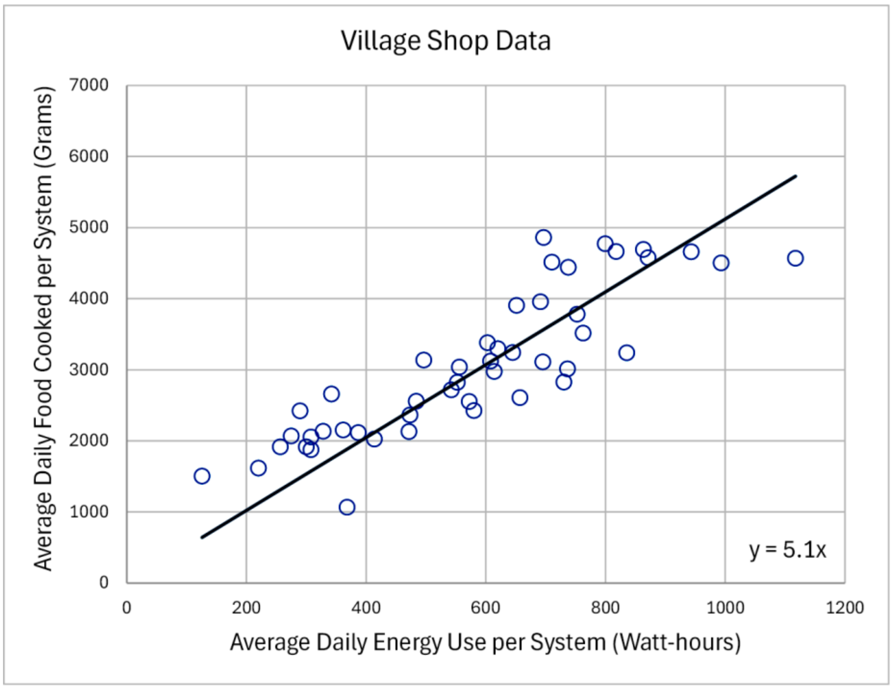


Figure 14: Cooking productivity from village shop data using daily average data for food cooked per OGSECS system vs. energy used per OGSECS system, averaged over the various systems in use in the shop.

Figure 14 shows the correlation between energy use and the amount of food cooked using daily average data from the village shop that did the most data collection. Because the data is averaged, it has less noise and variability and the correlation between energy use and amount of food cooked is much clearer. Roughly, 5 kilograms of cooked food is produced for every kWh of cooking energy consumption in the OGSECS that KLLC is distributing in Malawi.

High-time-resolution battery data

High-time-resolution battery data enables the detailed verification of cooking energy use in an OGSECS system. Here we present some example data. KLLC plans to organize a much larger database of anonymized, detailed OGSECS cooking energy use data in 2025.

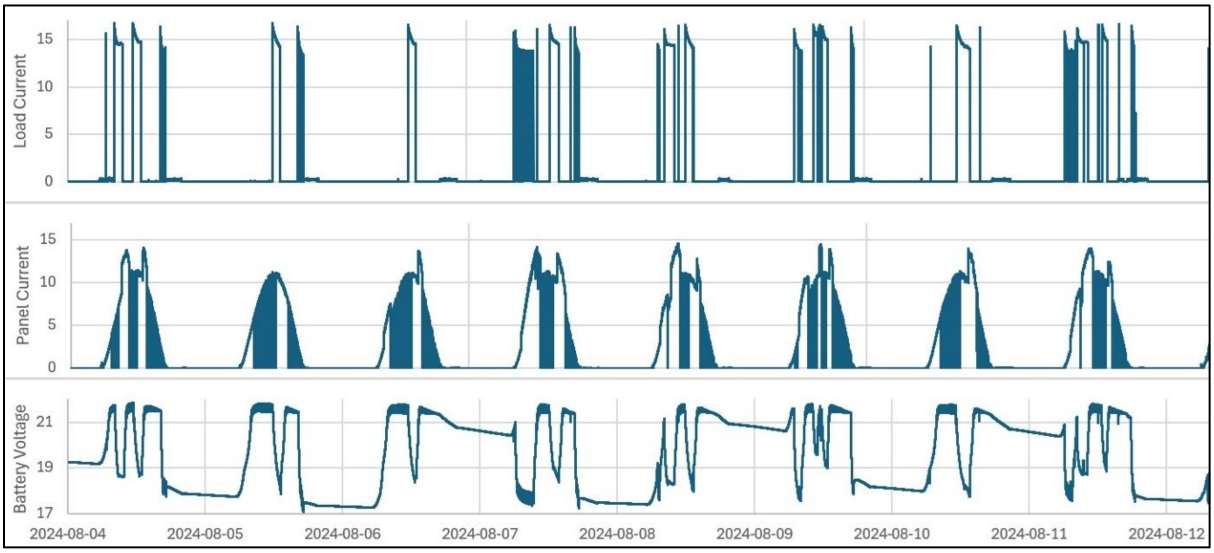


Figure 15: Battery monitoring data from an OGSECS with a 355Wp solar panel and 20V, 10Ah LTO battery.

Figure 15 shows an example of the monitoring data that obtained from a custom LTO battery. This particular data is sampled at a 5-second rate and shows load current, charge current and battery voltage plus other parameters such as battery temperature.

Note that in the case illustrated in the figure, the battery is charged and discharged several times per day. Yet, because the cycle-life of LTO battery cells is greater than 10,000 cycles, this should not be a problem for the custom-designed LTO solar battery that KLLC uses with its OGSECS.

6. Household benefits & impacts

When formulating our household impacts questionnaire, we were interested in several different aspects of household economics and energy use.

The first issue in characterizing basic household economics is delineating cash vs. non-cash expenditures, consumption and assets. To do this, the questionnaire asked: monthly cash expenditures, sources of income, types of food grown, fraction of food that is self-grown, characteristics of major assets (e.g. housing & transportation assets), and spending on batteries, cell phone charging and phone credits. The questionnaire did not ask details of on-farm expenditures (e.g. fertilizer, seeds, farm labour and pesticides) and income (e.g. crop harvests and sales) as this can be quite complicated and was deemed out of scope for this study.

The questionnaire asked how often each of 15 different dishes were cooked and/or consumed in the household. This provided a fairly detailed picture of which foods are cooked and how often.

It was found in preliminary interviews that people vary the cooking fuels that they used seasonally, thus types of cooking fuels used were queried for three times during the year: July, November, and March. July represents a period soon after harvest when agricultural residues are readily available, November represents the end of the dry season when agricultural residues are largely used up, and March represents the middle of the growing season when rain is fairly frequent and money for household spending is often scarce.

In addition to the types of fuels used, the questionnaire queried how much was spent on different fuels and how much time was spent collecting fuel.

With regards to the impact and desirability of the OGSECS, the questionnaire has households rank potential benefits of the cooker: (A) Convenience (i.e. it cooks without having to watch it), (B) It looks nice, (C) It cooks fast, (D) It saves time from not having to collect as much fuel, (E) There is no smoke, and (F) It saves money (that might be spent on wood or charcoal). In addition, the questionnaire asked how many dishes were cooked on sunny vs. cloudy days, and what fraction of household cooking is typically done on the cooker on both sunny and cloudy days.

Household data collection process

Household interviews were conducted during the months of July and August 2024 by a pair of contract enumerators. When possible, one interview was conducted before acquisition of the solar cooking system and another after acquisition and use of the solar cooking system. Interviews were made with a total of 34 solar system users and a total of 49 household interviews were conducted either before solar cooker use, or with households that did not acquire solar cooker systems. Data collection was conducted in two areas: one in the M’bangombe village area in rural Lilongwe district, and the other in rural Machinga district. Of the 34 solar system users, 10 users had a battery-free two-panel system (i.e. a total of >700Wp) while 23 users

Figure 16: Enumerators interviewing a solar cooking system user about household economics, cooking system use and impacts.

have a 19V LTO battery with a 355Wp solar panel. One user has two 355Wp solar panels an a 19V LTO battery.

Household economic characteristics

The key household income indicator collected during the survey was monthly household spending. Figure 17 shows the distribution of monthly household expenditure rates indicated by interviewees. The average monthly expenditure is 103,000 MWK with a fairly skewed distribution of monthly expenditure amounts with half of households spending less than 80,000 MWK/month.

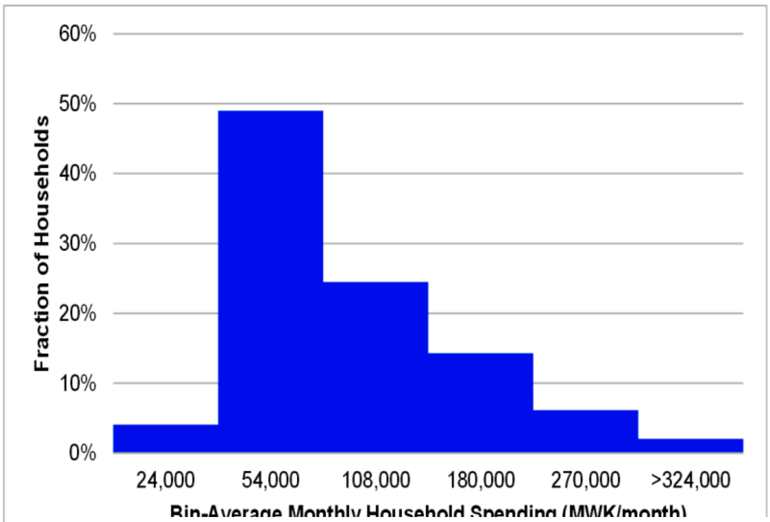


Figure 17: Distribution of monthly household expenditures for households participating in the study.

Figure 18 illustrates, the relatively weak correlation between household monthly spending and household size. The line illustrated in the figure shows the average relationship between spending household size. Average per-capita household monthly spending is 17,024 MWK/capita/month.

We note that given the interbank exchange rate of 1725 MWK/USD during this period, that this average monthly expenditure amount corresponds to $0.32/capita/day. We also note that the World Bank estimates per-capita income in Malawi in 2023 as $673/capita/year[14] = $1.84/capita/day. There are at least two reasons for this discrepancy: (1) Our rural customers are lower income, and have less than the average annual income, and (2) Rural Malawians self-produce with minimal cash expenditure: this includes most of the food that they consume, and housing and land which typically is not rented or purchased.

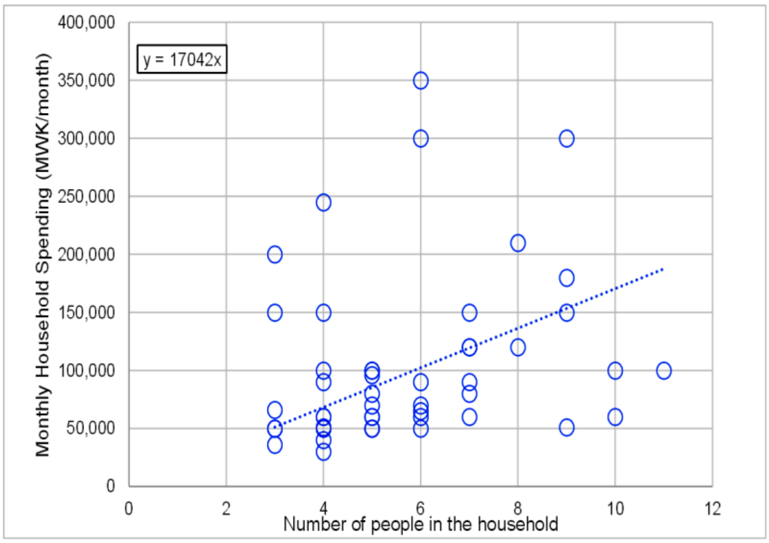


Figure 18: Dependence of household monthly spending on household size. The regression line is constrained to pass through the origin.

Let's discuss each of these factors in turn.

We first note that the income share held by the two lowest income quintiles of households in Malawi is 7%[15] and 11%[16] respectively. These means that, on average, the lowest income

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[14] https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=ZF-MW, downloaded October 2024

[15] https://data.worldbank.org/indicator/SI.DST.FRST.20?locations=MW, downloaded October 2024

[16] https://data.worldbank.org/indicator/SI.DST.02ND.20?view=chart&locations=MW, downloaded October 2024

40% of Malawian households have per-capita incomes less than half of the national average. This indicates that that for this population, per-capita income should be about 0.5 x \$1.84 = \$0.92/capita/day. But much of this income is non-cash income.

The survey of this study collected data on how much food each household produced for themselves. The average response was 59%, indicating that only 41% is purchased with cash. If we assume that in general only 41% of consumption is purchased with cash, then this implies that for a total per-capita income of \$0.92/day, then only 41% x \$0.92 = \$0.38/capita/day should be the typical cash expenditure. This is close to the \$0.32/capita/day figure indicated in our survey data.

Household assets vs. income

To further characterize household economic conditions, the survey asked households about asset ownership. To characterize housing assets, the residence size and roofing was recorded as small, medium, or large size, and thatched vs. metal roofing. Transportation assets recorded included any bicycles, motorcycles or cars owned by household members.

To summarize asset ownership, an "asset score" was calculated, where a small house and a thatched roof was given zero points, a medium-sized house was given one point, a large-sized house two points, and an iron roof was given one point. In addition, each bicycle was given one point, a motorcycle was given two points, and a car was given three points.

Figure 19: Correlation of household monthly expenditures with asset score. Note that the vertical axis is scaled logarithmically

Figure 19 shows that strong correlation between asset score and monthly household expenditure. The median expenditure households correspond to an asset score of three which typically consists of a medium-sized house with an iron roof, and the ownership of a bicycle. Lower-income households have small houses with grass-thatched roofs and may not even own a bicycle.

Types of food grown, consumed and cooked

The households participating in the survey grow an average of 5.2 different food crops at each household. These provide an average of 59% of the food that the households consume. Figure 20 shows an example of four different crops being grown at the same time in the same field using traditional intercropping methods that are common in Malawi. On average, each household grows 2.1 different starch crops (e.g, maize, sweet potato, rice, cassava, etc.), 2.0 different vegetable protein crops (i.e. soya, groundnuts, beans, cow peas or pigeon peas), and 69% of households grow green vegetables (i.e. mustard greens, Chinese cabbage, collard greens, pumpkin leaves, etc.). In the M'bangombe area, tobacco is the cash crop, while in the Machinga district, rice is the major cash crop.

The survey asked in detail the cooking frequency of 15 different foods. Figure 21 illustrates the relative frequency of cooking different foods in rural Malawi based on the survey data. The most frequently cooked food is *nsima* (known as *ugali* in Kenya, Uganda, and Tanzania) which is cooked on average twice per day in rural Malawi. The second and third most-cooked foods are vegetables (i.e. various greens), and starchy tubers (sweet potatoes, Irish potatoes, and cassava) which both have a cooking frequency that averages 0.84 times per day. These three most common foods appear to represent about 75% of all dishes cooked in rural households.

The foods comprising the remaining 25% of dishes cooked are largely proteins with the two most frequent being fish and soy pieces. Next in frequency are eggs, beans and meat (i.e. chicken, beef, pork, or goat) that are cooked on average about once per week

Figure 20: Typical farming field in Machinga district showing starches, vegetable proteins and greens being grown. These include maize and sweet potato, where sweet potato leaves are also eaten as green vegetables, as are pumpkin leaves. Also, beans can be seen being intercropped with the maize and other crops.

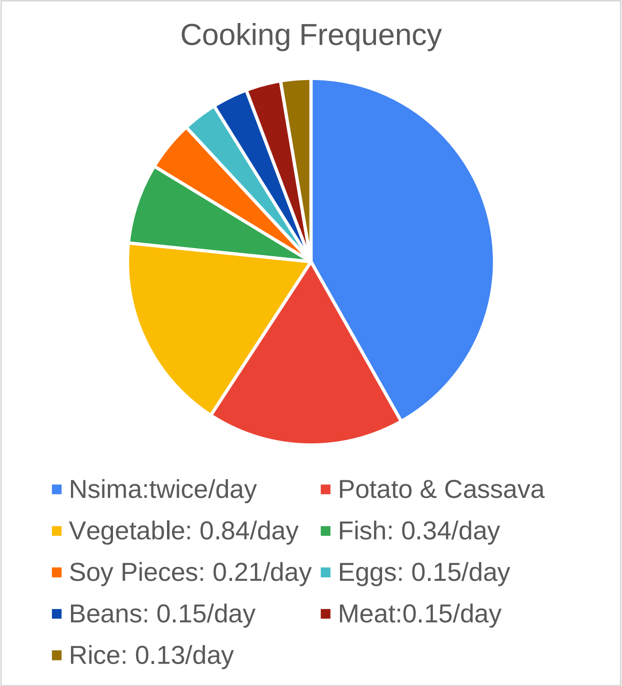

Figure 21: Average frequency of cooking different foods in rural Malawi

each. Rice is eaten less than once per week on average, as it is a cash crop that is more expensive source of starch-based calories than corn and starchy tubers.

On average, rural Malawian households cook five dishes per day: two *nsima*, another starch (potatoes, cassava or rice), a vegetable, and a protein (fish, soy pieces, eggs, beans, or meat). The survey data indicates that the total number of dishes cooked per day is roughly constant with household size.

Figure 22: Agricultural residues used as cooking fuel after harvest in rural Malawi

Cooking fuels used

In rural Malawi, three main fuels are used for cooking: (1) agricultural residues, (2) wood, and (3) charcoal. Charcoal is both the most expensive and most convenient fuel. It has greater energy density, can generate greater heating power, produces less smoke and lasts longer while cooking a dish of food compared to either wood or agricultural residues.

Agricultural residues in rural Malawi (shown, for example, in Figure 22) generally consist of dried corn stalks, dried tobacco stalks, and corn cobbs. During the right season, agricultural residues are easy to collect and are generally free. But agricultural residues are usually available only for a few months after harvest.

Wood is the most ubiquitous rural cooking fuel and is less expensive than charcoal. In contrast to agricultural residues, wood is available throughout the year, but is smokier, less convenient and is less efficient (in terms of amount of heat delivered to cooked food) than charcoal.

Roughly it takes about seven kilograms of wood to produce one kilogram of charcoal[17], but one kilogram of charcoal has about twice the energy content of one kilogram of wood and charcoal stoves can be twice as efficient as wood cooking.

Figure 23 shows the fuels used both after harvest from June to September, and during other times of the year. The percentages in the figure represent the fraction of households using the fuel. The percentages add up to more than 100% because many households use more than one fuel for cooking.

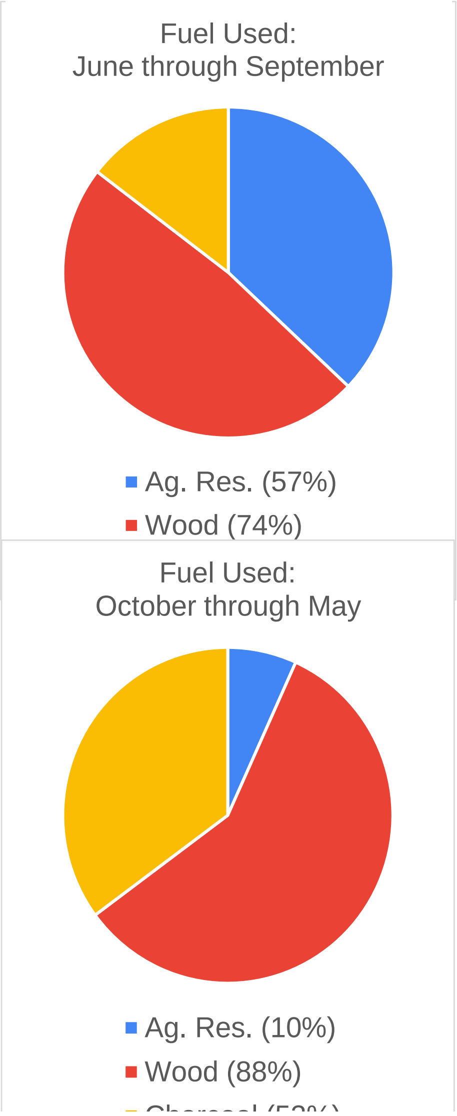

Figure 23: Frequency of fuel use for surveyed households

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[17] Production efficiencies range from 3 to 12 kg wood per kg of charcoal produced. See (FAO, 2017): https://openknowledge.fao.org/items/86176899-1b4f-411d-8644-965b8cf83f3d

As explained in more detail below, fuel choice and spending also correlate with household monthly expenditures, with the households that have the highest expenditure levels purchasing and using charcoal more often, and the households with the lowest expenditures having the heaviest reliance on agricultural residues and wood that are gathered with no cash expenditure involved.

Fuel collection time and expense

Figure 24 shows the distribution of fuel collection time and daily fuel expenses for households surveyed during July when agricultural residues are available as a fuel source. There is a weak anti-correlation between fuel spending and household fuel collection time. Presumably richer households can afford to conveniently purchase fuel (either wood or charcoal) that is available in local markets and not spend time collecting agricultural residues from their fields. During June through September, the average fuel collection time is 0.6 hours/day, and the total average household fuel spending is 250 MWK/day/HH. During other times of year (approximately October through May) fuel spending more than doubles to an average of 550 MWK/day/HH, and fuel collection times reduce to an average of 0.35 hours/day.

Figure 25 illustrates the correlation between household cooking fuel spending and total household spending. On average, even the lowest income households spend about 400 MWK/day (i.e. $0.23/day) on cooking fuels, primarily on wood. As incomes increase, 80% of the increased spending appears to be due to increasing purchases of charcoal.

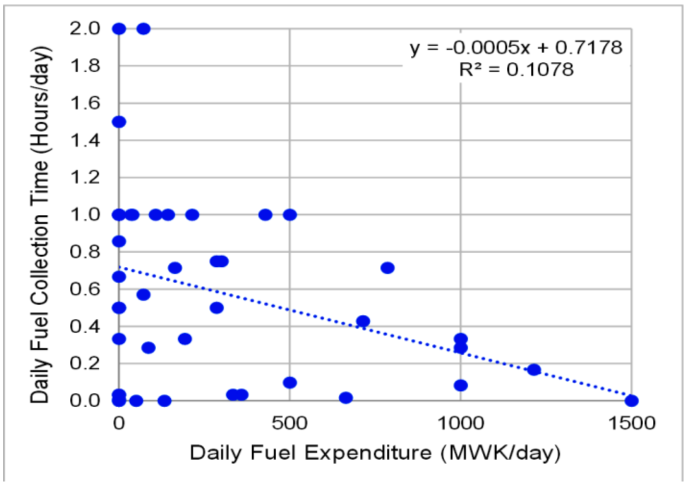


Figure 24: The distribution of daily fuel collection times and daily fuel expenditures for surveyed households in July. Average fuel collection time is 0.6 hours/day while the average daily fuel spending is 250 MWK/day

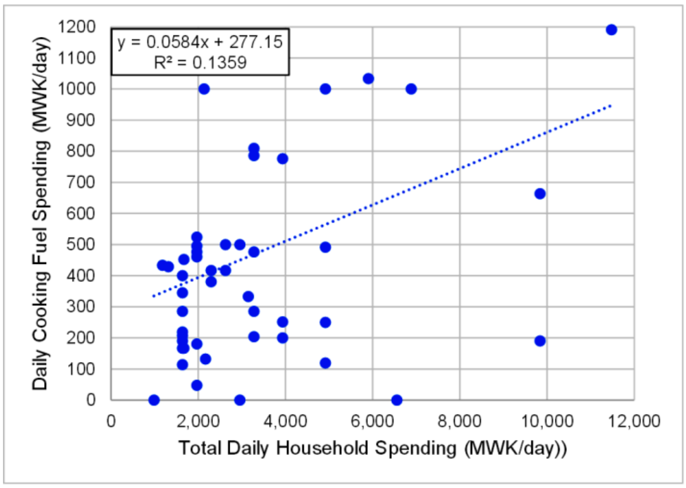
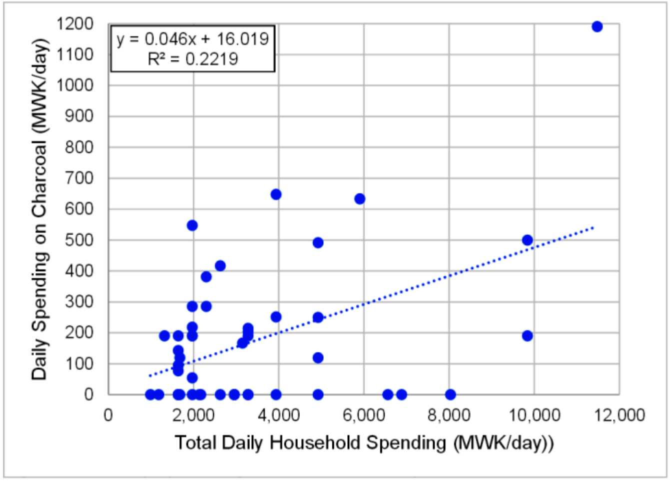


Figure 25: Daily cooking fuel spending compared to total household daily cash spending.



daily cash spending.

Figure 26 illustrates the correlation between charcoal fuel spending and total household spending. On average, the households surveyed spend about 4.6% of the household budget on charcoal fuels and the lowest income households may spend on average less than 100

MWK/day (i.e. $0.06/day) on charcoal. But as incomes increase, average spending on charcoal appears to increase proportionally to household monthly cash expenditures.

An increase in charcoal spending with increasing household cash expenditures appears to create a fundamental conflict between poverty-reduction goals of clean cooking access and the goal of mitigating climate change impacts of rural Malawian communities. This is because charcoal has 2 to 10 times the climate impact per megajoule of cooking energy delivered compared to wood (Bailis, et.al, 2004). Thus, any switch from wood to charcoal for cooking due to increasing income can potentially increase GHG emissions.

Figure 27: An OGSECS with LTO battery

Delivery of modern energy access to rural communities will hopefully increase household incomes and spending in many and varied ways. Diffuse poverty-reduction impacts could conceivably cause charcoal consumption and associated GHG emissions for lower-income households in rural communities to increase for those households that have not yet converted to solar electric cooking. This could thus create an indirect "backfire"[18] effect of increasing GHG emissions. While access to OGSECS may very well decrease net GHG emissions for many households, it is also impossible at this time with a high degree of confidence to promise that GHG emissions will decrease in this setting. A possible GHG emissions increase could potentially be due to what is called emissions "leakage" from possible "rebound" and "backfire" effects. This emissions reduction uncertainty, combined with the recent legal problems in carbon crediting for cooking projects in rural Malawi and Zambia,[19] probably means that it is not advisable to use the sale of carbon credits to finance OGSECS for low-income rural Malawians at this time. We also note in Appendix A that for OGSECS, only about 6% of the total monetized valuation of OGSECS benefits is from potential climate change mitigation effects.

OGSECS use, performance and benefits

The survey asked OGSECS users to rank six potential benefits of the OGSECS in order from most to least important. These six potential benefits were:

1. It is convenient to use (i.e. cooks without needing to be watched)
2. It looks nice (well-built, clean, modern)
3. It cooks fast
4. It saves time from not having to collect fuel

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[18] https://www.sustainablelifestyles.ac.uk/sites/default/files/publicationsdocs/2011_druckamn_et_al_rebound_energypolicy.pdf, downloaded Octobert 2024

[19] https://www.justice.gov/usao-sdny/pr/us-attorney-announces-criminal-charges-multi-year-fraud-scheme-market-carbon-credits, downloaded Octobert 2024

5. There is no smoke; and
6. It saves money

Figure 28 shows the average ranking provided by customers in the survey, for these six benefits. The most valued benefit is that the OGSECS saves money. A close next-rank in value is that the OGSECS saves time (either for cooking or from reduced fuel collection). Convenient cooking was the fourth ranked benefit but was given a similar value as saving time and money.

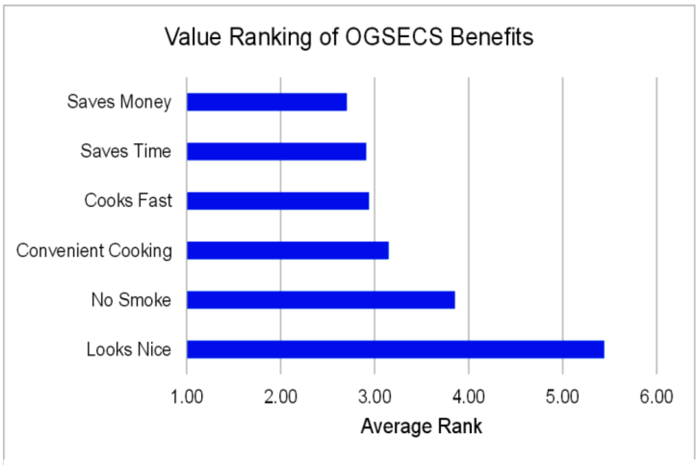

Figure 28: Customer ranking of OGSECS benefits

It appears that reduced smoke exposure is ranked behind convenience and saving time and money. We note that about 26% of households surveyed usually cook outside the house. And finally, the relatively superficial benefit of looking nice clearly ranked last.

How much the OGSECS cooked and saved in terms of time and money depended on the solar panel power of the OGSECS.

The owners of a >700Wp battery-free OGSECS that were surveyed have an average monthly household expenditure of 89,000 MWK/month. All of these customers claimed that the solar electric cooker saved cooking time with an average claimed cooking time savings of 2.2 hours per day. These same households claimed that for sunny days, they cooked an average of 4.2 dishes per day and cooked 2.1 dishes per day on cloudy days. They also claimed that 55% of food was cooked on the OGSECS on sunny days and 39% of food was cooked on the OGSECS on cloudy days. In addition, the owners of the 700Wp OGSECS claimed that on sunny days, the typical fuel collection time of 1 hour/day was reduced by 30%, and that they saved 116 MWK/day in cooking fuel expenses.

The owners of the 355Wp OGSECS with battery who were surveyed have an average monthly household expenditure of 134,000 MWK. Of these respondents, 61% of respondents say that the OGSECS cooks faster than using traditional methods, while 39% say it cooks slower. For those who claim it cooks faster, they say it saves 1.2 hours of cooking time per day on average. On average, these users claimed that they cooked 2.5 dishes per day on the system on sunny days. The 355Wp OGSECS owners claim that fuel collection time savings is on average 0.18 hours per day and that monetary fuel savings are 186 MWK/day on average for sunny days.

Given that rural households cook an average of 5 dishes per day, these results indicate that an OGSECS with capacity of 1 kWp of solar panels should be sufficient to cook most meals on sunny days, and an OGSECS of 2 kWp should be able to cook most meals on both sunny and cloudy days. Given that the factory door cost of solar panels can now be less than $0.10/Wp, it should be possible to provide 1 to 2 kWp of solar panels per household in rural Malawi for a total solar panel cost of less than $300.

7. Proposed Financing Mechanism for Scale-up

> *"Results-based financing includes a range of financing mechanisms where financing is linked and provided after the delivery of pre-agreed and verified results. RBF approaches can play a big role in the delivery of infrastructure and services."*[20]

We note that it is beyond the scope of this study to analyse, optimize and choose THE BEST financing mechanism for scale-up of OGSECS in rural Malawi that might work in the most general sense for most implementers and businesses. Therefore, this section describes the financing scheme that we think can work well to enable a social enterprise like KLLC to efficiently grow OGSECS distribution to large scale given the experience that KLLC has had with OGSECS to date.

KLLC has found in its eight years of working to provide access to solar technology in rural Malawi, that perhaps the biggest barrier to providing cost-effective, high-quality solar technology access is what is called the "principal agent problem" (PAP) (Aerni, 2006). The PAP is the conflict in interests and priorities that happens when an "agent" takes actions on behalf of another person or entity. Stritzke et. al, 2021 note in their review of results-based financing for clean cooking that the "application of RBF minimises the principal–agent problem." For eight years, KLLC has received RBF-like financing from US philanthropists.

Another manifestation of PAP is the "asymmetric information" market failure that creates what is called a "Market for Lemons" (MfL) (Akerlof, 1970) in low-income markets that lack access to accurate information. In such markets, sellers of low-quality products are incentivized to misrepresent product performance in order to sell inexpensive products at a larger volume and for a higher price. The sale of low-quality products that claim higher performance in the market creates competition that can make it impossible to profitably sell high-quality products with verifiable high performance at a sustainable price.

To solve the PAP and MfL problems, KLLC has partnered with a small US non-profit that is led by a clean energy policy cost-benefit analyst (i.e., Robert Van Buskirk[21]). The goal of the non-profit is to maximize the social benefit created by solar products distributed to rural Malawians and to maximize the benefit-cost ratio of philanthropic donations. To verify that the benefit created per dollar donated is maximized, unpaid US volunteers visit Malawi two to five times per year to meet customers and evaluate the impact that solar products are having on their lives. It is in the context of this partnership between a for-profit Malawian social enterprise and a US non-profit charity (Solar4Africa.org) that the OGSECS described in this report has been developed.

Various aspects of the PAP and MfL problems are solved by this institutional arrangement of a for-profit/non-profit partnership because KLLC gets more US donation support when it provides more benefits to rural Malawians. Thus, the financial interests of KLLC are closely aligned with the interests of its rural customers to improve their lives. At the same time, the unpaid US volunteers have no financial incentive to mis-represent rural Malawian impacts and benefits, because their motivation is to satisfy their personal objective of having greater social impact per hour of volunteer effort. They attain this objective when they solve problems that allows customers to report higher levels of social benefit per dollar of donated subsidy. Thus, US volunteers have a strong incentive to help KLLC innovate to improve impact efficiency.

There is still some measure of a PAP in that customers have an incentive to indicate a higher level of benefit than is true in an attempt to obtain higher subsidies for solar products

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[20] https://www.gprba.org/who-we-are/results-based-financing

[21] See: https://www.researchgate.net/profile/Robert-Van-Buskirk

that they may buy in the future. But this PAP is solved by putting digital monitoring devices on the solar equipment (when needed) to objectively verify solar product use levels. Furthermore, while solar product prices are subsidized, customers still pay a price for the products, and the price that they are willing to pay provides information to KLLC and the US volunteers regarding how much they value the benefits that the product produces for them.

The current KLLC finance model of getting individual donations from US volunteers and their friends who then verify impact performance is not, however, a scalable form of financing for OGSECS. But in spite of the small-scale nature of current impact-based KLLC financing, the financing model of combining US donations with in-country sales is similar to the recently developed Clean Impact Bond (CIB) (Stritzke, et.al, 2023) financing of clean cooking projects. In the next section, this report discusses a modified version of the CIB financing method that might efficiently finance large-scale OGSECS distribution in Malawi.

Adjusting Clean Impact Bonds (CIB) to efficiently support OGSECS

The application of a CIB to clean cooking solutions has recently been described in the academic literature (Stritzke, et.al, 2023). In that application of the CIB approach, there are five key stakeholders in the CIB arrangement: (1) A Clean Cooking Company, (2) An Impact Manager, (3) Outcome Buyer, (4) Investor, and (5) Impact Assessor. One key element of having different stakeholders verify contract compliance during CIB implementation is a set of impact measurement methods and procedures that can be expensive and complicated to implement.

For OGSECS in Malawi, at least initially, it will not be feasible to implement a series of complicated impact measurement and verification procedures in order to efficiently finance OGSECS distribution. We therefore propose simplifying this approach to having only three stakeholders operating in a more standard development financing arrangement: (1) A Clean Cooking Solution Provider who imports the solar equipment, distributes the OGSECS and who monitors and collects kWh usage data, (2) A Lender who provides the initial capital for importing the equipment, and (3) An impact-oriented Grantor who disburses a grant for the benefits provided by the OGSECS that is disbursed upon verification of kWh usage at a pre-agreed $ per kWh rate.

A key reason that a simpler CIB approach may be possible for supporting OGSECS distribution in Malawi is that an initial, entry-level battery-free OGSECS is relatively inexpensive and needs a subsidy of only about $0.20 to $0.30 per peak watt (Wp) of capacity to become affordable for purchase by low-income rural Malawian households. If we then consider that each Wp of OGSECS capacity can produce more than 2 kW of electricity over five years, then grant compensation of $0.20 per kWh delivered should be more than sufficient to enable a clean cooking solution provider to make OGSECS affordable to all. As detailed in Appendix A, this $0.20/kWh compensation from a grant provider is about 3.7 times less than the estimated per-kWh benefits generated through OGSECS use. A 3.7:1 benefit-cost ratio on delivering benefits to low-income rural Africans should be sufficient to enable many different donors and granting agencies to participate in a CIB financing scheme with simple impact measurement and verification procedures based on measured kWh delivered. Such a high benefit-cost ratio provides an assurance that even considering impact estimation uncertainties, the value of project benefits that are estimated with kWh usage measurements should exceed the amount paid (i.e. $0.20/kWh) with a high degree of confidence.

Even more economically efficient than a fixed $0.20/kWh RBF compensation rate might be a tiered rate that is based on the average daily usage level of the OGSECS. Figure 29 shows both the per-kWh cost of the OGSECS cooking electricity (amortized over 5 years) and a proposed RBF compensation rate that provides partial subsidy of the OGSECS at low utilization rates, and full subsidy of the OGSECS at very high utilization rates. Such tiered RBF compensation would provide an incentive to clean cooking system providers to educate and train customers on efficient system use in order to increase system utilization and benefits. This would enable a decrease in the per-kWh cost of clean cooking services supply to customers and an increase net household benefit. This compensation scheme would also allow the clean cooking grantor to decrease the marginal cost of clean cooking subsidies with increasing per-household cooking services delivery and increasing per-household clean cooking benefits.

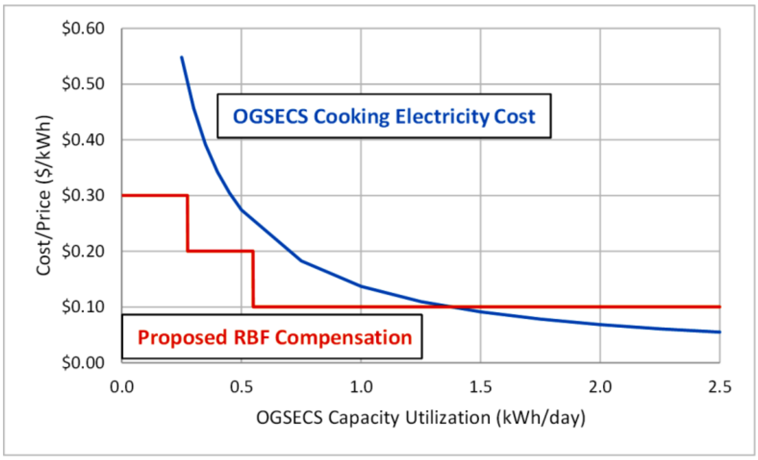

Figure 29: The blue curve represents the average cost of cooking electricity per kWh for a $250, 700 Wp OGSECS as a function of capacity utilization when the cost is amortized over five years. The orange curve represents a potential RBF compensation agreement that partially subsidizes the OGSECS at low utilization and fully subsidizes the OGSECS at high utilization while also decreasing marginal cooking subsidy with increasing cooking services delivery.

Estimation of per-kWh OGSECS benefits

Figure 30 summarizes the per-kWh social and economic benefits of OGSECS. Details of these per-kWh benefit estimates are provided in Appendix A.

Time savings from faster cooking is by far the highest value benefit when monetized. The combination of cooking and reduced wood collection time savings comprises 74% of the monetized value that the OGSECS provides. Monetary fuel savings provides about 15% of monetized OGSECS benefits while climate and health benefits each provide about 6% of monetized OGSECS benefits.

Total monetized benefits of OGSECS use are approximately $0.731/kWh, so an RBF compensation rate of MEC services delivery at an average rate of $0.20/kWh is highly cost-effective.

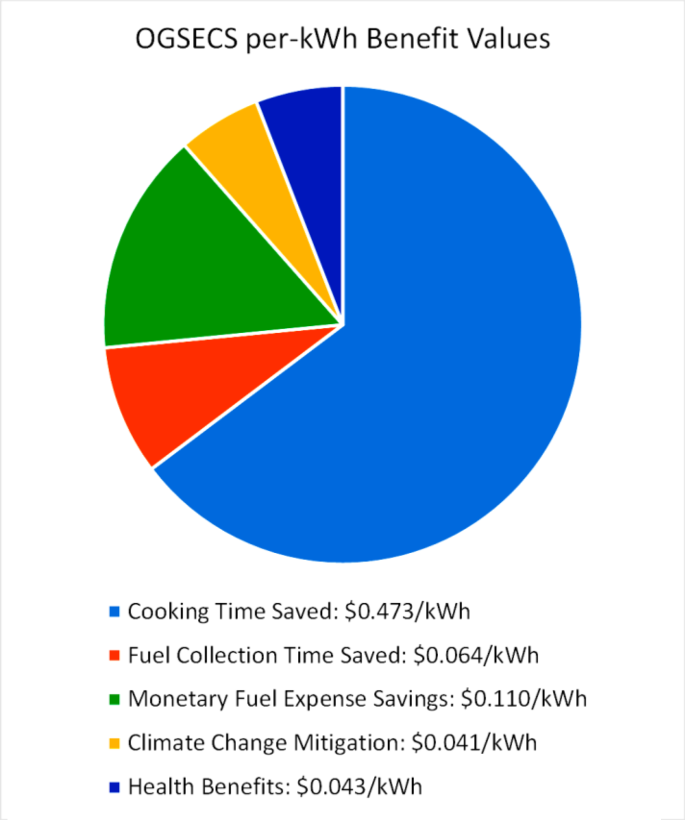

Figure 30: Per-kWh monetized benefits of OGSECS use

8. Conclusion

KLLC began developing off-grid solar electric cooking systems (OGSECS) for low-income rural Malawians in 2019. Since then, progress has been dramatic. In 2019, the factory door price of solar panels was \$0.30 per watt. Since then, the factory price of solar panels has declined to \$0.08 per watt, exceeding predictions.[22] This 4X decline in solar panel prices has allowed the capacity of OGSECS to increase by 5X from 150Wp to >700Wp. The higher capacity OGSECS can now provide an average of 1 kWh/day of efficient, electric cooking for 40% of the daily food requirement of a household of 5 people. The most valuable benefit that the OGSECS provides is 2 hours per day of time savings for women that use the system. But because of extreme cash shortages in villages, OGSECS users rank fuel expense savings (~\$0.110/day) higher than the time savings. We estimate total monetized OGSECS benefits as \$0.731/kWh, of which 74% is the time savings, 15% is monetary fuel savings, 6% is climate mitigation benefits and 6% is value of health benefits/impacts.

There is an affordability gap between the \$250 cost of a 700Wp OGSECS, and the \$145 price that a substantial number of rural Malawian customers can afford. This affordability gap can be financed with a simple per-kWh low-income electricity subsidy. For initial distribution of an OGSECS, this subsidy can be \$0.20/kWh, while for higher levels of OGSECS use the marginal subsidy can be decreased to \$0.10/kWh. We note here that a marginal subsidy of \$0.10/kWh can finance expanding the OGSECS capacity from 700Wp to 1.5kWp which has an incremental cost of \$100 per system because of the very low international market price of solar panels that currently exists. At 1.5 kWp, an OGSECS can allow rural households to cook their complete food requirement with off-grid solar electricity on sunny days.

KLLC has developed a 10-to-20-year lifetime solar battery based on lithium titanate (LTO) battery chemistry that can be used to enhance performance, benefits and reliability of an OGSECS at a cost of \$0.7 per Wh of battery capacity. One feature of these customized batteries is the inclusion of a high-resolution data collection capability. These batteries can be sustainably charged and discharged at rates greater than three times per hour, and thus a 170Wh LTO battery can regulate cooking loads greater than 500W. The KLLC LTO battery can be used as the data collection tool for creating a targeted per-kWh electricity subsidy that can make OGSECS affordable and accessible to all rural Malawians. KLLC does not think that LTO battery production needs a subsidy for affordability and production can probably be scaled with concessionary loan financing and without explicit grant financing.

Just a few years ago, it seemed impossible to feasibly provide clean, off-grid solar-electric cooking services to rural Malawians who have cash incomes of less than \$1/capita/day. But now with technology innovation and the continuing decline in the per-watt cost of solar panels, such off-grid solar electric cooking services can now have a marginal cost of less than \$0.10/kWh. Technologically speaking the clean cooking access problem for low-income rural Malawians is solved. The next challenge is to use this technological progress to create a scalable supply, distribution and financing system that can deliver clean, climate-friendly solar eCooking to several million rural Malawian households over the next decade and reduce significantly Malawi's electricity-access gap.

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[22] See: https://www.researchgate.net/publication/351853878_Estimating_and_projecting_solar_panel_costs_for_Sub-Saharan_Africa, accessed October 2024

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Appendices

Appendix A: Estimate of monetized per-kWh benefits of OGSECS use

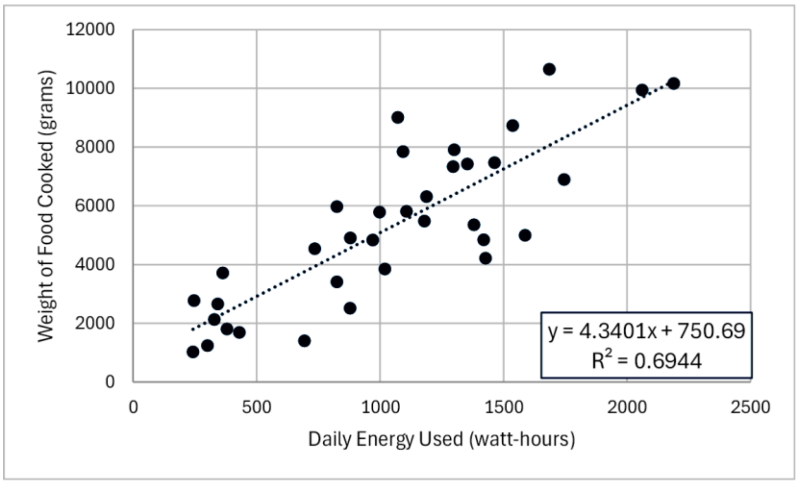

Figure A-1: Correlation between weight of food cooked and electricity use for cooking tests in a village shop. Daily average energy use is 1044 Wh/day

Figure A-1 illustrates the correlation between electricity used and total weight of food cooked in village shop cooking tests for a 700Wp OGSECS. Since the goal of a clean cooking intervention is to enable cooking on modern fuels, this figure illustrates how monitoring cooking electricity use should be an excellent proxy for amount of food cooked using modern fuels. If we assume that most of the benefits of modern energy cooking (MEC) scale with the amount of food cooked using modern fuels, then specifying the per-kWh benefits of MEC and then measuring the kWh of cooking energy use of an OGSECS should provide a very accurate measurement of the benefits that accrue from OGSECS distribution, ownership and use.

Time savings

The household surveys described in this study provide the time savings that OGSECS users report from use of an OGSECS, with 2.2 hours per day of cooking time saved and 0.3 hours per day of fuel collection time saved per day for sunny periods with a 700Wp battery-free OGSECS that delivers an average of about 1 kWh/day of cooking energy. If we rather conservatively assume that the OGSECS is used at about 50% of its sunny day capacity on average, then this provides an estimate of about 1.05 hours of cooking time saved and 0.15 hours of fuel collection time saved for every 0.5 kWh of OGSECS use. This corresponds to a time savings estimate of 2.5 hours per kWh.

To estimate the monetized value of this savings in household work time, we value time savings at the legal minimum wage rate in Malawi. In August 2024, the minimum wage in Malawi is 2,884.62 MWK per day[23] or 370.6 MWK/hour for an 8-hour day.

This means that the monetized value of time savings from a kWh of OGSECS use is 2.5 x 370.6 = 926.5 MWK/kWh = **$0.537/kWh** at an exchange rate of 1725 MWK/USD.

This would be the value of the savings in an economy where women could monetize their labour at a fair rate. But given a combination of gender and economic equality, women in rural Malawi are unable to get compensated for their labour at minimum wage rates. This above-market valuation of time savings to some extent also reflects the gender empowerment benefits of the OGSECS: while the local market does not value women's time at minimum wage rates, development policy should not mirror the gender inequality of a local market that often does not compensate women's work. To avoid replicating gender injustices, development policy and program design should value women's time savings at valuations that are greater than or equal to the legal minimum wage rate.

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[23] https://labour.gov.mw/images/documents/MINIMUM%20WAGE%20GAZETTE%202024.pdf, downloaded October 2024

Fuel expenditure savings

The household data collected in this study provides data that can provide three separate estimates of the potential monetary savings that may accrue to households that own an OGSECS.

The first and simplest estimate comes from 700Wp OGSECS users who reported that they saved an average of 167 MWK/day during sunny periods. Since a 700Wp OGSECS provides about 1 kWh of cooking on a sunny day, this corresponds to 116 MWK/kWh = $0.067/kWh.

Alternatively, households report that a 700Wp OGSECS allows households to cook 55% of their food on the OGSECS on sunny days and 39% of their food on cloudy days. If we estimate 1 kWh of cooking energy use on a sunny day, and a proportional decrease of average household fuel expenditures of 475 MWK/day, then this is 0.55 x 475 = 261 MWK/kWh = $0.151/kWh.

A third method is to estimate the total daily food requirements of an average household of 5 people by virtue of the fact that their calorie requirement is approximately 2000 calories per person per day, and the foods that they eat (nsima, sweet potato, greens, etc) have an average calorie content of about 0.8 calories per gram of cooked food. This implies that a household needs to cook (2000 x 5)/0.8 = 12.5 kilograms of food per day. Since 1 kWh of OGSECS use can cook 5 kg of food, each kWh of OGSECS use provides 5/12.5 = 40% of a household's daily cooking energy requirement. A 40% savings of fuel expenditure on average should be about 475 MWK x 40%/kWh = 190 MWK/kWh = **$0.110/kWh**, which coincidentally is approximately the average of the other two estimates.

Climate impacts

The value of the climate impacts/benefits of OGSECS use are highly uncertain because of the many variables involved in the estimation of such values. The factors that can influence such estimates include: (1) The types of fuels that might be displaced by OGSECS usage, (2) The fraction of biomass use that is non-renewable (fNRB), (3) The degree to which there is leakage due to rebound or backfire effects, and (4) The efficiency of the traditional fuels cooking that is being displaced.

To calculate a range of possible climate impact values, we will estimate climate impacts for two relatively conservative scenarios: (1) OGSECS displaces 75% wood and 25% agricultural residues where the wood has an fNRB value of 35% and where cooking is 10 times less efficient energetically than electric cooking; and (2) OGSECS displaces 75% wood and 25% charcoal where fNRB is 35%, wood cooking is 10 times less efficient than electric, charcoal cooking is 5 times less efficient than electric cooking and 7 kg of wood is necessary to make 1 kg of charcoal.

Estimation of Case #1

Equivalent energy intensity of wood cooking = 10 x 3.6 MJ/kWh = 36 MJ/kWh

(36 MJ/kWh)/16MJ/kg-wood = 2.25 kg-wood/kWh

75% x 2.25 kg-wood/kWh x 1.8 kg-CO_2/kg-wood x 35% (fNRB) = 1.06 kg-CO_2/kWh

Estimation of Case #2

Equivalent energy intensity of charcoal cooking = 5 x 3.6 MJ/kWh = 18 MJ/kWh

[(18 MJ/kWh)/30MJ/kg-charcoal] x [7 kg-wood/kg-charcoal) = 4.2 kg-wood/kWh

[(75% x 2.25 + 25% x 4.2) kg-wood/kWh] x 1.8 kg-CO2/kg-wood x 35% (fNRB)
= 1.72 kg-CO2/kWh

These estimates are assuming no rebound or backfire effects.

Reasonable valuations per unit climate mitigation impacts can range from CO2 verified emissions reduction market prices (e.g. about $10 per ton CO2) to the social cost of carbon (e.g. about $50 per ton). Using the range of emissions reductions represented by cases 1 and 2 and this range of emissions reduction valuations, we get the climate change mitigation value of OGSECS use at about $0.011/kWh to $0.086/kWh, with an average value of **$0.041/kWh**.

Health impacts

According to VizHub's Global Burden of Disease 2019 data,[24] the disease burden of "Household air pollution from solid fuels" for Malawi is cited at an average of 3401.98 DALY/100,000 people with a range of 2515.77 to 4459.86 per 100,000 people. Assuming that 2.5 kWh/day of OGSECS cooking could eliminate solid fuel cooking for a family of 5, this means that the per-kWh avoided disease burden could conceivably be:

(5 x 3401.98/100,000)/(2.5 kWh/day x 365 days) = 0.000186 DALY/kWh

To estimate the monetized value, we need a dollar value per DALY avoided. Daroudi et. al, 2021 find that the spending per DALY avoided is 0.34 times per-capita GDP for low-HDI countries, which would make the valuation of a DALY for Malawi at 0.34 x $679 = $231.

This gives the per-kWh health value of OGSECS at full adoption of:

$231/DALY x 0.000186 DALY/kWh = **$0.043/kWh**

We note that exposure vs. health impact relationships are not as simple as is presumed by the above calculation, but it is probably important to provide a very rough estimate of the health impact value of OGSECS so that its general magnitude can be compared to other benefits. What we might conclude from this rough calculation is that the monetized value of health benefits is approximately the same as the monetized value of climate benefits, and both values are substantially smaller than time savings or fuel cost savings that accrue to the customer household.

Comparison to LPG

Next, we compare the energy use of a kWh of OGSECS cooking with the energy use and cost of LPG cooking.

The retail price of LPG in Malawi is currently set at 3,245 MWK/kg.[25] The energy content of LPG is 49.3 MJ/kg.[26] If we assume that LPG cooking is approximately ½ as efficient as cooking in an electric insulated cooker, then the LPG energy requirement that is equivalent to 1 kWh of OGSECS cooking is 3.6 MJ/kWh x 2 = 7.2 MJ. We note that 7.2 MJ of LPG is 7.2MJ/(49.3 MJ/kg) = 0.146 kg. This amount of LPG costs 0.146 kg x 3,245 MWK/kg = 474

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[24] https://vizhub.healthdata.org/gbd-compare/

[25] https://mera.mw/2023/11/17/review-of-the-retail-price-of-lpg-for-november-2023/, accessed October 2024.

[26] https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html, accessed October 2024

MWK/kWh = $0.275. This is the estimated cost of cooking about 5 kg of food on LPG, which is the food cooked with one kWh on an OGSECS.

For households that have a choice between cooking with LPG or OGSECS, a kWh of OGSECS use should save them approximately **$0.275/kWh** in LPG fuel expenses.

Benefits summary

What these calculations highlight is that the most valuable benefit of an OGSECS is the time savings that it provides for the women who are cooking and collecting cooking fuels. The value of this time savings is about $0.54/kWh except for the fact that it is virtually impossible to monetize women's time saving in rural Malawi in practice at a rate that can correspond to a legal minimum wage.

Depending on estimation methods, there are a range of estimates for the per-kWh monetary fuel savings from using an OGSECS with an average savings value of $0.11/kWh. Because there are such extreme shortages of cash in rural Malawian village economies, monetary fuel expense savings are ranked as the most important benefit of OGSECS use by its owners (see household benefits section).

Coming in at a value of approximately $0.04/kWh, both climate benefits and health benefits appear to be substantially lower value than the time savings and monetary benefits to low-income households.

In total, the OGSECS produces about $0.647/kWh of benefit for the user household and about $0.084/kWh of climate and health benefits for a total monetized benefits of about **$0.731/kWh**.

OGSECS savings relative to LPG

Another key strategic benefit of MEC with an OGSECS is that at high levels of utilization, OGSECS cooking is much less costly than LPG.

Figure A-2 illustrates the relative fuel cost of LPG cooking per equivalent kWh of OGSECS cooking service, as a function of OGSECS system capacity utilization.

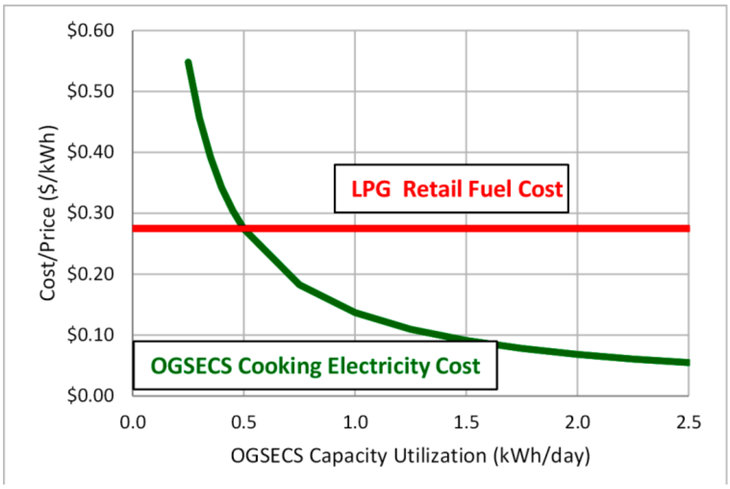

Figure A-2: Comparison of per-kWh of OGSECS cooking electricity and LPG fuel costs in Malawi for a $250 700Wp battery-free OGSECS. The OGSECS cost is amortized over 5 years and the per-kWh cost depends on daily system utilization.

If the 700Wp OGSECS system is utilized at an average of one kWh/day for five years, then the OGSECS electricity is about half of the LPG fuel cost at $0.137/kWh. Net savings of a well-utilized OGSECS over five years relative to LPG fuel cost is about $50/year per household.

The lower unit cost of OGSECS-based MEC means that if four million Malawian households transition to OGSECS-based cooking and utilize the systems well, this could save the Malawian economy hundreds of millions of dollars per year in fuel expenses relative to an LPG-based clean cooking transition.