MECS
Modern Energy Cooking Services

MECS Project Report (Final)

Date: 14 March 2023

Empowering Efficiency: Distributing off-grid solar electric cooking systems using women-lead organizing in rural Malawi

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ESMAP Energy Sector Management Assistance Program

'This material has been funded by UK aid from the UK government and is implemented by the Department of International Development; however, the views expressed do not necessarily reflect the UK government's official policies.'

Empowering Efficiency: Distributing off-grid solar electric cooking systems using women-lead organizing in rural Malawi

Version 1.2: 14 March 2023

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Document Control Sheet

Issue Status	Author(s)	Reviewed By	Loughborough University Approved By	Issue Date
Draft version	Lawrence Kachione, Gilbert Roberts, Christina Gilbert, James Majoni, Rachel Kanyerere and Robert Van Buskirk	Simon Batchelor	Simon Batchelor	27th February 2023
Final version	Lawrence Kachione, Gilbert Roberts, Christina Gilbert, James Majoni, Rachel Kanyerere and Robert Van Buskirk	Simon Batchelor	Simon Batchelor	14th March 2023

Executive Summary

In this report, ***Empowering Efficiency: Distributing off-grid solar electric cooking systems using women-lead organizing in rural Malawi***, we describe the results of a two-year project (2020 – 2022) to make off-grid solar electric cooking systems (OGSECS) affordable and accessible for some of the lowest income households in rural Malawi.

This report details the results and learnings from a grant-funded project that was originally titled: *Efficient empowerment: How 'Earn & Grow' can enable solar electric cooking access for African women*. For this report, we have changed the title of our work to better reflect our observation that the most effective women's empowerment process for enabling OGSECS access may be encouraging the organization and empowerment of collective groups of women. These women's collectives can share work and resources to help promote and distribute solar products and can share solar equipment to generate income.

At the beginning of the project, we envisioned that individual households could earn relatively higher-priced "climate justice credits," and that such "earnings" would help women in those households to purchase solar home systems with solar electric cooking in an incremental, multi-year process that we called "Earn and Grow." Instead we found rather than an individualistic empowerment process, that a community-based women's empowerment process around multiple types of income earning opportunities was likely to be more effective.

Kachione LLC (KLLC) is now exploring how a variant of the "Earn and Grow" cooking capacity expansion model can be used to grow the assets and income village women's collectives that partner with KLLC in operating rural villages solar shops. As of early 2023, KLLC plans to rapidly expand its network of collectively-operated solar shops and test the scalability of a results-based finance (RBF) approach to incentivising the use, adoption, and distribution of solar electric cooking systems more widely.

In addition to this project report, we documented technical and organizational progress of this project in a series of technical papers and blogs.

The peer-reviewed paper: *How to Make Off-Grid Solar Electric Cooking Cheaper Than Wood-Based Cooking*,[1] provides a technically detailed accounting of when and how OGSECS can provide cooking to rural African households at a cost that is less expensive than the current cheapest alternative: wood for cooking. Necessarily, making OGSECS cooking less expensive than wood cooking entails having a relatively long-term investment perspective and taking into account the social cost of wood cooking emissions. It is especially important to provide OGSECS that are durable and that can last a long time so that the long term benefits of an OGSECS can be fully realized.

The above peer-reviewed paper also provides a series of technical appendices that are directly relevant to providing affordable solar electric cooking access in rural Malawi, including:

> A simplified method for calculating the levelized cost of energy (LCOE) using amortization factors:[2] When an investment in a solar electric cooking system replaces or displaces wood cooking, an initial investment in a durable cooking system is displacing a continuing cost of wood collection and use. This appendix to the paper explains how to economically translate the initial investment in a solar

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

[2] https://www.researchgate.net/publication/351853971_A_simplified_method_for_calculating_the_levelized_cost_of_energy_LCOE_using_amortization_factors

electric cooking system into a cost per unit cooking energy that the system delivers to the customer.

A model-based methodology for estimating the efficiency of a diode-based solar electric cooker:[3] The factor that most impacts the utilization efficiency of a solar electric cooker is user behaviour. In this technical note, a simple cooker energy balance model is described that can be used to predict the relationship between utilization efficiency and use behaviour for small electric cooking systems.

Estimating and projecting solar panel costs for Sub-Saharan Africa:[4] The largest component cost of the lowest-cost designs of an off-grid solar electric cooking system is the solar panel cost. This technical appendix details the range of wholesale supply costs that are possible when solar panels are acquired at scale in Africa.

Estimating lithium titanate (LTO) battery costs for Sub-Saharan Africa:[5] The largest component cost of supplying more reliable off-grid solar electric cooking for solar home systems is a long-lifetime battery storage. This technical note details supply costs for very-long-lasting lithium titanate battery cells.

A series of blogs also provided accessible descriptions of three aspects of project progress during project implementation:

An Off-grid Solar Photovoltaic Electric Pressure Cooker system that costs only $200 in Malawi:[6] This blog describes how a DC electric pressure cooker can be operated without a battery by connecting it directly to solar panels on a sunny day. This allows for a very low-cost off-grid solar electric system that can be used for cooking meals during the daytime on sunny and partly sunny days.

Lessons from a women's empowerment exchange between Northern Tanzania and Malawi:[7] This blog details a training and knowledge exchange between the grant implementing organization (Kachione LLC) and a Northern Tanzania clean energy women's empowerment organization that works with Maasai women.

Integrating Hot Water, Hot Iron, and Long-cycle-life Batteries to provide Off-grid Solar PV Cooking Energy Storage in Malawi:[8] This blog describes the post-project strategy to upgrade over time low-cost daytime solar home cooking systems to systems that can provide energy for cooking during non-daylight times using a combination of energy storage strategies.

Last but not least, at the end of the project, the project technical lead formulated a policy concept note that describes a Results-Based Financing scheme that could be used to scale-up access to electricity—including solar electric cooking—for a majority of households in rural Malawi.

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[3] https://www.researchgate.net/publication/351867144_A_model-based_methodology_for_estimating_the_efficiency_of_a_diode-based_solar_electric_cooker

[4] https://www.researchgate.net/publication/351853878_Estimating_and_projecting_solar_panel_costs_for_Sub-Saharan_Africa

[5] https://www.researchgate.net/publication/353261371_Estimating_lithium_titanate_LTO_battery_costs_for_Sub-_Saharan_Africa

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

[7] https://mecs.org.uk/blog/lessons-from-a-womens-empowerment-exchange-between-northern-tanzania-and-malawi/

[8] https://mecs.org.uk/blog/integrating-hot-water-hot-iron-and-long-cycle-life-batteries-to-provide-off-grid-solar-pv-cooking-energy-storage-in-malawi/

Refining a business model for rapidly scaling-up efficient, empowering and affordable off-grid solar-electric cooking for all of rural Malawi:[9] This policy concept note provides a fairly detailed vision of how the lessons learned described in this report can be applied and integrated with policy and a specific design of a RBF scheme to create a process for ambitiously and cost-efficiently scaling up solar electricity access for a majority of households in rural Malawi using OGSECS.

This project report builds on and extends the learning and information contained in the above list of published documentation.

Specifically, this report details our project experience and describes how we came to develop the following list of 12 lessons learned during the course of project implementation:

Empowerment lessons learned:

(1) Income generation is empowerment: The most motivating type of empowerment increases income generation opportunities for participating women

(2) Solar pumps easily generate income: The easiest way to increase income for rural Malawian women using solar-electric technology is with solar-irrigated gardens in the dry season.

(3) Village solar shops provide solar sales income: Once irrigation-based empowerment is used to establish a women-run solar shop, it is easy and straight-forward to add distribution of clean cooking technologies, commission-based income, and RBF-based income.

(4) A "Ladder" of clean cooking options can aid access: Creating a "ladder" of clean cooking technologies may help households raise to the level of getting an OGSECS

Lessons learned re: solar electric cooker design and production:

(5) It is difficult to make workshop-assembled solar cookers long-lasting: It appears that local, workshop-based production of solar electric cookers has difficulty producing the long-lasting, durable cookers that are necessary for making off-grid solar electric cooking economically viable.

(6) Lithium titanate batteries and grid-backup can create reliability: Either LTO batteries or a grid-connected DC power source can help provide more back-up power for solar electric cooking during nighttime or when it is cloudy.

Lessons learned re: affordability and willingness to pay:

(7) Affordable solar panels are the key to affordable OGSECS: The biggest affordability barrier to initial adoption of off-grid solar electric cooking is the cost of the solar panels, and some rural households are willing to make this relatively large investment. When solar panels are affordable priced, DDS OGSECS are affordable.

(8) Solar panels used for solar pumps can be used for cooking: Linking solar irrigation of vegetable gardens to off-grid solar electric cooking creates synergies that can make off-grid solar electric cooking affordable.

(9) Affordable LTO batteries may be the key to making OGSECS reliable: The main barrier to reliable OCSEC is affordable, long-lasting batteries and custom LTO batteries might allow this barrier to be surmounted.

Scalable financing lessons learned:

(10) Leveraging the environmental value of wood savings may make OGSECS affordable: The existence of large positive "environmental externalities" in the adoption of OGSECS means that scalable, economically efficient subsidies should be possible

[9] https://www.researchgate.net/publication/361480695_Refining_a_business_model_for_rapidly_scaling-up_efficient_empowering_and_affordable_off-grid_solar-electric_cooking_for_all_of_rural_Malawi

for assisting affordability and adoption. But carbon offsets may not be economically efficient because they are priced at levels that are less than 20% of the value of environmental externalities.

(11) OGSECS electricity may be less expensive per kWh than grid electricity: OGSECS can be designed to provide solar electricity to off-grid households on a per-kWh basis that is less expensive than a standard SHS for non-cooking uses. This can create a relatively large willingness to pay for such OGSEC systems.

(12) Results-based Finance schemes may enable large-scale OGSECS adoption: Cost-efficient RBF schemes should be able to provide sufficient revenue to make OGSECS profitable to significant scale. Further cost-innovation and economies of scale should make OGSECS financially feasible at national scale by 2030 in Malawi.

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1. Introduction

1.1 *The Problem Setting*

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, charcoal, or some combination of the two fuels. A very small number of households use grid electricity for a relatively small amount of cooking that is done on electric hot plates.

Per-capita income in Malawi in current dollars in 2022 is $635/year on average according to World Bank data.[10] Yet a majority of 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 when one looks at the cash income earned 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.

Thus, the purchasing power of a dollar in Malawi is relatively high because the general shortage of cash in the Malawi economy creates conditions where people can purchase more goods relatively with less actual cash. Prices for locally produced goods and services deflate to create a local market equilibrium where the supply and demand of both goods and cash is balanced. When cash is in short supply, cash is expensive and participants in the economy have to sell more goods to get the same cash. This creates price deflation for locally produced goods and services. This is the general state of affairs in rural villages[11] where most people operate in a subsistence economy.[12]

The actual purchasing power per capita in Malawi is $1,638 according to World Bank figures in 2018.[13] This means that on average for every $1 that a Malawian possesses, they can purchase a basket of basic consumables that typically would cost ($1,638/$635) = $2.6 if those goods and services were sold at international prices. The fact that Malawians consume about $2.60 worth of goods for a cash expenditure of $1 reflects the generalized deflated level of product and service prices in Malawi.

The deflated price levels in the Malawi economy have plusses and minuses. On the minus side, it is very hard for Malawians to purchase imported goods. This is because imported goods tend to be about 2.6 times more expensive than locally produced goods ‘on average.’

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[10] https://data.worldbank.org/indicator/NY.GDP.PCAP.CD, accessed February, 2023.
[11] In 2021 in Malawi, 82% of people living in rural areas. See: https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=MW
[12] See for example: “Traditional production in … African economies” by George Dalton, (http://web.mnstate.edu/robertsb/380/tradafrprod.pdf) for a discussion of how subsistence economies can operate in ways that are different than market economies.
[13] https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD, accessed February, 2023.

This makes it very challenging to bring new, imported technologies to Malawi because of their high cost relative to the very limited local supply and availability of cash income.

But on the plus side, when a project or technology saves the equivalent of $1 of cash expenses or generates $1 of cash income in the local economy, this savings or income can generate about $2.60 of benefits in terms of actual consumed goods (e.g.: food, soap, housing, clothes, etc.) for the household that saves the money or earns the income.

1.2 *The challenges and opportunities created by price deflation in Malawi*

A huge challenge created by price deflation and low incomes is that it makes it extremely difficult to provide products to the majority of Malawians at affordable prices because the price of imported products that Malawians can afford is so low.

Malawian's inability to be able to afford imported products is even understated by the average per-capital income that the Worldbank notes is $683/capita. Perhaps a better indications of affordability is indicated by Malawi's current minimum wage levels.

At the end of 2022, the minimum wage in Malawi is 50,000MWK per month, while current exchange rate for MWK in exchange houses is 1400MWK/USD. This means that the foreign currency purchasing power of a minimum wage worker in Malawi is less than $36/month. If that minimum wage worker is supporting a family of four people, then the foreign currency purchasing power in that family is only ($36/month)/(4 people)/(30 days/month) = $0.30 per day per capita!

But if our ultimate goal is to produce large humanitarian benefits in rural Malawi, then the fact that wages and prices in rural Malawi are highly deflated suggests that when money can be put in the hands of Malawian households, it can have a relatively large impact on the standard living or low-income Malawians. For example if a household if 4 people is supported by a minimum wage worker, and if a $200 solar system or device can increase the income of that worker by just $500/year, then the solar device can effectively double the standard of living of four people at an investment cost of only $50/person.

In fact if it becomes possible to double the income of project beneficiaries for more than three years at an investment cost of less than $50/person in a solar electricity access project, then such a project has the possibility of competing as one of the most cost-effective charitable interventions globally.[14]

1.3 *Focusing on women's empowerment is supporting community empowerment*

We note from Kabeer (1999) that:

> "… women's empowerment is about the process by which those who have been denied the ability to make strategic life choices acquire such an ability. The ability to exercise choice incorporates three inter-related dimensions: resources … agency … and achievements (well-being outcomes)."

[14] Note that simple "cash transfers" are some of the most cost-effective, evidence-based methods of reducing poverty (See for example https://givedirectly.org/research-at-give-directly/). If a $200 solar device can generate $500/year income for three years, then a $200 investment produces $1500 of total income and is likely to be more impactful than a simple $200 cash transfer.

Such empowerment appears to reduce poverty in general (Wei, et.al, 2021). As such, if the acquisition of solar electric cooking access can contribute to women's empowerment, then in the process of bettering their own lives, women in rural Malawi will likely better the lives in their entire community

1.4 *Addressing limited purchasing power with "economically efficient subsidies"*

As explained by Triest (2007), if subsidies are designed properly and targeted appropriately, they can contribute to enhancing economic efficiency when they mitigate or resolve market failures:

> "Free-market economies promote the public interest, in the sense that they tend to promote an efficient allocation of economic activity and resources. The market mechanism leads to activities being undertaken only as long as the benefits of further activity equal the incremental cost. In a sense, market forces result in automatic benefit-cost analyses guiding decision-making. However, many circumstances bring about "market failures"—the market mechanism breaks down and the actions of the unfettered invisible hand may lead to undesirable outcomes. When market failure occurs, a situation arises that economists refer to as economic inefficiency: the potential to make someone better off without making anyone else worse off—in other words, when there is a 'free lunch.'"

Two extremely large and glaring market failures are addressed in the context of clean cooking activities in rural Africa: (1) Environmental market failure (climate and ecosystem sustainability), and (2) Poverty and inequality market failure. This means that because the externalized benefits of clean cooking are not priced in rural African markets, the 'free lunch' described by Triest can be obtained when clean cooking activities are subsidized by development aid or philanthropy at rates that are smaller than the externalized benefits accruing from the activity.

1.5 *Market Values vs. Social Values: How should we value climate mitigation?*

With respect to climate mitigation, the value of the externalized benefits of emissions reductions are characterized by a quantity that is called the "social cost of carbon."

The social cost of carbon is described by Nordhaus (2014) as follows: "The social cost of carbon (SCC) is an important concept for understanding and implementing climate change policies. This term represents the economic cost caused by an additional ton of carbon dioxide emissions." Nordhaus also notes in the same paper:

> "With an optimized climate policy (abstracting away from complications due to tax or regulatory distortions or inconsistent treatment in different sectors), the SCC will equal the carbon price; this in turn is equal to the marginal cost of emissions reduction and to the present value of the damages from a unit of emissions. In the more realistic case where climate policy is not optimized, it is conventional to measure the SCC as the marginal damage of emissions along the actual path."

Yet as acknowledged by many,[15] global climate policy is far from optimized because on a global scale the policies are not leading to sufficient investment in climate mitigation.

Since demand and purchases of climate mitigation fall far short of what is needed to avert large future climate damages, relatively, market demand for emissions reductions and offsets are low relative to the possible supply of needed climate change mitigation actions. Thus by the law of supply and demand, the price being paid for climate mitigation (i.e. carbon offsets) is currently too low to suficiently mitigate climate change. This causes the social cost of carbon is to be much higher than current market prices for climate change mitigation or emissions reduction because demand for mitigation is falling far short of what is needed to avert the damages.

In this report, we take the longer term view that government policy and development aid will eventually demand enough climate mitigation to avert the worst consequences of climate change. In that case, as noted by Nordhaus, the carbon price will rise and approach a value that is closer to the social cost of carbon. Thus, we value the climate mitigation benefits generated by solar electric cooking in rural Malawi as represented by the social cost of carbon rather than current market prices for emissions reduction credits or offsets.

Aims 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 so that they can not only have lights and other electronics, but so that they can cook with off-grid solar electricity. Our aim is to provide this access 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 either inexpensive battery-free solar systems or 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 "Earn & Grow" where donation and aid revenues are channelled into a new credit that efficiently delivers full benefit value to low-income women for their efficient climate-change-mitigating actions

To accomplish such ambitious aims at scale will of course 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.

[15] See: https://unfccc.int/news/climate-plans-remain-insufficient-more-ambitious-action-needed-now accessed February, 2023.

Objectives of the project

The objective or short-term outcomes that we seek to accomplish in order to support progress towards our longer term aims are as follows:

1) To demonstrate that changes in behaviour can be harnessed to improve the efficiency of appliances

2) To show that decreases in appliance life-cycle cost in off-grid systems can be accelerated by simultaneously increasing the efficiency of a) panel utilization, b) the appliance, and c) user behaviour

3) To demonstrate that off-grid solar can initially be battery-free thus radically reducing the initial financial and environmental (i.e. e-waste) cost of the system. Additionally to demonstrate that when batteries are added to the system, these batteries can last 10 years or more.

4) To create a means by which families living in subsistence economies can “earn” their solar system even though they may have only minimal cash resources; and

5) To demonstrate new ways that women can increase their influence over clean energy investment decisions to increase household assets and wealth

2. Methodology

The methodology we utilized in this project is an Action Research type of process where we combined test deployments and data collection to create in continuing cycle of innovation. The innovation that was created by the Action Research process lead to continuing improvements in both technologies and business models that allowed the project to attain the project aims and objectives.

Applying an Action Research approach[16]

Action research is a research methodology that involves a collaborative and iterative approach to problem-solving. In action research, researchers work closely with practitioners to identify a problem or challenge, develop and implement interventions or changes, and then evaluate the results to determine their effectiveness. This process is often cyclical, with further changes and improvements made based on the evaluation of interim results.

The higher priority aim of action research is to bring about positive change in a particular context, with an emphasis on collaboration and participation. It is a process that leads to the co-creation of knowledge, where both researchers and practitioners learn from each other through the research process.

Action research is often contrasted with more traditional research methods, which prioritize objectivity and detachment from the subject matter. Action research is instead characterized by its active engagement with the subject matter and its focus on real-world problems and solutions.

In the context of the Efficient Empowerment project, the participation and control exercised by the women's collectives in implementation lead to greater emphasis on empowerment and income-generation. This lead to the development of strong linkages developing between the distribution of solar electric cooking and solar irrigation pumps. It also lead to the ultimate abandonment of artisan-made solar electric cookers and the adoption of higher quality, more durable, and aesthetically more pleasing imported DC EPCs.

Focusing innovation on long-term project aims

We kept the project implementation focused on long-term project aims by engaging in five key activities:

1. Developing and improving the women's empowerment process
2. Reducing the levelized cost of electricity in off-grid solar electric cooking systems
3. Improving the durability and efficiency of solar electric cooking
4. Testing and development improved custom LTO batteries
5. Piloting results-based payments to help integrate behaviour and technology

1.6 *Developing and improving the women's empowerment process*

We initiated the women's empowerment component of our project by performing both formal and informal data collection. This data collection attempted to determine what Malawi women themselves would consider the most empowering types of intervention. We found generally that the most desired interventions where those that allowed women to increase

[16] Elements of this subsection were written with the aid of ChatGPT (https://chat.openai.com/chat)

their income through their own actions and production. Our results are consistent with recent commentary in the academic literature. Specifically from Ngono, (2021):

> “[W]omen who turn to self-employment rather than being employed by others tend to do better and to do more to reduce income inequality. The primary role of self-employment in reducing income inequality is reflected in the work of Banerjee and Newman (1993). Self-employment improves the economic situation of the entrepreneur and as a result, that of the society, notably with the reduction of unemployment thanks to the hiring that follows (Gawel, 2020). In the case of women in particular, it is an opportunity to escape wage inequalities, harassment and sexism. Moreover, as Kabeer's (2005) work explains, the division of labor between men and women is rarely renegotiated within the household, and women, even while working, must continue to fulfill their roles as housewives. The flexibility of self-employment is a very good solution to work despite their other tasks. Self-employment can therefore be a viable channel through which to empower women and significantly reduce income inequality.”

Thus, consistent with the Action Research approach, we explored in partnership with rural women’s groups, how best to distribute and apply solar technologies so that they can support women’s income generation and self-employment.

1.7 *Reducing the levelized cost of electricity in off-grid solar electric cooking systems*

To lower the cost of off-grid solar electricity for rural Malawian households, the project conducted key cost analysis research to determine the factors that are most important in attaining this goal. This resulted in the peer-reviewed paper *How to Make Off-Grid Solar Electric Cooking Cheaper Than Wood-Based Cooking.* This paper concludes:

> “The key to making SEC cost-competitive relative to WC is four-fold: (1) assuring long lifetimes for solar panels … batteries [and cookers], (2) arranging a low marginal cost of capacity by efficiently importing and distributing batteries and solar panels at scale to keep overhead costs low, (3) utilizing the solar panel and battery capacity in the SEC system with high efficiency, and (4) accounting for climate impact externalities in the existing cost of wood.”
>
> ‘’Approximate targets for each of these cost parameters for SEC are roughly as follows: (1) >10 years for solar panels and battery subsystem lifetime, (2) solar panel costs below USD 0.36/Wp and LTO battery subsystem costs below USD 0.35/Wh, (3) solar panel utilization efficiencies of greater than 25% (i.e., portion of solar panel potential output delivered to food), and (4) a valuation or subsidization of climate benefits that exceeds USD 20/tCO_2e. By meeting all four targets, it should be possible to have off-grid solar electric cooking compete with wood-based cooking in SSA.’'

At the conclusion of this project, these goals have been largely attained (adjusting for inflation).

1.8 *Improving the durability and efficiency of solar electric cooking*

After two years of efforts in developing custom-made insulated solar electric cooker designs, it was eventually concluded that imported DC EPCs provided greater durability and efficiency at lower cost than would could be possible in an artisanal workshop setting. Thus the project obtained this objective by adopting the eWant DC EPC that is described in the report: report *eWant 24V DC 5 litre cooker – fit for purpose and a good size.*[17]

1.9 *Testing and development improved custom LTO batteries*

Unsatisfied with batteries that can last 3 to 5 years, KLLC in the course of this project decided to begin the development of a >10-year batter using lithium titanate battery chemistry. As described later in this report, this also enables the creation of an extremely inexpensive data collection system that can solar electric system operational data at high resolutions for a very long period of time. By the conclusion of the Efficient Empowerment project, this battery and data logger development is approximately 50% complete.

1.10 *Piloting results-based payments to help integrate behaviour and technology*

The project also pilot-tested results-based financing incentives for the utilization of solar electric cookers and on a preliminary basis has found an excellent initial response to such incentives. As described later in this report, cooker utilization with an RBF-type incentive can average as high as 0.49 kWh/day for battery-free solar electric cooking systems utilizing a 0.20 kWp solar panel during the rainy season using an RBF incentive of 1000 MWK/kWh.

[17] https://mecs.org.uk/blog/ewant-24v-dc-5-litre-cooker-fit-for-purpose-and-a-good-size/ accessed February, 2023.

3. Implementation

Exploring a variety of solar electric cooker designs

The project extended from middle of 2020 through the end of 2022, and utilized three different types of cooker designs through this period. Through 2020 and early 2021, a diode-based cooker design was used. During the latter half of 2021 through the middle of 2022, the project used less expensive and easier-to-build resistance-based cookers. Meanwhile after October 2022 the project transitioned to using imported, professionally manufactured direct-current (DC) electric pressure cookers (EPCs).

2.1 *Initial diode-based cooker design*

The cookers with the diode-based heating elements were made from stainless steel pans which then had diode/resistor heating elements attached to the bottom, as shown in Figure 1. The cookers were designed for 30 volt operation with a 60-cell 270W solar panel. The heating element consisted of 1N5404 diodes connect in series with resistors such that each chain of diodes was expect to take approximately 1 amp of current. Eight diode/resistor chains were connected in parallel to comprise the heating element of one cooker. The two resistors connected in series with the diodes consisted of seven 1W 10R component resistors connected in parallel (making for a 7W, 1.4R resistor). All diode chains are connected to the power through a 140 deg. C temperature control switch and glued to the stainless steel pan with high temperature epoxy.

After preparation of the electronics of the diode-based heating element, the entire heating element was encased in a mixture of sand and epoxy to create a uniform, durable DC electric cooking pot.

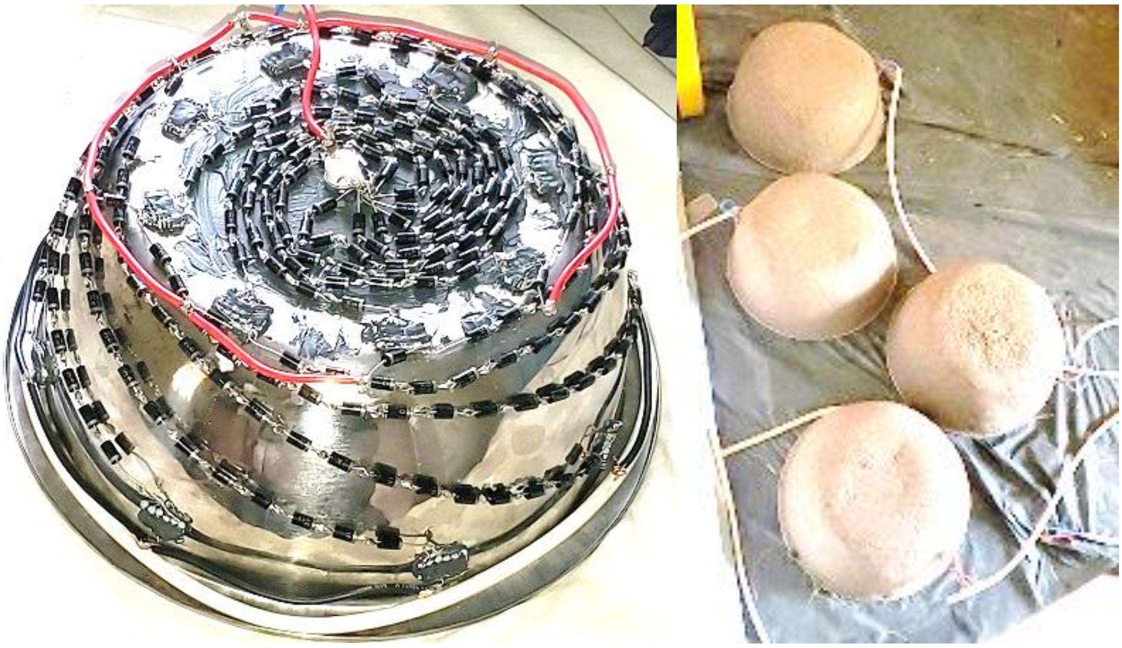

Figure 1: Heating element of the diode-based cooker (left0 and picture of cooking pot after heating element is encased in sand/epoxy mixture (right).

After the core DC electric cooking pan is constructed, the pan is assembled into an insulated bucket cooker. To assemble the bucket cooker, the bucket is filled with insulation, the cooking pan is placed into the bucket and held with screws, and then the gap between the pan and the bucket is sealed with an epoxy/sand mixture and sealed with silicone seal. The bucket lid is insulated and the whole assembly creates an insulated bucket cooker/water heater as illustrated in Figure 2.

Figure 2: illustrates the assembly of the parallel diode-based heating elements for ISEC cooking pot.

2.2 *Using resistive heating elements*

Given the complexity, time and effort of making cookers with diode-based heating elements, KLLC explored the assembly of a variety of cookers with resistive heating elements. Heating elements were constructed out of high-power ceramic resistors where the heating element was designed to operate within the design constraints of the resistor.

In spite of extensive efforts, ultimately when the locally-assembled resistive cookers were compared to the professionally manufactured DC EPCs described in the next subsection, the locally-assembled cookers could not compete in terms of both quality and cost.

Figure 3: Cookers with resistive heating elements being locally assembled in Malawi. Both simple cooker and pressure cookers were assembled and distributed.

2.3 *DC EPC (direct current electric pressure cookers)*

The project received a prototype of a relatively high-quality factory-made electric pressure cooker in September 2021 that is described in the MECS report *eWant 24V DC 5 litre cooker – fit for purpose and a good size*.[18] We tested the cooker in battery-free mode and found the cooker to work well as described in the blog article *An Off-grid Solar Photovoltaic Electric Pressure Cooker system that costs only $200 in Malawi*.[19] After discussions with the manufacturer, a version of the cooker was developed that had a "low power" button which could run at 250W at 24V in addition to running at 500W at 24V as originally designed.

The project received a shipment of 300pcs of the new factory-made DC electric cookers in September 2022, and are now is distributing that cooker as the primary off-grid solar electric cooking option for customers.

Figure 4: KLLC staff testing the ability of the cooker to cook chips (left) and a member of the Lundu women's collective cooking the local corn meal stable *nsima* (i.e. *ugali* in Kenya/Tanzania/Uganda) on the cooker (right).

[18] See: https://mecs.org.uk/wp-content/uploads/2021/08/eWant-24V-DC-5-litre-cooker.pdf
[19] See: https://mecs.org.uk/blog/an-off-grid-solar-photovoltaic-electric-pressure-cooker-system-that-costs-only-200-in-malawi/

Building a network of women-run village-based solar shops

KLLC performed initial exploratory discussions with women's groups in areas where it distributed solar lights to learn what empowerment meant to them. Not surprisingly, many women expressed a desire for increased income as the key to empowerment for them. They requested that KLLC should provide them with income generating opportunities.

2.4 *The initial shop in Lundu*

As part of its previous work distributing solar lights, KLLC had developed a relationship with a local women's group in one of the rural areas of Blantyre district at Lundu trading center. This women's collective calls itself *The Rise and Shine Federation* (or the Federation). As part of this project, KLLC approached the Federation and asked what "empowerment" meant to them. The primary answer provided by the Federation members was that the most empowering thing for them would be growing a "business" that they could run which could earn them money.

Figure 5: KLLC staff reviewing the operation of the solar electric cooker with members of the Rise and Shine Federation women's collective in June 2021.

One woman offered the idea of a goat business and suggested that the project could provide them with goats to help them create a goat business. KLLC explained that we were not in the business of distributing goats, but we were in the business of distributing solar systems and suggested that solar water pumps in particular might be a good business that KLLC could support. The solar water pumps could either be used directly by the women, or the women's collective could rent the pumps to farmers to make money.

In July 2021, the project delivered an initial inventory of cookers, solar pumps and solar panels and the Lundu shop began operations, selling the cooker systems as a discount price of $100. As explained in the technical note *Estimating the "Willingness to Invest" in Solar Home Systems with Cookers for Rural Households in Malawi*, by pricing the solar cooking system at slightly below the retail price of a large solar panel (i.e. $100 for a $270W system), the women were able to sell dozens of solar cooker systems to the surrounding community.

Figure 6: Delivery of the initial stock of solar panels and solar electric cookers to the women's collective in Lundu in July 2021.

Figure 7 shows the cumulative sales of solar cooker systems after the opening of the Lundu shop. Note that the sunny season lasts until the end of October, and that November through March is the rainy cultivation season. January through March is also known in Malawi as the "hunger season" when most rural households all putting all of their resources into farm inputs during the growing season while they wait for the next harvest which will feed their family.

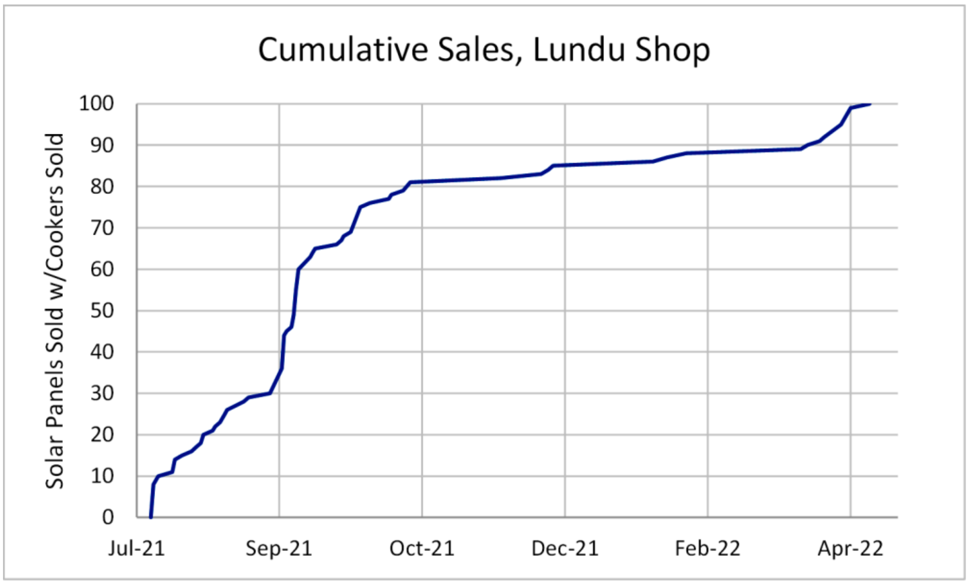

Figure 7: Cumulative sales of solar panels with cookers for the Lundu shop during its first 10 months.

2.5 *Expansion to Machinga and other districts*

After establishment of the women's collective solar shop in Lundu, KLLC's lighting distributor in Machinga district requested that KLLC meet the women's groups near the Mpita trading centre in Machinga district and establish a similar shop. That meeting took place in early October of 2021 with the shop being established a few months later in January 2022.

Figure 8: Members of women's collectives of the Mpita area of Machinga district meeting to discuss the set-up of a local solar shop in October 2021.

Figure 9: A meeting to discuss solar cooker system sales and solar pump distribution with the Mpita women's collective.

Near the time when shop was being established in Machinga, an attempt was also made to establish a shop in a village in MChinji district. Unfortunately the local leaders and distribution contact in MChinji did not actively involve the local women's groups in the organizing of the effort and they sold the delivered stock of solar panels to other men for profit rather than keeping them for use for cooking and solar pumping for women's groups.

A subsequent, much more successful effort established a women-run shop in M'bangombe village on the outskirts of Lilongwe. In that effort, the local women's groups was given a solar pump, a follow-up visit verified the proper utilization of solar pumps, and then a local shop was established similar to the Lundu and Machinga shops.

2.6 *Arrival of women's empowerment organizers*

As part of the project plan, two women's empowerment organizers were originally scheduled to come to Malawi from the US and Ghana during the summer of 2021. But unfortunately, because of a wave of COVID infections at that time in Malawi, it became difficult or impossible to arrange travel permission for both the organizers. Thus the women's empowerment organizers—Lesia Whitehurst and Evelyn Anasbile--visited Malawi in June/July 2022.

In mid-2022 when the empowerment organizers arrived, it was becoming clear that women's groups in the villages were very excited about the possibility of accessing solar pumps because of their very large income-generating potential. In addition, the solar panels used for the solar pumps can be used for solar electric cookers. This means that while individual women might not be able to afford the solar panels for a cooker, a group of women might be able to afford a solar pump in the dry season, and then could potentially use the solar panels from the pumping system for a solar electric cooker when the pump is not needed.

The women's empowerment organizers were therefore assigned the task of examining the interest and enthusiasm of women's groups in our service areas for solar pump adoption. Solar pump adoption is intended as a first step in generating income that could allow low-income women to buy the solar panels that would also enable off-grid solar electric cooking (OGSEC).

Figure 10: Community meeting with women's groups in Mwambo area of Zomba district. About 200 women's groups signed up as initially interested in the solar pumping systems.

The empowerment organizers worked with KLLC staff to assess interest in income-generating solar pumping systems amongst women's groups in rural Malawi. Collectively in Machinga and Zomba districts, approximately three hundred women's groups signed up as interested in the solar pumping systems.

Given the strong interest and the limited supply of solar pumps, KLLC decided to charge approximately $100 per solar system for a system that comprises 200W to 300W of solar panels and a solar pump. The $100 is essentially the market price of the solar panels in Malawi. Given this offer 130 women's groups purchased solar panels for their donated solar pumps from July until December 2022. A map of the women's groups purchasing solar panels is provided in Figure 11.

2.7 *Expanding solar cooker distribution by leveraging solar pumps*

The somewhat unexpected success of solar pump distribution as a "first adopted" technology appears to create infrastructure and income for the follow-on purchase and use of solar electric cooking systems by newly empowered low-income rural Malawian women. As such KLLC and its US philanthropic partners are preparing to distribute solar pumps to between 500 and 1000 women's groups in 2023. This will provide access to between about 5,000 and 10,000 new potential solar electric cooking customers in 2023.

In preparation for a 5X expansion in 2023, KLLC will be establishing an additional 5 to 15 women-run village solar shops and organizing those shops to be continuously demonstrating

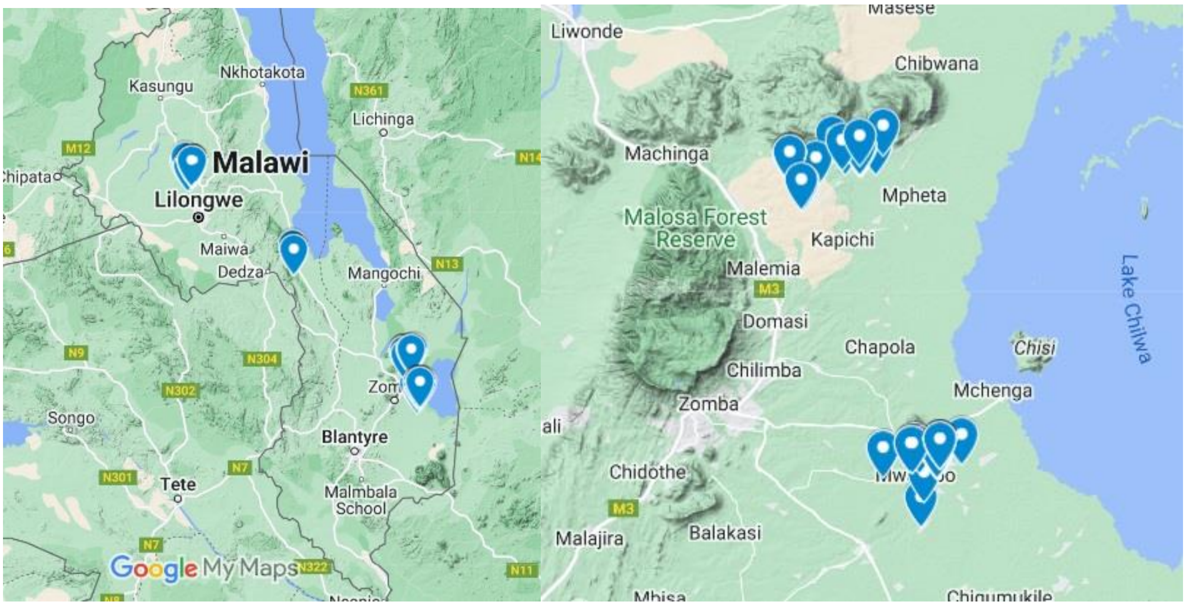

Figure 11: Locations of the Women's groups served by the solar-pump-based empowerment activities. The left hand map is a large scale map that shows the locations of the four clusters of groups: (1) North of Lilongwe, (2) Near Golomoti in Dedza District, (3) Southern Machinga District, and (4) Eastern Zomba District. The right-hand map shows a zoomed-in view of the clusters of women's groups in Machinga and Zomba districts.

solar electric cooking systems to the community through a commission/incentive arrangement that is based on results-based finance. At the beginning of 2023, KLLC has begun the process of equipping the women's solar shops with new DC EPC cooking systems and with meters that can be used to quantify cooker usage for result-based finance payments.

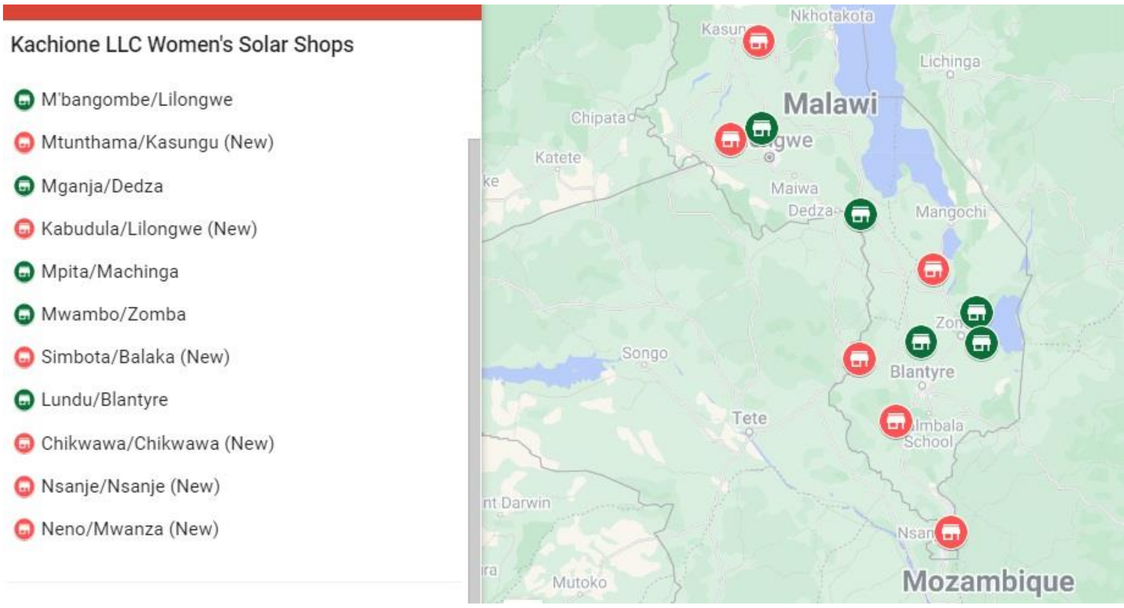

Figure 12: Locations of existing and planned village-based women's solar shops

Based on the experience per date, KLLC will testing a business model where each of the retail solar shops will receive a commission to demonstrate cooking on the solar electric cookers daily, while distributing solar pumps and marketing the solar cookers to the women's groups that buy solar panels for the solar pumps.

Figure 13: Incentivized demonstration of solar electric cooking at the M'bangombe women's solar shop. The small meters with the blue screens record instantaneous voltage, current and power and record cumulative energy use

2.8 *Solar electric cooker utilization in RBF incentive scheme*

Starting at the end of October 2022, KLLC started experimenting with results-based financing business model for encouraging demonstration and adoption of direct-use DC solar electric cooking in the village shops run by the women's collectives.

As illustrated in Figure 13, the first shop to engage in the scheme has been the M'bangombe shop which from October 31, 2022 to February 8, 2023 used 96 kWh of cooking electricity with three cookers during the beginning of the rainy season. This corresponds to 0.95 kWh/day or 0.32 kWh/day/cooker.

Similarly a pilot of the scheme has been started in the Lundu shop, which over the course of 39 days in late January and early February 2023 used 57 kWh for cooking. This corresponds to 1.46 kWh/day for three cookers or 0.49 kWh/day/cooker. The cookers in the Lundu shop were powered by high-quality 200W solar panels.

In the KLLC Blantyre workshop, a related pay-for-performance scheme was implemented with the workshop housekeeper to cook food for the workshop workers who get to purchase the cooked food at the end of the workday at a subsidized price.

At the Blantyre workshop, three cookers used 15.1 kWh during a 12-day period. During this 12 day period, two days had no cooking because it was Sunday. For the remaining 10 days, three days (30%) had no solar electric no cooking because it was cloudy, and on one day, the beans where only half-cooked. The average kWh per utilized per day was 2.16 kWh/day for three cookers or 0.72 kWh per cooker per utilized day. The total food cooked was 28.0 kg of cooked beans and 10.2 kg of cooked rice. The average energy use per kg of cooked food was 395 Wh per kg of cooked food. The detailed use data while cooking gives an energy intensity of 367Wh/kg which indicates 7% of total cumulative kWh consumed was lost during non-cooking times. The energy intensity for beans averaged 404Wh/kg, while the energy intensity of cooking rice averaged 267Wh/kg during the cooking sessions.

Initiating development of Malawi-assembled LTO batteries

KLLC in its development of small lighting systems for rural Malawians realized that a battery lifetime of 3 to 5 years is too short for a solar system that is subsidized by philanthropists or development aid in order to reduce poverty. This is because there can be a relatively large transaction cost to providing poverty-reducing aid to a low-income rural household. In fact that transaction cost can often be more than the cost of the solar system. And if that cost can be amortized over 10 to 20 years rather than 3 to 5 years, the social and humanitarian benefit-cost ratio of a poverty-reducing, partially-subsidized solar system can be dramatically improved.

In addition, as shown by a paper published by the KLLC team (Van Buskirk, et.al, 2021), the reasonably-priced very-long-lifetime battery chemistry of Lithium Titanate (LTO) appears to provide the lowest levelized cost of electricity for off-grid cooking applications. This is because of the extremely long cycle life of LTO battery cells (Hall et.al, 2018)

Figure 14: Assembly of an early version prototype of the LTO BMS circuit.

Currently, KLLC is importing single 10Ah, 2.4V LTO pouch cells at a cost of about $6 each (i.e. $0.25 per watt-hour). Five LTO cells connected in series make a 12V battery, while two 12V batteries connected in series make a 24V battery.

But when battery cells are connected in series, it is important to maintain the cells in balance, because if one cell is overcharged, while another is under-charged, it becomes impossible to either charge or discharge the battery without damaging either the overcharged or under-charged cell respectively.

Because LTO is a relatively new and more expensive battery chemistry, as of the end of 2022, there has not been a large variety of reasonably-priced assembled batteries available with battery-management system (BMS) that can maintain the individual cells in balance.

Fortunately, KLLC has received the volunteer technical support of a skilled electrical engineering Ph.D. student who has been providing a custom design for a BMS for LTO 12V batteries that can be assembled from pouch cells. A key advantage of a custom-designed microprocessor-based BMS controller is that an extremely inexpensive data collection system can be added to the board by adding an interface for an SD card.

Figure 15 show the end-of-project version of custom BMS controller with the SD for data collection.

Figure 15: End-of-project version of prototype of the LTO BMS circuit with data collection capabilities.

The SD card can be configured to collect data for more than a decade so that both the utilization and the durability of the battery can be precisely verified and quantified for philanthropists and aid agencies that may be willing to subsidize the distribution of very-long-lasting solar electric cooker batteries for very-low-income rural Africans.

4. Next steps

The next steps for scaling up our Empowering Efficiency approach to providing OGSECS access to low-income rural Malawians at larger scale are as follows:

1. Expanding the shop network using philanthropy-supported solar pump distribution
2. Rolling out the Empowering Efficiency solar electric cooking service/business model to more shops and customers
3. Organizing custom LTO battery assembly and distribution (including data collection)
4. Integrating RBF incentives into OGSECS that are sold to households

In June 2022, the technical lead on the project posted a fairly ambitious vision of how the Empowering Efficiency approach could potentially be brought to large scale to provide electricity for much of rural Malawi. This technical concept note, *Refining a business model for rapidly scaling-up efficient, empowering and affordable off-grid solar-electric cookingfor all of rural Malawi*, describes in some detail how the above-mentions four "next steps" can integrate into a larger vision of OGSECS distribution expansion.

With the implementation of the four next steps listed above we believe that:

> "… the following five preconditions to RBF-based OGSEC access scale-up in rural Malawi will be met:
>
> 1) ***Clean cooking market conditions***: OGSEC systems with good technical performance will be available and proven in the rural Malawi context
>
> 2) ***Efficient clean cooking distribution***: Low-overhead last-mile distribution will be demonstrated and easily scalable. This will assure OGSEC system affordability for rural households
>
> 3) ***Which technologies are incentivized and how?*** Cost-efficient impact verification will be available to measure and incentivize people converting to solar electric cooking. This will keep administrative overheads low so RBF benefits accrue to customers as price discounts. This will also allow for a wide variety of off-grid solar electric system designs to compete with respect to price and performance.
>
> 4) ***Building the market***: RBF incentives will be sufficient to allow implementers to make OGSEC affordable to rural customers.
>
> 5) ***Access to expansion capital***: A business model for providing expansion capital– through discounted equipment supplied to implementers on credit—will have been proven or clearly demonstrated"

5. Conclusion

For low income households in rural Malawi with per-capita incomes of $1/day or less in imported goods purchasing power (i.e. not adjusted for local purchasing power), it is an extremely difficult challenge to provide a clean cooker solution that can potentially be affordable using imported solar technology. In spite of this, we believe that through the course of implementing this project we have found a solution for providing off-grid solar electric cooking access for rural Malawians. We also believe that this solution can be best demonstrated and distributed through a last mile distribution system built on rural solar shops operated by collectives of empowered women.

Our affordable, entry-level, 200 watt-peak off-grid solar electric cooking system (OGSECS) has a cost of about $200 and can provide off-grid cooking electricity at a rate of 0.5 kWh/day or more during the rainy season if the cooker is utilized at a relatively high level of efficiency. Customers in rural Malawi appear to be disposed and willing to utilize such systems at high levels of efficiency if given sufficient incentives.

During the course of project implementation, we at KLLC believe that we have learned the following 12 lessons relevant to off-grid solar electric cooking access in rural Malawi:

Empowerment lessons learned:

(1) Income generation is empowerment: The most motivating type of empowerment increases income generation opportunities for participating women
(2) Solar pumps easily generate income: The easiest way to increase income for rural Malawian women using solar-electric technology is with solar-irrigated gardens in the dry season.
(3) Village solar shops provide solar sales income: Once irrigation-based empowerment is used to establish a women-run solar shop, it is easy and straight-forward to add distribution of clean cooking technologies, commission-based income, and RBF-based income.
(4) A “Ladder” of clean cooking options can aid access: Creating a "ladder" of clean cooking technologies may help households raise to the level of getting an OGSECS

Lessons learned re: solar electric cooker design and production:

(5) It is difficult to make workshop-assembled solar cookers long-lasting: It appears that local, workshop-based production of solar electric cookers has difficulty producing the long-lasting, durable cookers that are necessary for making off-grid solar electric cooking economically viable.
(6) Lithium titanate batteries and grid-backup can create reliability: Either LTO batteries or a grid-connected DC power source can help provide more back-up power for solar electric cooking during nighttime or when it is cloudy.

Lessons learned re: affordability and willingness to pay:

(7) Affordable solar panels are the key to affordable OGSECS: The biggest affordability barrier to initial adoption of off-grid solar electric cooking is the cost of the solar panels, and some rural households are willing to make this relatively large investment. When solar panels are affordable priced, DDS OGSECS are affordable.
(8) Solar panels used for solar pumps can be used for cooking: Linking solar irrigation of vegetable gardens to off-grid solar electric cooking creates synergies that can make off-grid solar electric cooking affordable.

(9) Affordable LTO batteries may be the key to making OGSECS reliable: The main barrier to reliable OCSEC is affordable, long-lasting batteries and custom LTO batteries might allow this barrier to be surmounted.

Scalable financing lessons learned:

(10) Leveraging the environmental value of wood savings may make OGSECS affordable: The existence of large positive "environmental externalities" in the adoption of OGSECS means that scalable, economically efficient subsidies should be possible for assisting affordability and adoption. But carbon offsets may not be economically efficient because they are priced at levels that are less than 20% of the value of environmental externalities.

(11) OGSECS electricity may be less expensive per kWh than grid electricity: OGSECS can be designed to provide solar electricity to off-grid households on a per-kWh basis that is less expensive than a standard SHS for non-cooking uses. This can create a relatively large willingness to pay for such OGSEC systems.

(12) Results-based Finance schemes may enable large-scale OGSECS adoption: Cost-efficient RBF schemes should be able to provide sufficient revenue to make OGSECS profitable to significant scale. Further cost-innovation and economies of scale should make OGSECS financially feasible at national scale by 2030 in Malawi.

We at KLLC look forward to continuing this work over the coming years and exploring to what extent we can grow our relatively small-scale women's-empowerment-based clean cooking access model to a larger scale.

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Appendices

Appendix A: Updated calculation of household cooking energy use

Food Item	Dry weight kg/cap/day	Wet weight kg/cap/day	Wh/kg	Wh/cap/day
Corn (nsima)	0.367	1.836	200	367.3
Beans	0.042	0.106	450	47.6
Rice	0.112	0.224	270	60.5
Cooking Oil	0.021	0.021	400	8.6
Tea (water)	0.000	0.400	150	60.0
Sugar	0.019	0.019	150	2.9
Salt	0.004	0.004	400	1.8
Onions	0.008	0.008	400	3.4
Tomatoes	0.079	0.079	400	31.6
Vegetables	0.128	0.192	400	76.9
Eggs	0.008	0.008	400	3.3
Fish	0.031	0.061	450	27.6
Chicken	0.005	0.010	450	4.4
Goat	0.011	0.011	450	4.9
TOTAL	0.839	2.981	235	701

Table A-1: Updated estimates of household cooking energy consumption using updated energy intensities for component foods.

Table A-1 provides updated estimates of cooking energy use in typical rural Malawian households. Not surprisingly, the diet and cooking energy use is dominated by the key staple food items *nsima* (known as *ugali* in Kenya/Tanzania/Uganda).

The updated estimates utilize the household survey from an earlier project.[20] The household survey provides average per-capita daily spending on different food items and average prices for the food items. The different food items come in different units, and by converting those units into equivalent kilograms we get prices in units of currency (MWK) per kilogram. This allows us to translate daily average spending into daily kilograms of food consumption for different foods.

Recent experience with cooking on with a DC EPC provides the energy intensity values for the different foods. The energy intensities include behavioural "inefficiencies" such as keeping the food warm after it is cooked.

We calculate the wet kilograms of food from the dry kilograms of food by multiplying by the appropriate ratio that represents the amount of water that is typically used to cook the food. For corn meal which is used to make *nsima*, we use the ratio of 5:1 to convert from dry to wet kilograms. For beans we use the ratio of 2.5:1 and for rice, we use the ratio 2:1.

[20] See: https://www.researchgate.net/publication/339826975_MECS-TRIID_Project_Report_public_version_Customizing_Malawi-made_solar_electric_cooking_technology_and_business_models_to_provide_access_to_very_low_income_villagers

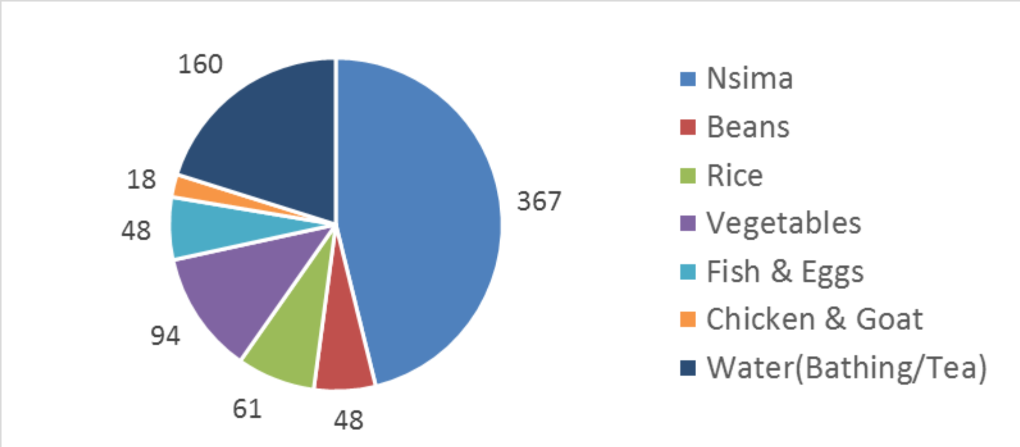

Figure A-1: Updated estimates of household cooking energy consumption using updated energy intensities for component foods.

Figure A-1 gives the updated estimates in the form of a pie chart. The overall energy use of 796 Wh/capita for cooking, tea and bathing water are quite similar to the earlier estimates. Changes in the relative amounts of cooking energy for different foods comes primarily from corrections in the ratio of cooked weight to dry weight which was overestimated in the previous report. Also in this estimate it is assumed that one cup of tea per capita per average is consumed, which was not included in the earlier estimate.

These updated estimates highlight the fact that if the cooking of the main staple food of *nsima* and heating water can be converted to off-grid solar electric cooking and water heating for rural households in Malawi, then nearly two thirds of the task of converting households to clean cooking will have been accomplished.