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Bridging the Affordability Gap for Off-Grid eCooking in rural Malawi

Kachione LLC
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Executive Summary

This report, ***Bridging the Affordability Gap for Off-Grid eCooking in rural Malawi***, describes the results of a 1-year project (2024 – 2025) 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 grant from the MECS-STARSS (Standalone or rooftop solar systems inclusive of e-cooking)[1] program and implemented by the Malawi social enterprise, Kachione LLC (KLLC).

The progress reported in the present report is built on a foundation of 5-years of off-grid eCooking research in Malawi. The results and learnings from the 2023/4 research are documented in the report: *Empowering Efficiency, Phase II: Refining an affordable Solar Home System with eCooking for rural Malawi*.[2]

The 2023/4 research identifies a relatively low-cost, technically feasible off-grid eCooking system that rural Malawian households can use for daytime eCooking. The 2023/4 research noted that customers were willing to pay about $100 to $150 for a ~700Wp daytime off-grid solar eCooking system that had a minimum delivered cost of about $250.

This report documents the 2024/5 research which investigated improvements in the technical system details, household behaviour and business models that can help make the system affordable to rural households. We call this process: "bridging the affordability gap."

The 2024/5 research investigated three distinct strategies for bridging the affordability gap:

(1) ***Implementing cost reductions*** in the entry-level Off-Grid Solar eCooking System (OGSECS)
(2) ***Impact-based subsidy financin***g: Developing an efficient and "economically justified" system for financing affordability subsidies that are based on an "Impact Bond" that can be paid with verified cooking kWh that are delivered to household beneficiaries, and
(3) ***Cross-subsidizing entry-level OGSECS purchases*** with profits from either solar pump sales or high-end products to higher-income customers.

To fully investigate these strategies, the research develops a multi-faceted understanding of affordability for the households that are to be served by eCooking systems. The different facets of off-grid eCooking affordability that we investigated in this study include the following:

1. Household willingness and ability to pay
2. Household diet and baseline food cooking behaviour
3. The multidimensional benefits of eCooking use
4. The detailed cost structure of different variants of OGSECS design
5. The influence of cooking behaviour on the cooking output of an OGSECS
6. The impact of OGSECS output on the unit cost of eCooking
7. The impact of OGSECS output on the household benefits of eCooking
8. How to choose an OGSECS design to maximize benefits & affordability

Interviews with 150 OGSECS-owning households were used to provide information on facets 1, 2 and 3. Cost modelling combined with an OGSECS operational simulation model was used to explore facets 4, 5 and 6. The operational simulation model was validated with

[1] https://mecs.org.uk/challenge-fund/current-funds/mecs-starss-standalone-or-rooftop-solar-systems-inclusive-of-e-cooking/

[2] https://mecs.org.uk/wp-content/uploads/2024/12/Empowering-Efficiency-Phase-II-Refining-an-affordable-Solar-Home-System-with-eCooking-for-rural-Malawi.pdf

60 day-long cooking tests at the KLLC workshop that realistically simulated a household's attempt to cook a typical complement of Malawians dishes. And finally, household interview data combined with cost modelling and system simulation was used to elucidate facets 7 and 8.

The key learnings of this OGSECS Malawi affordability gap research include the following:

- **Purchase subsidies are difficult to administer efficiently**: Customers will buy a subsidized OGSECS system even if they are only marginally interested in eCooking. Because most of the cost of a battery-free OGSECS is the solar panels, a substantially subsidized OGSECS has a price that is lower than the market price of just the solar panels. Thus, any customer who wants the solar panels that are contained in a battery-free OGSECS is motivated to buy an OGSECS even if they have no interest in eCooking.
- **Median/average household monthly expendures:** is between 300,000 to 400,000 MWK in 2025 for KLLC OGSECS customers. This means that a subsidized OGSECS price of 350,000 MWK or less per system can be affordable as it represents less than 10% of household annual expenditures.
- **Women's gardening groups,** or other types of local rural women's groups can be organized as cooking system customers. This project tested an approach of using an OGSECS as the entry-level solar system for an integrated plan of providing both eCooking and solar pumping to such organized gardening groups.
- **A higher subsidy seems needed for the women's group customers:** At the current OGSECS prices which have a 50% subsidy, Regular customers that buy the system are dispersed and live far apart. During this project, it was necessary to negotiate a 75% subsidy in order to get high levels of participation from an organized network of Women's Group customers.
- **What customers cook**: The somewhat higher income customers in this study (i.e. 370,000 MWK of average monthly household expenditure), cook 6 to 7 dishes per day in addition to making tea and heating water for bathing and washing. The cooked dishes consist on average include: 2 pots of *nsima*, an additional starch dish (i.e. potatoes, cassava or rice), a green vegetable, and two protein dishes.
- **OGSECS technical cooking output**: Workshop tests of cooking realistic household food menus indicate that current, realistic output of an OGSECS with 350Wp to 1200Wp of rated solar panel capacity is 1 kWh to 2.5 kWh and 5 to 10 kg of food.
- **eCooking costs vs. OGSECS output**: Cost modelling indicates that the unit cost of OGSECS eCooking can drop 20% to 40% by increasing average output from 1 kWh/day to 2 kWh/day.
- **OGSECS with 2 Cookers**: An OGSECS that has >600Wp of solar panels can cook 50% to 100% more food on a sunny day with two 500Wp cookers compared to an OGSECS with only one 500Wp cooker.
- **The food eaten by a typical Malawian household can be cooked** on a 1000 Wp $500 battery-free OGSECS with two cookers on sunny and mostly sunny days, when we project from workshop tests and system simulations conducted during this study.
- **Impact bond financing model and pilot**: Impact bond financing of OGSECS procurement and distribution can likely provide efficient and effective financing of affordability subsidies for OGSECS, especially for Women's Group customers. The crediting level to make such impact-based subsidies feasible is likely around $0.10 to $0.25 per measured kWh of use. A $40K pilot of this financing mechanism will be conducted in 2025/6.
- **Integrating pump, battery & cooker sales may allow profit cross-subsidies that enable affordability:** We propose a new approach of integrating pump, battery and cooker sales that can allow extending credit to Women's Group customers and allowing their profits from irrigated gardening to enable them to afford a combined purchase of solar cooker, solar pump, and LTO power-regulating battery box.

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1. Introduction

The global picture

Kachione LLC (KLLC) and its collaborators fundamentally treat the problem of eCooking access as an electricity access and affordability problem for the 80% of Malawians that live in rural areas, 90% of whom lack any access to electricity. This is because if all households can afford to have access to enough electricity for cooking, they can also afford to have access to enough electricity for most other high-priority electricity uses.[3]

More generally, the world is on track to miss by a substantial margin the 2030 targets of Sustainable Development Goal #7 (SDG7): 'Ensure access to affordable, reliable, sustainable and modern energy for all." The report: *Tracking SDG 7: THE ENERGY PROGRESS REPORT* is released annually and provides detailed data in this regard. The 2024 version of report estimates that in 2022, 685 million people remained without electricity access and 2.1 billion cooked primarily with highly polluting fuels (i.e. wood, charcoal, dung, crop waste, coal and kerosene) [1]. Most people without electricity access—85%—are in Sub-Saharan Africa. At the pre-2024 pace of progress, the report estimates that in 2030, 660 million will remain lacking in electricity access while 1.8 billion people globally will still be cooking with polluting fuels. Though this may change with some very recent electricity access financing initiatives such as *Mission 300*. [2]

Electricity access is not a simple binary phenomenon. To track different levels of electricity access, the Energy Sector Management Program (ESMAP) has created a Multi-Tier framework (MTF) for energy access that defines five levels of electricity access (i.e. Tiers 1 through 5). Only the higher levels of access—i.e. Tiers 3 through 5—can provide sufficient electricity for satisfying some or all of a household's cooking energy needs [3].

The Malawi context

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%[4] of households in Malawi's four largest cities (Lilongwe, Blantyre, Mzuzu and Zomba) used electricity for cooking, and about 6% use LPG [4]. Only 18% of Malawi's population lives in urban areas.

Per-capita income in Malawi in current dollars in 2024 is $508/year on average according to World Bank data. 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 currency purchasing power. Because of declining exchange rates, such local currency income tends to have a declining purchasing power when it comes to purchasing imported technology.

[3] With the exception of air conditioning, which we would argue is lower priority than cooling fans which would provide at least a basic cooling service.

[4] i.e. "71.8% were connected to the grid at midline, only 30.2% of those HHs reported using electricity for cooking" [4] and 71.8% x 30.2% = 21.7%

In surveys that we have conducted with a non-random sample of actual solar eCooking system customers for this study, the average household non-farm cash expenditure in mid-2025 is about 370,000 MWK/month (i.e. $200/month at the bank exchange rate and about $110/month at the open-market exchange rate[5]) for a household of slightly more than 5 people on average. Rural customers that can afford to purchase an OGSECS in Malawi tend to have higher incomes than the average rural household, even when the systems are sold at subsidized prices.

Project history and background

KLLC has been researching and developing Off-Grid Solar-Electric Cooking Systems (OGSECS) for rural Malawian households since 2019. The current project is the fourth in a series of four research and development projects conducted by KLLC with the support of the Modern Energy Cooking Services program (https://mecs.org.uk/). The three previous projects were:

- ***Customizing Malawi-made solar electric cooking technology and business models to provide access to very low-income villagers*** (2019 – 2020) [5],
- ***Empowering Efficiency: Distributing off-grid solar electric cooking systems using women-lead organizing in rural Malawi*** (2020 – 2022) [6], and
- ***Empowering Efficiency, Phase II: Refining an affordable Solar Home System with eCooking for rural Malawi*** (2023 – 2024) [7]

Since the beginning of its six years of solar-electric cooker system development, KLLC has pursued the strategy of making OGSECS less expensive and more flexible by designing a modular system. This way, households can purchase an initially small modular system with components that can incrementally increase in capacity over a period of several months or years with new purchases. This allows rural subsistence farming households to purchase components of an OGSEC system incrementally after harvest when cash from selling the crop harvest is available.

A key element of creating an affordable entry-level OGSECS has been designing a day-time off-grid solar electric cooking system that can work well without a battery. An initial version of the battery-free system was reported in a blog in 2021: https://mecs.org.uk/blog/an-off-grid-solar-photovoltaic-electric-pressure-cooker-system-that-costs-only-200-in-malawi/. By 2024, a 600-700Wp battery-free OGSECS had been created that can cook >5kg of food and which costs approximately $300 to deliver to rural Malawian customers.

The 2024/5 OGSECS system distributed by KLLC operates at substantially greater efficiency than the 2021 system described in the blog post. The addition of a maximum power-point tracking (MPPT) converter between the solar panel and the DC cooker maximizes the power output of the panel and thus helps maximize the power at which the cooker operates without a battery.

Beginning with the first *Empowering Efficiency* project, KLLC began encouraging the organization and empowerment of collective groups of women to help with solar product distribution. In the *Empowering Efficiency* projects, these women's groups created local solar shops supported by KLLC that promote and help distribute and sell solar systems to the surrounding community. The solar systems sold by KLLC include solar pumping systems

[5] The open-market exchange rate represents the exchange rate that typical private wholesale providers need to pay to get foreign currency to import goods. It more accurately represents the local purchasing power with respect to imported products.

and solar lighting systems in addition to solar cooking systems. These women-run village solar shops are the core of KLLC's current solar product distribution system.

Also, during the *Empowering Efficiency* projects, KLLC began developing a small, long-lasting, high-power solar battery that utilizes lithium titanate (LTO) battery chemistry. This LTO battery is designed to be incrementally added to an entry-level battery-free OGSECS system to provide power regulation and power for lights and electronics at night.

But in spite of the progress made over the last six years, low-income rural Malawian customers still cannot quite afford to pay the full cost of an off-grid SHS system with cooking at the current time in 2025. We call this difference between OGSECS cost and the maximum price that customer is willing and able to pay: the OGSECS *affordability gap*. In this project, we want to learn how to better bridge this gap between cost and affordability for our cash-poor, rural customers that rely on subsistence farming.

This project has investigated three possible strategies for bridging this affordability gap as follows:

(1) ***Implementing cost reductions*** in our basic system, primarily by taking advantage of recent solar panel price reductions (where we can now obtain solar panels at factor door prices of only $0.10/Wp),
(2) ***Developing efficient subsidy financing*** that is "economically justified" for financing affordability subsidies that are based on verified estimates of social, economic and environmental benefits experienced by customers. Specifically, we investigate an "Impact Bond" mechanism for financing subsidies, and
(3) ***Cross-subsidizing prices paid by low-income customers using profits from sales to high-income customers***. KLLC has several potential solar product offerings that could generate profits from sales to higher-income customers. For example, KLLC has developed customized lithium titanate (LTO) small-capacity/high-power battery that is designed to last 10 to 20 years and which has built-in, long-term, high-resolution data logging. This battery has many potential applications across Sub-Saharan Africa and beyond.

The rest of this report describes the progress made after one year on using these three strategies to bridge the OGSECS affordability gap for rural Malawians. The ***Methodology*** section describes our definition of affordability and the various modelling and field data collection tools that were used to investigate the affordability gap. The ***Results*** section describes the collected data and modelling results, The ***Analysis of Results and Learning*** section describes how we might apply the results to create business models for addressing the affordability gap for rural Malawians. And the ***Conclusion*** section summarizes the project outcome and outlines planned next steps.

The KLLC business: a model adapted to the Malawi context

After experimenting with several business models, KLLC has evolved to a business model that reflects and matches the business dynamics of the subsistence farming households that it serves.

The challenges of organizing a start-up venture in Malawi

During the first few years of its existence, KLLC and its US partners tested the business model of providing rental solar systems and implementing service provision as a for-profit high-growth start-up venture but soon found that such a business model was mismatched with the economic realities faced by its rural Malawian customers. There are four reasons for this.

First, the seasonal economic cycle of subsistence farming households is that they invest in cultivation during the growing season to maximize income during the dry season by maximizing their harvest. This means that most rural households experience a "hunger season" when all resources are invested in maximising yield for the next harvest. During the January to March hunger season, many households are skipping meals to save money for investing in a larger yield that will produce more food after the harvest in April and May. This means that the money that households have to invest in solar system purchases is highly seasonal and volatile.

Second, the Malawi economy in general is cash poor and has an economy with subsidized imports. In 2023, overseas development assistance (ODA) to Malawi was 39.5% of imports of goods, services and primary income.[6] The high ratio is due to the fact that 75% of Malawi's population lives below the World Bank poverty line of $3/day.[7]

This ODA that Malawi has received has been critical in allowing Malawians to obtain access to health care, education, and the inputs necessary for growing enough food to mitigate hunger and malnutrition. This ODA has saved hundreds of thousands if not millions of Malawian lives over the past decades. In spite of the relatively large amount of ODA, stunting due to malnutrition is still seen in about 30% of Malawian children, and about 6,000 adult deaths per year are attributable to deficient dietary composition and low weight.[8] So there is substantial humanitarian benefits that can still be created with additional ODA.

But despite the humanitarian benefits, financial ODA flows also suppress the market prices that are seen for imported goods, because it makes subsidized foreign currency available for imports. These suppressed market prices make it difficult if not impossible to profitably import high-quality goods for sale to the 80% of Malawians who are subsistence farmers unless the products can be subsidized. This means that most Malawians can afford to buy only the cheapest (or most critical) imported goods or goods and services that are subsidized by foreign aid or government programs.

Third, the Reserve Bank of Malawi (RBM) controls the inflow and outflow of foreign currency, giving priority to critical and strategic imports. This means that a divergence occurs between the official bank exchange rate for buying US dollars (USD) with Malawi kwacha (MWK) and the market rate that private sector importers need to use to get foreign currency for non-strategic imports. Generally, the market rate for buying USD is about 1.5 to 2.5 times the bank rate. This makes it extremely difficult to use profits from solar system sales which are in MWK for procurement of new imported components which need to be paid in foreign currency.

And fourth, the Malawian economy is highly inflationary. The 2024 inflation rate in Malawi is 32%, and inflation has averaged 18% per year over the last decade.[9] This high inflation rate combined with the difficulty of obtaining foreign currency that inflates more slowly than the local currency makes it very difficult to accumulate financial capital in the local Malawian context. But long-lasting physical capital tends to increase in value in proportion to inflation. This means that imported solar equipment inventory does not devalue with inflation and long-lasting solar systems tend to be an inflation-protected investment for rural Malawian households.

[6] https://data.worldbank.org/indicator/DT.ODA.ODAT.MP.ZS?locations=MW
[7] https://data.worldbank.org/indicator/SI.POV.SOPO?locations=MW
[8] https://globalnutritionreport.org/resources/nutrition-profiles/africa/eastern-africa/malawi/
[9] https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?locations=MW

The KLLC model: For-profit distribution of aid-financed solar procurement

Because of the conditions described above, KLLC has not yet found it to be possible to utilize foreign investment capital to accumulate sales profits in Malawi to repay foreign investment. Instead, KLLC uses a business model where most local capital accumulates as physical assets and organizational capacity. In this model, procurement capital is provided by aid and philanthropy. Thus, the KLLC business focus is to cost-efficiently import and distribute imported solar equipment that has procurement that is financed by aid and philanthropy. As local physical and organizational capital grows, KLLC can deliver the procured solar equipment with increasing cost-efficiency over time. The model is focused on increasing the cost-efficiency of delivering humanitarian benefits to rural Malawians in order to increase the positive impacts that limited quantities of foreign donor funds can make over time. In essence, philanthropic and development aid and donations is "repaid" through documented humanitarian benefits that result from the distributed solar products when they are used by rural customers.

Is this business model sustainable? Over the past 10 years, KLLC has received $100,000 to $200,000 of philanthropic support from US donors to support its solar research, development and distribution activities. At this continuing level of support from Solar4Africa.org,[10] KLLC can continue to sustainably deliver more than 1000 solar pumping and cooker systems per year to rural Malawians over the next decade.

Sustainability vs. scalability

While a detailed analysis of the sustainability or scalability of the KLLC business model is beyond the scope of this study, we can mention that according to our internal analysis and forecasting the KLLC business model is sustainable over the next 10 years. But while the activities of KLLC are sustainable, the business is not predicted to grow to large scale (i.e. have sales grow to over 10,000 systems per year by 2035), unless at least one of three conditions can be met:

1. KLLC can access foreign currency at bank rates to finance international procurement from MWK sales revenues.
2. Philanthropic or aid-based finance grows to a level that is greater than $2 million/year; or
3. The procurement cost of the solar systems relative to sales price drops more than 50%

We note that access to private capital or temporary start-up grants is not sufficient to scale solar system sales by 10X because—as discussed further in this report—sales of solar cooker systems at affordable prices is not profitable. And without profitability—or an expectation of future profitability—neither a profitable investment exit, nor a likely repayment of debt can be used to justify private investment and loans. BUT, if any of the three conditions mentioned above can be met, then access to private capital or temporary grants can assist in more rapidly growing the business model to large scale.

Thus, the current expectation for KLLC is that we will continue operating at roughly the current scale, while also continuing to research ways to solve at least one of the unmet challenges for sustainably scaling the business. Once we find a condition for scalability that can be met, then we can turn our attention to the details of how best to organize sustainable growth.

[10] https://www.solar4africa.org/

Addressing affordability

Ultimately the project addressed affordability by testing which customers can purchase an OGSECS at which price. During the course of the project, a natural experiment was created where two very distinct classes of customers were developed. One class of customers is individuals that purchase an OGSECS through the KLLC regular retail network of women-run village shops. The second class of customers are organized women's groups that purchase an OGSECS through a development initiative that also provides access to solar pumping. The second class of customers needed a discount relative to the already subsidized price of the systems distributed through the village shops in order to be convinced to purchase 85 systems as a collective of 85 women's groups represented by the Joyce Banda Foundation, a local Malawi NGO.[11]

Thus, we can examine the differences between the two classes of customers to better understand the relationship between price and affordability and other issues of interest.

Defining affordability: the academic literature

Clean cooking affordability is potentially a very complex issue [8] and depends specifically on details of the business model for providing cooking energy supplies and services to households. But most affordability frameworks for clean cooking in the academic literature use "the idea that income is the primary determinant of the use of modern energy." [8]

One of the most widely used affordability frameworks is that developed in the context of the ESMAP Multi-tier framework for energy access. ESMAP defines affordable electricity access as access that costs less than 5% of a household's income. When the cost of modern energy services for households is "higher than 10 to 20 percent of their income, temporary subsidies should be considered" [9] (p. 31). Using this admittedly simplified framework, if three things are known (1) the kWh of electricity demand, (2) the per-kWh cost of electricity (where "cost" is the levelized cost of both the fuel and the energy use equipment), and (3) the income, then it is possible to estimate if the electricity access is affordable. Alternatively, given knowledge of income and electricity demand, it is possible to calculate an "affordability threshold" for different household income levels. Such a threshold specifies that if the per-kWh costs are below the threshold, then electricity access is affordable (i.e. less than 5% of income).

This study therefore makes a simplified evaluation of affordability where the amortized energy supply cost is compared to income, and where affordability is determined by how the energy services supply cost compares to household income.

Affordability in the Sub-Saharan Africa (SSA) context

To place our work in this project in a continent-wide context, we calculate a distribution of affordability thresholds for SSA. To do this, we use World Bank data to calculate population bins with their corresponding per capita income levels as explained in more detail in Appendix A. Then the per-kWh affordability threshold for each bin is estimated as 5% of the per-capita income divided by the kWh of per-capita electrical energy cooking requirement. The calculation assumes that the cooking energy requirement in kWh will determine household electricity demand for basic needs for a stand-alone solar PV system with cooking because cooking energy requirements are so much larger than other basic needs like lighting, phone charging and electronics. The calculation assumes that the minimum cooking energy requirement is what might be needed by an efficient electric pressure/multi

[11] https://www.facebook.com/mwaimalawi/

cooker (EPC) for cooking about 2 kg of food per capita per day. In KLLC's experience, such cooking has an energy intensity of about 200 Wh/kg [7]. If 25% (i.e. 100 Wh/capita) is added to this basic cooking energy requirement to cover other potential electricity uses, then this implies a daily electricity requirement for basic needs of 0.5 kWh/capita/day.

Figure 2 shows the cumulative SSA population that needs electricity to cost less than the affordability threshold in order to be financially accessible (i.e. cost less than 5% of income). Approximately 150 million Sub-Saharan Africans need electricity to cost less than $0.10/kWh if electric cooking is going to be accessible. More than 500 million Africans need electricity to cost less than $0.20/kWh for eCooking electricity use to cost less than 5% of income. About 600 million Sub-Saharan Africans can theoretically afford a cost of eCooking electricity of greater than $0.20/kWh according to the "5% of income" criteria.

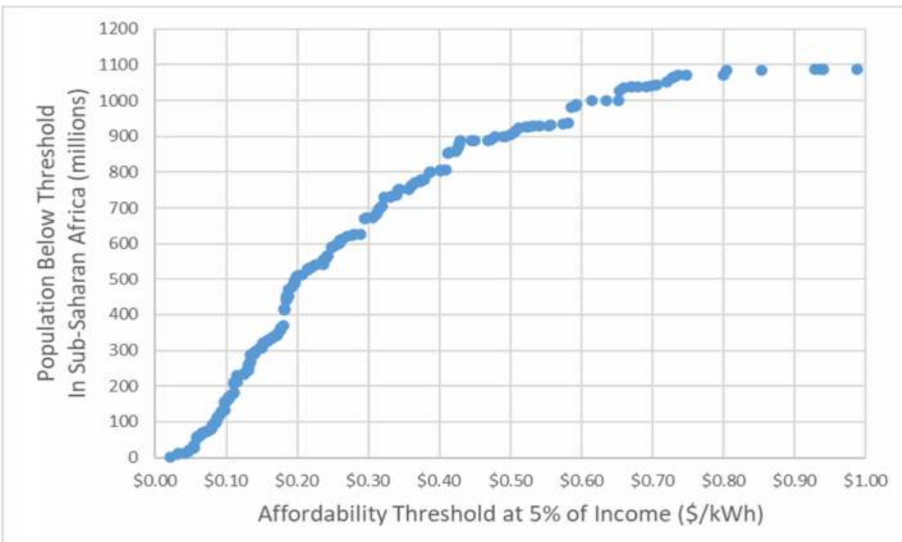

Figure 1. *Cumulative distribution of SSA population at different electricity access affordability thresholds. At each threshold value, the vertical access provides the cumulative population that requires a lower $/kWh cost for the electricity to be affordable (i.e. cost less than 5% of income).*

Household data collection process

Household interviews were conducted from May through and September 2025 by half a dozen contract enumerators. When possible, an initial interview was conducted before acquisition of the OGSECS or before it had been used extensively and a follow-up interview was conducted after acquisition and use of the solar eCooking system for some period.

Interviews were made with more than a total of 150 solar system users. Data collection was conducted in more than five areas: one in the M'bangombe village area in rural Lilongwe district, another in rural Machinga district, near the rural town of Lundu in Blantyre District, in MChinji District, and near the village of Mganja.

Figure 2*: Enumerators interviewing a solar cooking system user about household economics, cooking system use and impacts. Photo by Robert Van Buskirk.*

Cooker system sales & pricing

Five of the six areas are near where KLLC has a local village women-run solar shop that sells solar systems to private customers on a commission basis. From August 2024 through February 2025, the price of the system was 250,000 Malawi Kwacha (MWK). The bank exchange rate for US dollars was about 1730 MWK/USD during this period, though the market exchange rate varied from 2,000 to 2,500 MWK/USD. Also, during this period, the market price of solar panels in Malawi was 700 to 900/Wp, i.e. $0.40 to $0.52/Wp. Though the cost of bulk import (i.e factory door price + shipping +import taxes and fees) of solar panels at this time was less than $0.20/Wp.

We note that solar panel capacity of the OGSECS that KLLC sold was >650Wp. Thus, just in terms of solar panels prices, the cooker system cost was 55% lower than the market price of just the solar panels.

From August 2024 through February 2025, the OGSECS consisted of three key components: (1) an eWant 5-liter 24V DC insulated multi-cooker, (2) a 600W maximum power point tracking (MPPT) voltage converter and (3) two solar panels … each panel being either a 72-cell 370Wp panel or a 72-cell 335Wp panel. The two panels were connected in parallel to the input of the MPPT, with the output of the MPPT connected to the DC cooker.

After February 2025, the two solar panels were replaced with one 655Wp solar panel, which cost approximately $0.15/Wp to import.

By May 2025, because of inflation, the market value of the Malawi Kwacha dropped to 3000 MWK/USD while the bank exchange rate remained the same. Meanwhile the market price of solar panels increased to between 900 to 1100 MWK/Wp. Given these market dynamics, KLLC raised the price of the 655Wp OGSECS to 350,000 MWK after April 1 and has maintained that price through September 2025. This price still represented a 40% discount relative to the market value of just the solar panel, though the cost of importing the 655Wp solar panel would theoretically be only 170,000 MWK at the bank exchange rate.

In early 2025, KLLC made an agreement with the "Market Women Activities Initiative" (MWAI) of the Joyce Banda Foundation (Joyce Banda was the first and only woman president of Malawi) to offer to organized/registered women's groups of their rural network an integrated cooker and solar pump adoption process.

***Figure 3**: KLLC staff visiting Women's Group customers in MChinji District. Photo by Robert Van Buskirk.*

First a participating group gets a cooker system with a 655Wp solar panel with training on how to use it.

To ensure that the cooker system was affordable to a large number of MWAI women's groups, the system was offered at a 75% subsidy of cost (where system cost is estimated at 600,000 MWK) with payments in two installments. The first 50% installment of the subsidized price of 150,000 MWK for the solar cooking system was due in the first month of the partnership. This contribution was made before the system was delivered and installed. The remaining 50% of the subsidized price was paid by the groups at the time of receiving the solar cooking system.

The women's groups were told that they had to utilize the cooker systems well in order to qualify for subsidies for solar pumping systems.

A total of 85 MWAI women's groups purchased OGSECS and had the systems installed by the end of July 2025.

This means that this research project has two very distinct sets of OGSECS customers: (1) Individual customers who were provides systems at approximately 50% subsidy, and (2) registered women's gardening groups which received the systems with 75% subsidy who were incentivized to use the system well with the promise of future discounts on solar equipment.

Some details regarding MWAI women's gardening groups

The MWAI women's groups that participated in the project are groups that have been previously organized by the Joyce Banda foundation to participate in activities that increase their income. While KLLC did not involve itself in the detailed organization and dynamics of the groups, it did survey the groups regarding cooking system use and it verified the dry season gardening activity of most groups.

During the dry season gardening verification survey, KLLC collected the names and phones numbers of each member of 77 5-member subgroups. In reality most of the women were members of groups that have more than 5 members, but each group with 10 members or more divided into sub-groups for the purposes of receiving subsidized solar cooking and solar pumping systems. The actual number of larger women's gardening groups is 30 groups with distinct names which divided into the 77 smaller 5-member subgroups. The largest "super-group" has 7 5-member subgroups which means that the larger group actually has more than 35 members in total.

Each 5-member subgroup has a group leader and 4 regular members. All but 2 of the 77 group leaders have a cell phone contact number, while roughly only half of regular members appear to have a cell phone.

About 90% of the 385 group members were actively gardening in August 2025 to earn dry season income. Beans were being grown in roughly 2/3 of the visited gardens with irish potato, sweet potato, vegetables, and maize crops commonly being grown at the time of the verification survey.

Estimating the energy requirements for eCooking

A fairly detailed analysis of cooking energy requirements for Malawian dishes was reported in the *Empowering Efficiency Phase II* report. [7] In that 2024 report, the energy requirements of Malawian cooking in an OGSECS were found to be largely proportional to the amount (i.e. kilograms) of final food cooked. In this report, we build on the previous results and build a simplified OGSECS operational simulation model that is described in detail in Appendix C. The simulation model helps elucidate how cooking energy use and OGSECS efficiency depends on the details of cooking behaviour and the specifics of OGSECS design. To calibrate and validate the system simulation model a series of day-long cooking tests were performed on a large variety of OGSECS configurations at the KLLC Blantyre workshop in September 2025.

For many of the tests, a customized LTO battery with data logging was used to monitor energy use and OGSECS operation in detail.

An example of the data collected during these tests is shown in Figure 4. This data allows detailed characterization of energy use of cooking in an OGSECS for different dishes that are customarily cooked in Malawi. Specifically, it allows for characterizing how energy use and cooking time changes for different cooking behaviours and different OGSECS component equipment configurations.

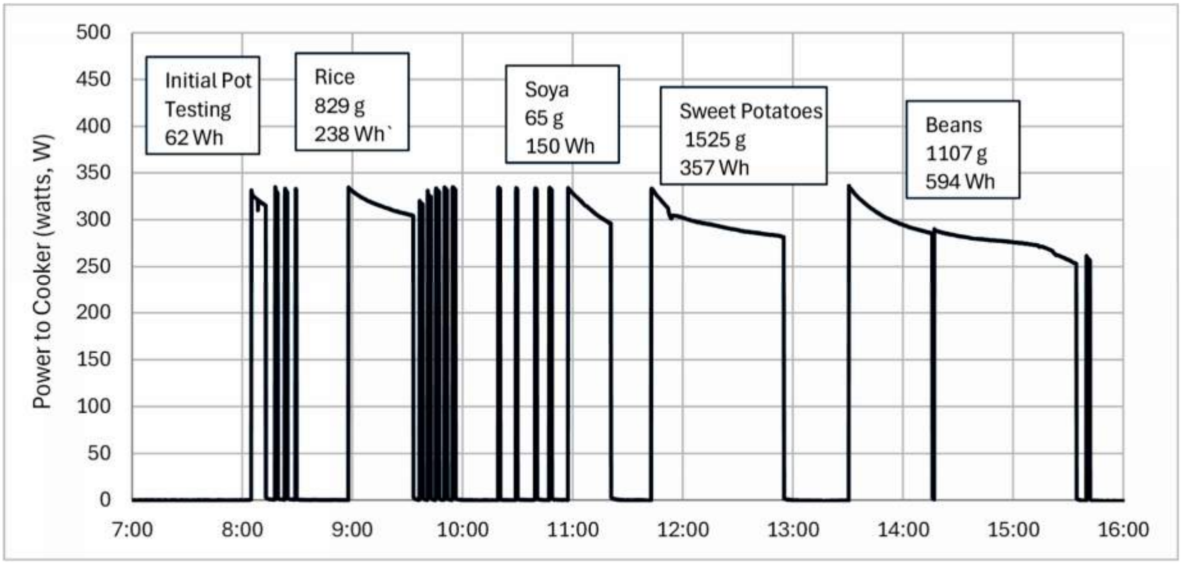

Figure 4: *The detailed power consumption during the cooking of four dishes in an OGSECS over the course of a day.*

Figure 4 illustrates shows an OGSECS day-long cooking test. Different dishes have different energy intensities. In this case, boiled sweet potatoes has a relatively low cooking energy requirement of only 234 Wh/kg, while the beans were cooked with a relatively high energy intensity of 537 Wh/kg.

In Figure 4, initially the cooker is turned on shortly after 8AM, to make sure the system is working well and ready for cooking. Then initially rice is cooked: the cooker brings it up to temperature and then the cooker switches on and off to maintain cooking temperature until cooking is complete. Then it appears that the cooker is left on, while the inner pot is removed to prepare the next dish. When the cooker is left on with no pot, the heating element heats up to the maximum temperature (about 180 degrees C) and then shuts off. Then a small portion of soya pieces is cooked, and after that, boiled and steamed sweet potatoes. And finally, a 1kg pot of beans is cooked.

Optimizing system configuration

There are dozens (or perhaps even hundreds) of different system configurations that one can use for an OGSECS. The solar panels can have potentially a wide range of different capacities and voltages. The cookers used in the system can operate at different voltages and power levels. Different types and voltages of voltage converters can be used to match power requirements and characteristics between the solar panel, the batteries (if present) and the cooker or cookers. Different battery chemistries, voltages, and capacities can be used. And data on system operation can be measured, displayed and recorded in a variety of ways.

System configuration variants

An OGSECS has five key components:

1) Solar panels
2) The Cooker/s
3) Voltage converters
4) Batteries
5) Data logging/recording

A daytime OGSECS technically needs only the first two components but works much more efficiently with an MPPT voltage converter between the solar panel and the cooker.

There are many different variations of potential system configuration that come from choosing different combinations of system components. The different variations that we considered in this project are as follows:

Solar panel capacity: Solar panel capacity can vary from 300Wp to 2kWp, is 30% to 50% of system cost, and has a very big influence on how much food per day can be cooked on the system.

The Cooker/s: The peak power of the cooker, whether the cooker is insulated and whether there is more than one cooker has the biggest influence on the amount of time that the cooking system needs to cook a meal. Cookers comprise 15% to 30% of OGSECS cost.

Voltage converters dynamically convert DC voltages from one system component to another. Two types of voltage converters are used in the OGSECS systems that are included in this study: (1) a step-down maximum power point (MPPT) tracking converter that is used to convert the output of the solar panels to the input of either the batteries or the cookers. When there is no battery in the system, the MPPT output goes directly to one or more cookers. When there is a battery, the MPPT charges one or more batteries that power the cookers. Voltage converters cost from $20 to $60.

Batteries: If customers are willing to cook primarily during the day, then batteries in an OGSECS are optional. This study investigated including two types of batteries in an OGSECS: (1) A custom-made lithium titanate (LTO) battery with built-in data logger that primarily regulates power to the cooker and provides electricity for nighttime lighting and small electric loads that can cost as little as $100, and (2) a 1 kWh lithium iron phosphate (LFP/LiFePO4) battery that can cook up to 5kg of food at night, and costs approximately $200 in Malawi with bulk wholesale procurement.

Data logging and recording: This study uses two types of data logging and recording. One method is simply to add an inexpensive power meter display that costs about $10. This meter displays voltage, current, power and cumulative energy. The cumulative energy value does not reset when the power is turned off to the display, thus the display can record cumulative energy use for a period of months or years. This is the most inexpensive data recording method. The second type of data recording is built into the custom-made LTO battery and can record essentially any voltage or current attached to the battery at a wide range of time resolutions and then records this data in a CSV file on an SD card that is inserted into the battery.

Workshop tests and OGSECS modelling

In order to understand how the different OGSECS design variations and cooking behaviours can affect the daily food production of an OGSECS, the project conducted a series of simultaneous workshop tests of different variants. In these tests, 15 to 20 cookers were operated simultaneously to cook similar menus during the course of the day. The menus were chosen to roughly reflect the cooking menus that rural Malawian households would normally cook as determined by results from the field surveys. These menus generally consisted of a combination of the following dishes: *nsima*,[12] sweet potatoes, Irish potatoes, rice, vegetables, beans, soya pieces, fish and eggs.

The Results section summarizes the results of these tests in terms of how different design variations affect total daily output in side-by-side tests.

The Analysis of Results and Learning section discusses how we can use the results obtained from the workshop tests and simulations to re-optimize our OGSECS design and business model process moving forward.

2. Results

Customer income

The key household income indicator collected during the survey was monthly household spending. Figure 5 shows the distribution of monthly household expenditure rates indicated by interviewees. The average monthly expenditure is between 350,000 MWK and 400,000 MWK per month for customers surveyed in 2025. This is about three times the income indicated for customers surveyed in the *Empowering Efficiency Phase II* report when adjusted for inflation.

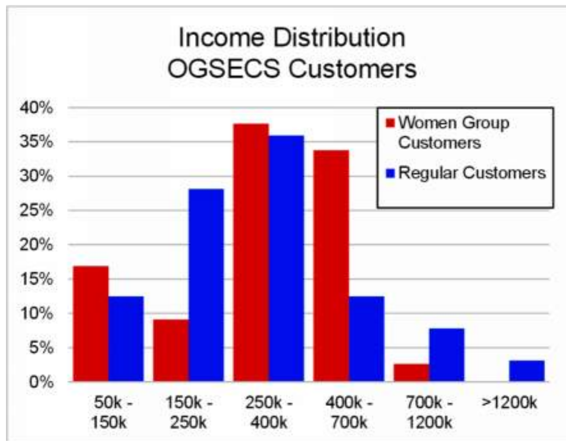

Figure 5: *Distribution of monthly household expenditures for households participating in the study.*

Most of the regular customers purchased the cooker system for 250,000 MWK, while the Women's group customers purchased the system for 150,000 MWK. In contrast, most of the customers interviewed in the *Empowering Efficiency Phase II* report purchased the system for 100,000 MWK or less.

There does not appear to be a substantial difference between the incomes of the women group customers vs. the regular customers. The income of the women's group customer households is only about 5% lower than the regular customers on average even though the price they paid for the system was 40% lower.

On average, the price paid for the OGSECS was 3.4% of annual expenditure for the women's group customers and 5.5% of annual expenditure for the regular customers.

Types of food grown, consumed and cooked

The customers participating in the survey described an average of 3.6 different food crops that they grow themselves. Virtually everyone grows maize, while both soya and ground

[12] A dish made from cooked maize meal, otherwise known as *ugali* in Kenya, Uganda and Tanzania

nuts are also frequently grown. Sweet potato is another frequently grown starch crop as is Irish potato and rice is selected areas. Tobacco is a common cash crop, and the women's groups in the MChinji district often grow peppers and sunflower. Other crops such as beans, tomatoes, peas, pumpkin, greens, cassava, onions and sugar cane are also commonly grown.

Regular OGSECS customers estimated that they grew about 70% of their own food on average, while Women's group customers estimated that they grew 76% of their own food on average.

The survey asked in detail the cooking frequency of 14 different foods plus tea and hot water for bathing. Figure 6 illustrates the relative frequency of cooking different foods for OGSECS customers based on the survey data. The most frequently cooked food is *nsima* which is cooked on average twice per day in rural Malawi. The second most-cooked food is a second starch, sweet potatoes, Irish potatoes, and cassava. Also vegetables (i.e. various greens), are cooked almost daily on average. Rice is a relatively expensive starch in Malawi, so it is cooked only once out of every three days on average.

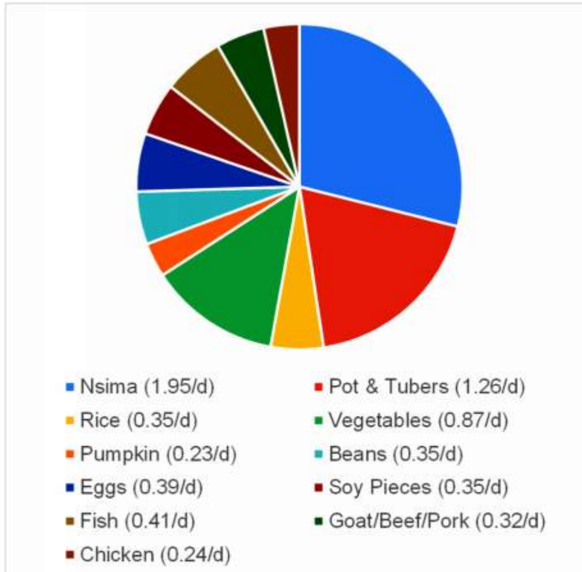

***Figure 6**: Average frequency of cooking different foods in rural Malawi*

The starches and vegetables represent approximately 2/3 of dishes cooked. The remaining third is mostly divided amongst various protein options: fish, soy, beans, eggs, red meat and chicken. In sum, about two protein dishes are cooker per day on average. This contrasts with the *Empowering Efficiency Phase II* report where only one protein dish was cooked per day typically. This is most likely explained by the fact that customers surveyed in this study have about three times the monthly expenditures as households interviewed in the 2023/4 *Empowering Efficiency Phase II* study.

OGSECS customers appear to cook between six and seven food dishes per day on average in addition to typically drinking tea once per day and heating water for washing almost twice per day.

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. Charcoal has greater energy density than wood or crop residues, can generate greater heating power, produces less smoke and lasts longer while cooking a dish of food compared other traditional biofuels.

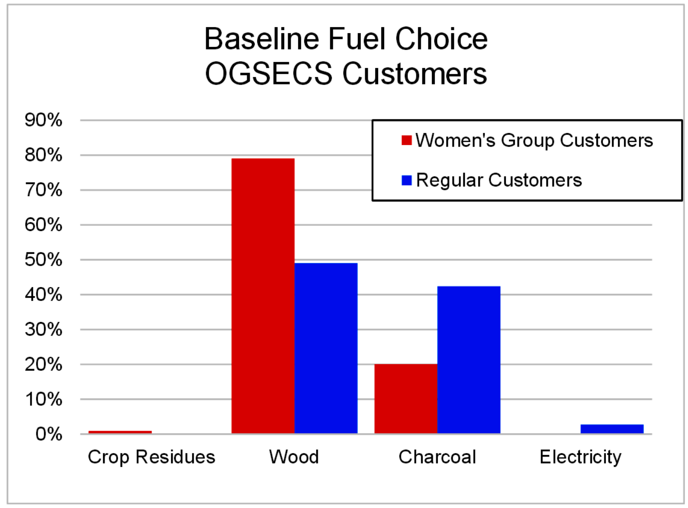

Figure 7: *Baseline fuel choice for the customers surveyed in the project. The rural women's group customers have a strong preference of wood over charcoal.*

Figure 7 shows the usage frequency of different fuels for the two customer classes in this study. Regular customers (who include some customers in cities and towns) use wood and charcoal with a similar frequency. A few customers also mention using electricity for cooking. The Women's group customers are more exclusively rural compared to the Regular customers, and thus use wood with about four times the frequency of using charcoal.

In contrast to the *Empowering Efficiency Phase II* report [7], we do not find that a substantial number of customers are reporting the use of agricultural residues as fuel in the household interviews for this study. This may be due to two reasons: First because the customers in this study pay a higher price for OGSECS than the 2023/4 study, they appear to have much higher incomes. Secondly, this version of the interview did not ask specific seasonal fuel choice questions, which may have suppressed responses regarding crop residues that are used during only part of the year.

Roughly it takes about seven kilograms of wood to produce one kilogram of charcoal[13], but one kilogram of charcoal has about twice the energy content of one kilogram of wood and charcoal stoves can be roughly twice as efficient as wood cooking.

Fuel collection time and expense

Even though Regular OGSECS customers use charcoal more frequently than the Women's group customers, both customer classes spend about the same amount of money on purchased fuel on average. The Women's group customers spend an average of 1300 MWK/day on fuel (about 800 MWK/day on wood and 500 MWK/day on charcoal), while the Regular customers spend about 1200 MWK/day (about 600 MWK/day on wood and 700 MWK/day on charcoal).

But on average, customers who gather most of their own wood spend much more time on fuel acquisition than customers who don't gather wood. Those who gather their own wood spend an average of 53 minutes per day gathering wood, while those who purchase their

[13] 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

fuel spend on average only about 6 minutes per day acquiring fuel according to the interview data. Wood gatherers spend about 1120 MWK/day on fuel while non-wood gatherers spend 1560 MWK/day, a 440 MWK/day difference. For comparison, during 2025 through June 1[14] the Malawi minimum wage was 3,461 MWK/day which is 432 MWK/hour assuming an 8-hour work day.

About 56% of the Women's Group customers gather their own wood while about 30% of the Regular customers do so.

Cooking system benefits

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

A. It is convenient to use (i.e. cooks without needing to be watched)
B. It looks nice (well-built, clean, modern)
C. It cooks fast
D. It saves time collecting wood
E. There is no smoke; and
F. It saves money
G. It cooks clean food
H. It saves time cooking

Figure 8 shows the average ranking provided by Regular OGSECS customers[15] that were surveyed, for these eight benefits. No smoke, fast cooking, convenience and saving money are the top four benefits of the cooking system.

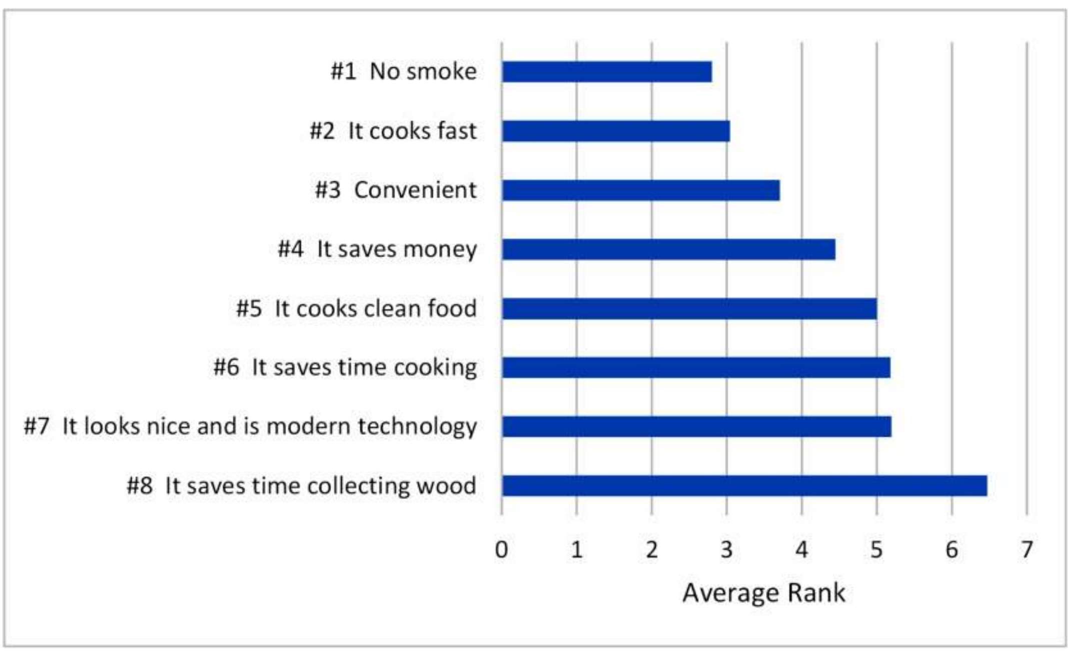

Figure 8: *Customer ranking of OGSECS benefits by Regular customers*

[14] https://www.ecammw.com/wp-content/uploads/2025/06/Minimum-Wage-Gazette-2025.pdf
[15] This particular survey for Women's group customers is still pending.

These results highlight how the ranking of OGSECS benefits can change with the particular category of customers being served. The Regular customers largely buy their fuel from local markets (i.e. they don't gather wood from the farm or forest), and even customers that gather wood also spend substantial money on purchased fuel. Thus, wood collection time savings is ranked at the bottom. Both Women's Group and Regular customers have about three times the monthly spending of customers interviewed for the *Empowering Efficiency Phase II* report. Thus, money savings ranks in the middle rather than at the top like in the 2023/4 study. For this study's customers, the convenience and comfort of the cooking process ranks the highest.

Cooking system utilization and affordability subsidies

A key issue with development subsidies in general is making sure that the subsidies actually provide the intended effect. For off-grid eCooking, the intended effect is for the buyers of the systems to use it for clean cooking rather than something else. This is a key challenge that OGSECS affordability subsidies needs to overcome, if subsidies are going to be used to bridge the affordability gap.

Are subsidies required? We note that if a 700Wp OGSECS in Malawi was offered at a full, for-profit cost in Malawi, the price of such an OGSECS in 2025 would be approximately 900,000 MWK. KLLC is currently-in September 2025--offering such an OGSECS for a subsidized price of 350,000 MWK through its village shop network. KLLC estimates that approximately 22% of the price reduction can be obtained relative to the normal for-profit market price through cost reductions from organizing a cost-efficient distribution network. This can bring OGSECS cost down to about 700,000 MWK. But KLLC finds that an additional 50% of the cost needs to be subsidized with grants or donations to bring the price down to a level that a substantial number of villagers can afford. By applying such subsidies, KLLC finds it possible to offer a >600Wp OGSECS at an affordable retail price range of 250,000 MWK to 350,000 MWK for regular customers.

KLLC started selling OGSECS in earnest in September 2024. Within a few months, rumours were heard that some customers were buying the OGSECS because they wanted to get cheap solar panels for their solar pumps, and some customers were not actually using the cookers. This was investigated further in the present study.

in March 2025 KLLC was approached with the opportunity of distributing OGSECS and solar pumps to nearly 100 organized rural women's groups. In order to address the diversion of subsidized OGSECS equipment to non-OGSECS uses, a plan was developed to distribute subsidized solar products in steps. To do this, an explicit agreement was made with customers that in order for a women's groups to qualify for future solar product subsidies, they had to show that they would utilize a subsidized OGSECS well and the OGSECS would be metered to verify use.

Figure 8 illustrates the resulting contrast of using a stepped, conditional subsidy approach with the Women's Group customers, versus using a simple unconditional subsidized price as was done with Regular OGSECS customers.

The contrast between the two customer classes is quite stark: While more than half of the Regular customers appear to be using the cooker barely, if at all, more than 90% of the Women's Group customers are using the cooker system significantly and >70% of them are using the cooker rather well (i.e >0.5 kWh/day on average: which corresponds to about two hours of cooker use per day on average). But in negotiating the affordability subsidy for the Women's Group program, an additional 200,000 MWK of subsidy had to be provided so that the systems could be sold at 150,000 MWK per group. The extra discount that was added to the purchase price, allowed systems to be distributed more cost-effectively in groups of 40 women's groups at a time.

The average daily eCooking use for the Women's Group customers shown in Figure 8 is 0.79 kWh/day, while daily energy use is 0.40 kWh/day for the Regular customers. We note that if the subsidy for such a 0.39 kWh/day difference is amortized over three years of eCooking use on a per-kWh basis, then this extra 200,000 MWK of subsidy would correspond to 183 MWK/kWh which is approximately $0.10/kWh subsidy at the current (September 2025) bank exchange rate.

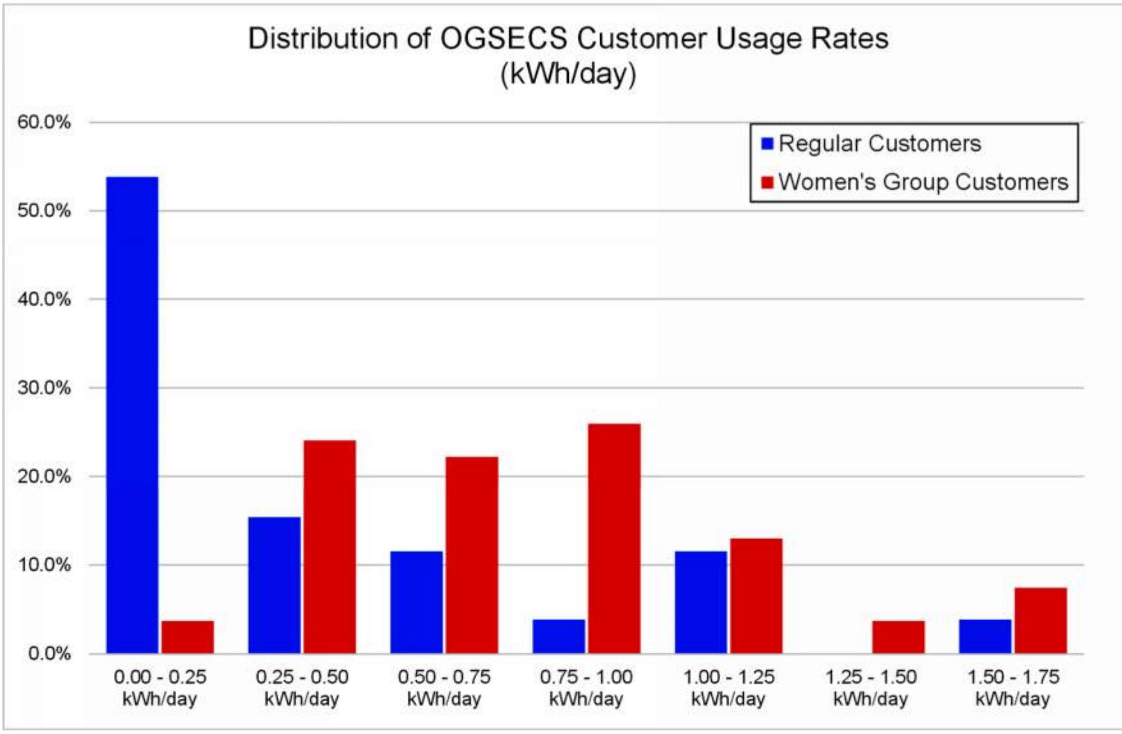

Figure 9. *Distribution of OGSECS utilization rates for different OGSEC customer classes. Usage rates are measured as kWh/day. The average usage rate for Women's Group customers is about twice that of Regular customers because about half of Regular customers barely utilize the cooker in the system (for a variety of reasons that are still being studied).*

While Figure 9 shows how customer behaviour is a key element of how much a system gets used and how much cooked food it produces, This project also examined constraints on OGSECS cooking output that is based on physical design characteristics of the system. This is described in the next section.

Cooking system technical performance

Depending on the details of the OGSECS design, different elements of the OGSECS cooking process can constrain the amount of food that be cooked on any day. During the course of this study, an operational OGSECS simulation model was developed, and the model results were qualitatively validated by a series of workshop OGSECS tests and measurements. Details of the simulation model are described in Appendix C.

OGSECS simulation model results

Figure 10 (which is taken from Figure C.8 in the appendix), shows the levelized cost of the electrical energy output by an OGSECS with a 240Wh LTO battery. System output depends on how much cooking is attempted on the system, and the solar panel capacity. The three curves represent three different demand scenarios (i.e. 1200Wh, 2000Wh 3000Wh of total cooking demand). Each symbol represents a system with a different solar panel capacity, where the capacity increases from left to right from 300Wp to 1200Wp in increments of 100Wp.

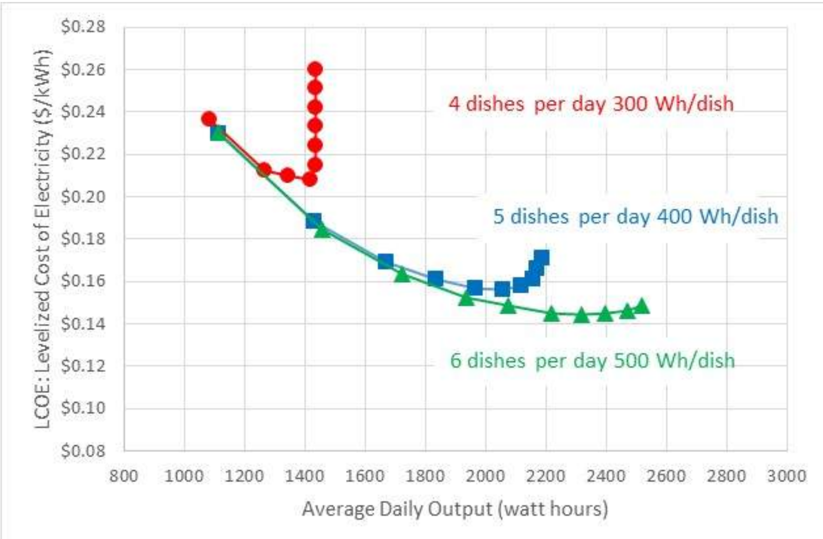

Figure 10: *The levelized cost of electricity (LCOE) of an OGSECS as a function of the daily power output of the OGSECS for different system designs and cooking demands. Note that they key factor that influences a decreasing LCOE is increasing system output that is utilized by the customer. This includes both cooking demand and any excess nighttime energy that may be remaining in the battery after sunset that may be used either for other loads or for early morning cooking the following day. Symbols represent systems with different solar panel capacity, with capacity starting at 300Wp and increasing in increments of 100Wp from left to right.*

As can be seen in Figure 10 that the total energy (and cooked food) output of an OGSECS is perhaps most sensitive to two key parameters: solar panel capacity and cooking demand.

If a household is only going to cook four small dishes per day in an OGSECS, then a system with a 600Wp panel can satisfy demand. But as described in previous sections of this report, current OGSECS customers cook between 6 and 7 dishes per day and also heat water for bathing and tea. Thus, 3000Wh of demand is probably more representative of a household's needs if a large fraction of its cooking and water heating is going to convert from traditional biofuels to solar eCooking. Also when an OGSECS is utilized at high output capacity, the per-kWh cost of eCooking drops because the fixed system costs are spread over more kWh. Thus going from a 1.4 kWh/day OGSECS to a 2.4 kWh/day OGSECS is estimated to drop the levelized cost of off-grid eCooking by 30%

Another sensitivity analysis that we would like to highlight from Appendix C, is the dependence of output on peak cooker capacity. Figure C.9 illustrates how increasing the operating power of the cooker from 300W to 500W will tend to increase OGSECS system output by 10% to 15%

Workshop OGSECS test results

The OGSECS workshop tests performed side-by-side daily production and output measurements for up to 15 simultaneously operating OGSECS. By comparing different OGSECS configurations side-by-side, the study is able to roughly estimate the output impact of different design and configuration variants.

We summarize some of the observations here:

Two cookers are better than one: This is perhaps an obvious observation. But when an OGSECS has two cookers, after one cooker heats up, a second cooker can start cooking before the first dish has finished cooking. This allows the cookers to operate continuously and utilize a maximum fraction of the solar panel output. Initial indications are that when the solar capacity is greater than 700Wp, two cookers can increase system output by 50% to 100%, with the number of dishes cooked on a sunny day increasing from 4 to 6.

18V batteries are better than 12V batteries: 12V LTO batteries are less expensive to make than 18V LTO batteries and have the added advantage of being able to power standard 12V loads like lights and small DC electronics. But to use a 12V battery with a DC cooker, a DC/DC step-up converter is necessary. Preliminary results are that an OGSECS with a 12V set-up that has a DC/DC step-up converter from the battery to the cooker and a Maximum Power-Point Tracking (MPPT) for charging the battery with the solar panel has the same output as an OGSECS with an 18V battery and no converters or MPPT that is connected directly to low-voltage panels (i.e. Vmp ~ 18V). If the 12V set-up does not have an MPPT and is connected to low-voltage panels directly, its output decreases about 25% relative to the system with an MPPT. In general, we find the 18V LTO battery set-up more reliable and robust than the set-up with a 12V battery and a set-up converter for the cooker.

An upgraded 18V battery could run a 2 cooker system: We ran tests of an OGSECS with an 18V battery connected directly to low-voltage panels and found that a 2-cooker system could output more than a kWh of cooking with the 18V panel connected directly to low-voltage solar panels and without an MPPT. But in this case we found the system output to be limited by the current throughput of the battery, which was about 20 amps. By upgrading the battery with thermally conductive epoxy in the power electronics, the current throughput can be increased to above 30 amps for more than 750Wp of solar panels, and the battery should be able to support OGSECS daily output of more than 2kWh/day in a 2-cooker system.

A 1000Wp battery-free OGSECS with two cookers can output >2kWh & 10kg of food per day: During the cooking tests, a set-up with a 600W MPPT and three 360W solar panels output 2.3 kWh and 10.4 kilograms of food. The power of the OGSECS system in this case was limited by the power rating of the MPPT, and thus power input to the cookers was limited to about 500W total. For an extra $30 cost, the system can be provided with a 2000W MPPT that should allow the system to operate at 50% to 100% more power. In that case, the OGSECS should output >3kWh and 15kg of food on a sunny day and should be able to provide 2kWh and 10kg on average. This should be enough to satisfy most of the cooking needs for a typical rural Malawian household.

A battery-free OGSECS with two cookers and low-voltage panels does not need an MPPT: Preliminary tests indicate that a battery-free OGSECS with four parallel 180W solar panels and two cookers can output >1.5kWh/day of cooking and 5 kilograms of food on a sunny day. This may allow for a very low-cost entry-level OGECS that consists solely of cookers and solar panels, and that can be later upgraded with an 18V battery and more solar panels.

In-person OGSECS customer data collection and monitoring

Details of customer energy use data collection and analysis efforts are provided in Appendix E. By the end of the project only a few months of energy use data had been collected, primarily with small cumulative DC power meters that were read by visiting technicians.

The OGSECS workshop tests were organized because of technical issues that arose from the initial deployment of 12V LTO battery systems with the first 20 women's group customers in early September 2025. The workshop tests conducted later that month clarified that upgraded 18V LTO batteries needed to be deployed in systems that are used intensively by rural customers. This deployment of upgraded 18V LTO batteries will be conducted in 2026.

More technical details regarding these issues are provided in Appendix E.

OGSECS customer check-in calls

As part of the incipient development of a more systematic customer support system for regular customers, KLLC in September 2025 is beginning to make regular customer check-in calls to customers based on data received in cooker system purchase receipts. The paper receipts are used by the village shops to document sales and digital copies of receipts are sent to KLLC for record-keeping and follow-up customer support.

The first round of these customer support calls was made in September and October 2025 with approximately 65% of listed customers successfully contacted from an initial list of approximately 300 receipts from more recent sales. We note that in the current KLLC system, the local village solar shop is initially the entity responsible for arranging delivery and installation of the solar cooker system for the customer at the local level. The median installation date of the cooker systems for the customers contacted in this set of customer support calls was April 2025.

The calls asked customers if the system has been successfully installed and if the system is working well, or if there is breakage or problems. In this round of calls 73% of customers noted that the system was installed and of these, 95% of the systems were working without breakage.

Anecdotal information about the 27% of customers whose systems are not installed indicate a variety of reasons for this occurring. One fairly common reason is that customers are sometimes located at large distances from the village shop and unwilling to pay the transportation costs for a technician to visit the customer from the shop. At other times it may be various forms of mis-communication or lack of coordination. Details of the reasons for non-installation of the systems will be investigated further in the coming months.

All customers with working systems said that they were benefitting from the systems and when asked to describe the benefit, about half mentioned the ease, speed and convenience of cooking while the other half mentioned money and fuel savings as the primary benefit.

When asked for questions or comments at the end of the call, slightly more than half provided further comment, with 40% of the commentors asking about availability of batteries, 22% of commentors expressing gratitude and appreciation for the system, 18% expressing their need for installation, or repair of the system, and with the remaining 20% commenting about miscellaneous issues such commenting about an impending house move, asking questions about light bulbs and other equipment for the system, or requesting an upgrade (e.g. adding a solar panel).

Theoretical system cost modelling

Note that as described earlier in this report, it is theoretically fairly straightforward to estimate how much of different types of foods can be cooked in an OGSECS with a certain amount of electricity used by the cooker. Very roughly, different foods have different energy intensities which may range from 100 Wh/kg for simple boiled water to above 400Wh/kg for beans, but typically the cooking energy required is 150 to 300 Wh per kg of cooked food. In addition, even the smallest dish will require 100 Wh to 200 Wh of cooking energy because it takes energy to heat up the cooker and while the cooker is heating up, some energy is lost to the environment. Thus, if we know the cost per kWh of owning and operating an OGSECS, we know the cost of cooking food in that OGSECS.

In order to estimate the per-kWh cost of off-grid solar eCooking, it is necessary to elucidate at least three different inputs to create a cost estimate: (1) The OGSECS component costs, (2) the total cost of the OGSECS once it is delivered and installed in the customer's house, and (3) the daily and/or annual output of the OGSECS in kWh.

Appendix B provides estimates of both (1) and (2) by providing estimates of component costs and estimating the cost of importing, assembling, distributing and installing those components into a system that is operating in a rural Malawian household. The cost factors in Appendix B are derived from KLLC's experience over the past several years of importing and distributing OGSECS.

Appendix C describes the operational modelling calculations that we use to estimate the kWh output of the OGSECS. This provides the third cost component: OGSECS output. The combining of cost and operational models in appendices B and C enables the calculation of the levelized cost of electricity (LCOE) for OGSECS cooking for a large variety of system designs and operating conditions.

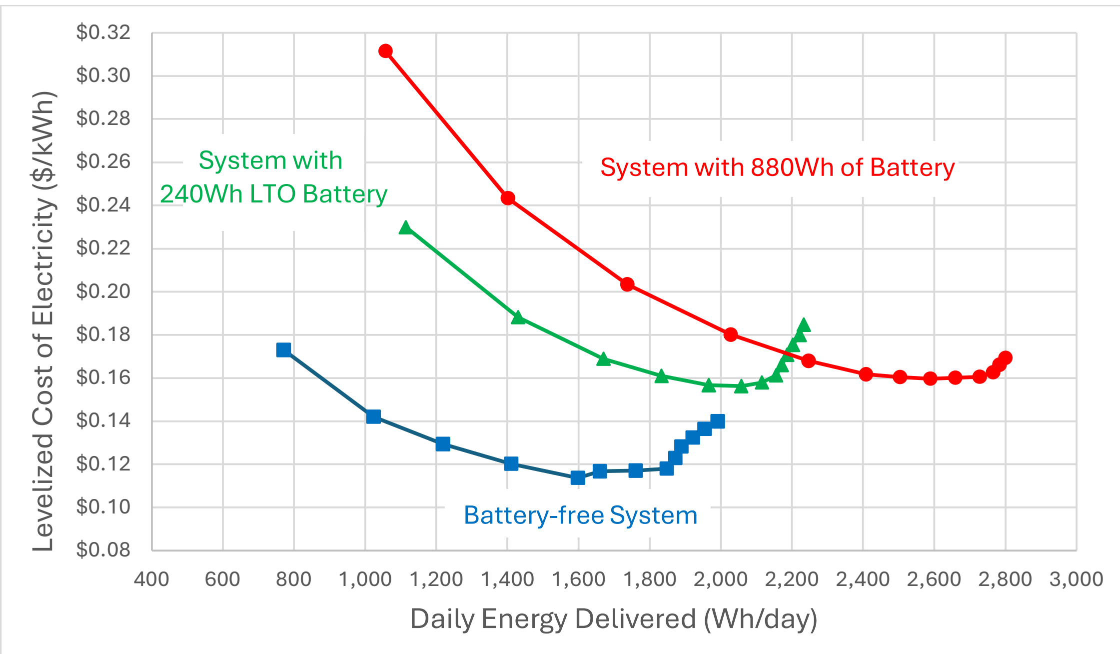

Figure 11. *LCOE for OGSECS electricity for different system configurations. The lowest line represents the cost vs. output for a battery-free OGSECS, while the next line represents an OGSECS with a 240Wh LTO battery and the upper line represents the results for an OGSECS with a 240Wh LTO and a 640Wh LFP. Delivered energy includes both cooking and available nighttime electricity for other uses. The symbols represent systems with different solar panel capacities from 300Wp to 1500Wp in increments of 100Wp. The minimum LCOE OGSECS has a solar panel capacity of about 1000Wp.*

Figure 11 shows the per-kWh cost of OGSECS use as a function of different system configurations. These curves assume day-time cooking demand of 2 kWh/day, plus nighttime electricity for lights, electronics cooking and water heating. The lowest cost system configuration is the battery-free system because batteries are fundamentally more expensive than solar panels. In addition, the per-kWh cost for each system generally decreases as the OGSECS output increases above 1 kWh/day towards 2 kWh/day due to economies of scale. The minimum LCOE OGSECS designs tend to have about 1000Wp of solar panel capacity.

We note from Figure 9 previously, that the current average output of the OGSECS distributed by KLLC is about 1 kWh/day for customers that are using the system. Thus, a key factor in reducing the current cost of OGSECS electricity in Malawi, will be incrementally increasing the power of the system and teaching customers how to utilize the system to get more cooking output. The cost modelling presented in this report indicates that this can decrease the unit cost of off-grid eCooking by 20% to 40%.

Investment cost of an OGSECS vs. daily cooking capacity

Figure 12 shows the delivered cost of an OGSECS system as a function of solar panel size, battery features and system output. The least expensive system is a battery-free OGSECS with a solar panel capacity ranging from 300W to 700W, which has an expected output of 800 to 1600 Wh/day. This is an entry-level OGSECS which can be affordable to many Malawians with a 50% to 75% subsidy.

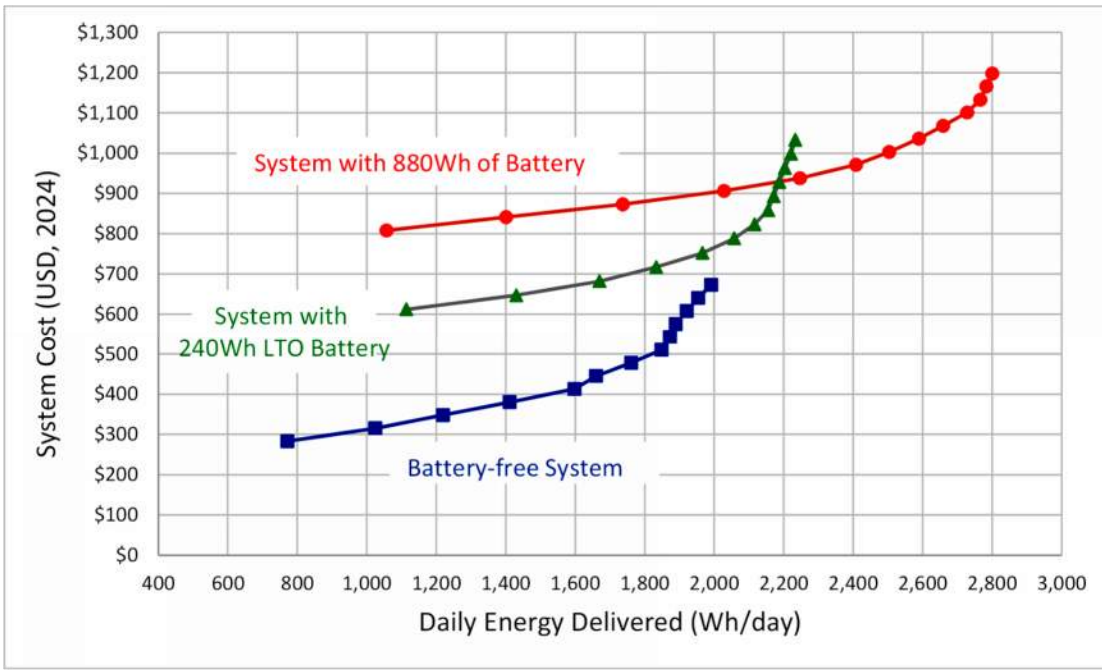

Figure 12. *System cost vs. daily average energy output for three types of OGSECS configurations for a medium level of cooking demand (i.e. 5 dishes per day, each with a 400Wh cooking energy requirement). The lowest line represents the cost vs. output for a battery-free OGSECS, while the next line represents an OGSECS with a 240Wh LTO battery and the upper line represents the results for an OGSECS with a 240Wh LTO and a 640Wh LFP. Delivered energy includes both cooking and available nighttime electricity for other uses.*

The data from the figure illustrates how when adding a 240Wh LTO battery to the system, the system output can increase approximately 20% to 40% relative to a battery-free system when the solar panel capacity is between 300Wp and 1000Wp. This is because the LTO battery may charge and discharge several times per day, allowing some of the solar panel power produced during cooking idle time to be used in cooking the next dish. This battery-enabled system has a delivered cost about $300 higher than the battery-free system.

When adding a lithium iron phosphate (LFP) battery, the capacity of the system essentially increases by an amount slightly less than the battery capacity for systems with a solar panel capacity greater than 1000Wp. This is because the LFP battery stores day-time solar panel electricity for nighttime cooking, water heating, and electronics usage that would not be possible without a battery that has substantial capacity.

In summary, for an OGSECS, a $300 to $400 investment can provide a battery-free OGSECS that can provide 1 to 1.5 kWh/day of daytime cooking. While a $900 to $1200 investment can provide an OGSECS with substantial battery capacity that can provide more than 2 kWh/day of daytime cooking along with substantial night-time cooking and water heating.

But the minimum eCooking LCOE of a battery-enabled OGSECS is about $0.16/kWh, while for a battery-free OGSECS, the LCOE of eCooking can be 25% lower, or $0.12/kWh.

OGSECS repair, replacement and customer support costs

Given that most of the OGSECS evaluated in this study have been installed for less than a year, an accurate characterization of repair, replacement and customer support costs is beyond the scope of this report. None-the-less, at this time, we can share some anecdotal information and preliminary statistics on what has been seen so far, including the following observations:

A. Replacing and repairing cookers appears simple and inexpensive with repairs costing $5 to $10 per repair, and sometimes less.
B. The cost for a technician to visit a customer is approximately $5 to $15 per customer:
C. When intensively used, a population of cookers has a breakage frequence of once per every 750 cooker-days. A collection of 58 women's group users had 6 cooker failures after a total of 4500 cooker-days of use.
D. The failure rate of the 600W MPPT appears to be substantially less than 1% per year. Only one or two have been known to fail out of several hundred that have been distributed and installed.
E. So far, solar panels appear to have a failure rate of about 1% per year, mostly due to wind and weather damage. Though damage due to children throwing rocks at the solar panels may occur at a much higher rate than this.

We elaborate on some of these observations as follows:

While KLLC has been selling and distributing the current OGSECS system configuration for only about a year, demonstration and development of the system with the eWant cookers has been going on for several years. While detailed breakage and repair statistics have not been collected during this period, KLLC has implemented a policy of replacing any broken cookers for free and has been storing the broken cookers received and repairing a portion of them. The main body and heating element of the cooker is extremely durable, and generally cooker malfunctions are the result of malfunctions of sensors and electronic parts. When the broken cookers are examined in more detail, typically a temperature or pressure sensor gets dirty or clogged, or a power relay burns out. Once sensors are cleaned and adjusted, or electrical parts are replaced, the cooker typically functions as new.

Another issue that arises, is that while the main body of the cooker is returned when a cooker breaks, often the inner pot is missing. To resolve this issue, KLLC has ordered replacements for the inner pots which cost approximately $5 each to replace. Thus refurbishing a cooker typically costs $5 for the inner pot, perhaps $3 for replacement electrical parts, and $2 for labour for a total of $10 per refurbished cooker.

A technician visit to a customer typically serves multiple purposes at once. If a cooker needs repair or replacement, the replacement cooker is installed and the broken cooker is returned to the central office in Blantyre. Monitoring data is collected to be used in verification of customer benefits and impact. System repairs and reconfigurations are made if necessary. And in addition, customers are educated on system use and new products and services that they can buy to expand or enhance the system that they have. It is envisioned that any cooker customer that is actively using the system for cooking and who wants customer support services will be visited every six months to a year.

Cooker breakage rates are going to depend on usage. In this project, a substantial population of active users were found with the women's group customers. For the initial usage period of approximately 100 days for these customers, cooker breakage rates were about 6 broken cookers for 4500 days cooker days of use. This corresponds to one breakage per 750 days of use where the average usage per day was approximately 0.8 kWh of cooking. This corresponds to a cooker being able to cook about 3000 kg of food before it needs a repair.

Amazingly, the 600W MPPT has shown almost no breakage during the last two years with more than 500 in use in customer households throughout Malawi.

While more than a thousand solar panels have been distributed along with cooker systems over the last year, there have been a few reports of solar panels suffering weather damage. Anecdotally, damage from thrown rocks has also been observed. The rate of solar panel damage due to weather and vandalism is a topic that deserves future study.

3. Analysis of Results and Learning

For a delivered cost of $300 to $400, it is now possible to provide to customers in rural Malawi an OGSECS that provides 0.5 to 1.5 kWh of off-grid solar eCooking. Perhaps it is possible to find a market segment within Malawi that could pay a cost-based price for such a system up front, but this market segment would be only a very small fraction of the general population, and KLLC has not yet connected with this market segment.

We conclude therefore that a substantial affordability gap exists for OGSECS-based eCooking in rural Malawi.

To make OGSECS more accessible to more Malawians, it is necessary to provide the systems at a subsidized or discounted price. But efficiently administering affordability subsidies for OGSECS is a substantial challenge.

To address this challenge, we can make three improvements or innovations to current OGSECS procurement, distribution and business model:

(1) Improve the cost-efficiency of OGSECS technical design and utilization
(2) Efficiently administer affordability subsidies to customers who utilize the system well through efficient impact-based financing; and
(3) Create a business model that can allow profits from irrigated gardening with solar pumps to cross-subsidize equipment of OGSECS cooking

We now discuss different aspects of these areas of improvement in turn

Cost-efficiency: Re-optimizing the OGSECS design

Promoting a 2-cooker OGSECS

The "lowest hanging fruit" for the cost-efficiency of an OGSECS system is to measure system use with existing customers, and to provide an additional cooker to the customers who are using the system well. Such a program might increase OGSECS output by up to 0.5 kWh/system at an incremental cost of less than $50.

Using low-voltage panels for a low-cost entry-level system

The cost of a 600W MPPT can be the same as the cost of 200 to 300 watts of solar panels. This means that by eliminating the MPPT and decreasing the solar panel capacity somewhat, it may be possible to drop the bulk procurement cost of an OGSECS to only $100. This could lower the delivered cost of an entry-level OGSECS to only $200.

Such a system might consist of simply a cooker and three 150W solar panels connected in parallel. If after monitoring it is verified that the customer is using the system well, then the customer can be offered additional solar panels and cookers with a generous discount. Eventually with the addition of a $200 1kWh LFP battery the customer would attain Tier 4 electricity access at a cost of $500 to $600 that is spread over potentially several years of incremental, affordable purchases.

Upgrading the LTO cooker batteries

With a low-cost high-current design upgrade, the continuous throughput power of the current 18V LTO cooker batteries can be increased from 300W to 600W. This will allow the 18V battery to power a 2-cooker OGSECS with a 2kWh to 3kWh daily output capacity which will be enough to provide the entire food cooking requirements of a typical rural Malawian household.

Testing LFP battery integration for the OGSECS

As part of the project, KLLC has ordered 20pcs of 100Ah LFP batteries that should arrive in Malawi in November 2025. These batteries cost about $200 to import to Malawi and should provide about 1 kWh of nighttime cooking (i.e. about 5 kg of food). Anecdotally, customers frequently ask about buying batteries for their OGSECS to enable it to cook at night. The import of these 20 test batteries will allow us to test the customer willingness to pay for an LFP battery upgrade of the OGSECS.

Control and conditionality of price subsidies and discounts

A key, preliminary result from this study is that unconditional subsidies result in roughly half as much eCooking in the subsidized OGSECS compared to a more controlled subsidy program that focuses on distribution to motivated women's groups. But such control and conditionality comes at a cost. Purchase and adoption of OGSECS by a more restricted set of customers usually means that a lower system price is needed to attain the same volume of sales. Similarly, purchase discounts or loans may be necessary to convince customers to purchase systems at a time and schedule that is convenient for organizing installation, distribution and usage monitoring activities.

Over the coming year, KLLC will develop systems for better controlling the application of subsidies and for creating an offer of impact-based discounts that allows subsidies to be targeted to those customers who will utilize the OGSECS the best.

Design of an efficient impact-based financing system

Efficient administration, control and application of affordability subsidies can be greatly assisted by access to financing that efficiently rewards and incentivizes economic benefits and leveraged impact. The *Empowering Efficiency Phase II* report discussed how a simplified Clean Impact Bond (CIB) financing approach could facilitate efficient adoption and utilization of OGSECS. The simplified CIB approach described in that report proposed:

> *"[T]hree 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."

As a follow-on to the present project, we have simplified the approach further and set up Solar4Africa.org as both the lender and the grantor for an Impact Bond focused on economic benefit and poverty reduction. The draft Impact Bond agreement is included in Appendix D of this report.

A very nice feature of the proposed Impact Bond approach is that it aligns the interests of all participating actors in the same direction. This allows all participants in the development effort to operate with high levels of transparency. The project implementer, KLLC can frankly tell customers that donor subsidies for the solar systems depend on them utilizing the systems well and maximizing the benefits they attain. In fact, this was done explicitly with the Women's Group customers in this project. Furthermore, in the next phase of implementation, it is possible to give customers discount certificates based on their measured solar system usage that they can use to expand the capacity of their solar systems. Such a discount certificate mechanism will then illuminate and clearly monetize the connection between development benefits, the business of solar sales and distribution. and donor goals.

Such economically leveraged impact-based financing means that everyone can be working on the same goal: i.e. maximizing the economic benefits that customers receive from the solar systems that they purchase. The better that customers learn how to use and benefit from their systems, the more their life improves AND the more discount certificates they can earn. The more discount certificates that customers earn, the more financing that the import and distribution business can obtain for importing more solar products. The more financing that the donor provides for importing solar products to Malawi, the more economic benefit and poverty reduction that the donor is able to create, accomplish and document for her supporters. This should allow donor organizations to raise more donation revenues.

We note that given the "impact price" currently proposed in the Impact Bond agreement in appendix D (i.e. $10 of benefit per $1 of finance), then the $40,000 in financing is expected to produce $400,000 in economic benefits and poverty reduction in rural Malawi. If this can be clearly demonstrated and documented, then it should be possible to recruit additional donors that are interested in participating in such cost-effective development financing.

Initial administration and management of Impact Bond pilot test

For the initial Impact Bond (IB) pilot test described in the agreement provided in Appendix D, the administration of the IB will be the same as administration of any normal non-profit or development aid grant. In this case, Solar4Africa.org is the grantor, and KLLC is the grantee, and Solar4Africa.org provides verification services to KLLC for essentially free, as the grantor bears the costs of grant management.

Under a larger scale IB financing test, a different entity would be the grantor, KLLC would be the grantee, and Solar4Africa.org would provide non-profit technical assistance to KLLC. Standards, methods and compensation for verification would be specified in a subsequent IB financing agreement. Conceptually, data collection that is compliant with a minimum standard would be the responsibility of KLLC with costs borne by regular monitoring and customer support budgets, while the costs of independent auditing and verification would be borne by the grantor as part of grant management and auditing.

At a much larger, institutionalized scale, there might be a coalition of grantors, who are represented in a coalition committee that sets standard procedures and practices for eCooking IB projects. Ultimately, such a coalition might create a non-profit registration organization to record, document, approve and register projects that meet standards and that follow best practices: analogous to what currently exists with carbon credits and the Gold Standard organization (See: https://www.goldstandard.org/)

Integrating an affordability solution for Women's Group customers

We now propose an integrated OGSECS and solar pumping affordability solution that we can pilot test in the coming year with our existing base of Women's Group customers.

We note that a 36V or 48V DC/DC converter can be connected to the output of the 18V LTO battery and the battery can be used to power a DC solar pump. KLLC currently has an estimated 1000 active solar pump customers. And the Women's Group customers are active women's gardening groups that also earn income through irrigated gardening during the dry season.

Preliminary tests indicate the addition of the battery and converter to a solar pumping system can substantially increase the output of solar pump. This will allow the same solar pump to generate more agricultural income. Yet the same battery can be used for solar eCooking.

We therefore plan to package the 18V LTO battery with a DC/DC converter into a energy-regulating power box. The power box will have an input connector for the solar panel (which will be connected to an MPPT if the customer has a high-voltage panel), and three output connectors: one for the solar pump. one for the solar cooker and one for generic 12V loads.

The customer can then either buy or rent the power box. If they rent the power box, the battery can be programmed to turn off after the rental period, when the power box is returned. If they buy the power box, they can earn discount credits for further purchases based on the impacts that are measured by the data logging chip in the battery.

When they have crops to irrigate, they can use the power box in the field for the crops. Whenever they are not irrigating crops, they can be using the power box to cook. No matter what they use the power box for, if KLLC collects the usage data, then the power box usage will earn impact-based Verified Economic Benefit credits (VEB) that can efficiently finance solar system subsidies and future procurement of solar equipment and materials for battery production.

It will be extremely interesting over the coming year to see if this integrated affordability approach can be made to work, and how much leverage the impact-based financing can create in terms of generating economic and social benefits for solar pump and OGSECS customers during 2025/6 and beyond.

OGSECS and grid-based eCooking

The approach that KLLC currently takes with regards to the relationship between OGSECS and the grid is that OGSECS are primarily an off-grid product that can at times they might receive some electricity from the grid as back-up power when electricity is not available from the solar panel or a battery. But the expectation is that OGSECS will mostly operate independently from the grid for the next 5 to 10 years and perhaps beyond. There are three reasons for this as follows:

1. Fundamentally OGSECS electricity is less costly than new connections to grid electricity in Malawi, and the supply of solar PV in Malawi is rapidly expanding such that it should be able to provide off-grid solar eCooking at scale by 2030.
2. The Malawi grid fundamentally does not have sufficient capacity to provide eCooking to most Malawians
3. Supplying eCooking electricity from the grid exacerbates Malawi's foreign currency shortages and decreases the current economic viability of electricity service from the national electric utility.

We discuss each of these three issues in turn:

Because of recent declines in solar PV prices, shipments of solar panels to Malawi and other African countries are starting to take-off.[16] From June 2024 through June 2025, exports from China to Malawi of solar PV was 69 Megawatts. If all of this capacity was used for eCooking, this is a quantity of solar PV that is sufficient to provide OGSECS to more than 70,000 homes per year. African solar imports have risen 60% in the last 12 months. If Malawi solar imports can continue to grow at more than 30% per year for the next 5 years, then by 2030, Malawi could be importing more than 250 megawatts of solar PV. If more than 20% of this solar capacity can be used for eCooking, then this is enough to provide off-grid eCooking for 50,000 to 100,000 new households per year.

We note from the 2022 Malawi Integrated Energy Plan[17] that for grid-connected customers the cost per connection is estimated at $476. This is approximately the cost of a 800Wp OGSECS and does not include the cost of the electricity that would be delivered for cooking. The IEP notes that grid electricity is subsidized and provided at a price of $0.065/kWh. Recent news articles note that the national utility is purchasing electricity from Mozambique at $0.14/kWh. If an 800Wp OGSECS provides 1 kWh/day, then the cost of grid eCooking is at least $0.14/kWh x 1 kWh/day x 365 days/year = $51/year more expensive than OGSECS eCooking for customers who are currently off-grid. Thus, if the policy choice is between providing eCooking for a million customers with OGSECS or grid electricity, it might be something like $50 million per year cheaper to provide a million Malawian households eCooking with OGSECS.

Further, we note that total grid-based electricity generation in Malawi for all electric uses and all customers is approximately 150 GWh/day or about 5 GWh/day.[18] This compares to a total Malawi eCooking demand of 12 GWh/day if 20 million Malawians obtained their 0.6 kWh/day/capita eCooking needs from the grid. For at least the next decade the Malawi grid will have the capacity to supply eCooking to only a relatively small fraction of this demand. Thus, at least for the near term, a national OGSECS development strategy should probably not rely on obtaining a significant amount of electricity from of grid-based electricity supplies.

And finally, we note the following quote regarding Malawi imports of electricity from Mozambique from an August 2025 news posting:[19]

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[16] https://ember-energy.org/app/uploads/2025/08/Report-Ember-The-first-evidence-of-a-take-off-in-solar-in-Africa.pdf

[17] https://www.seforall.org/system/files/2022-10/Malawi_IEP-Electrification_Report.pdf

[18] https://www.ceicdata.com/en/indicator/malawi/electricity-production#:~:text=Electricity%20Production%20in%20Malawi%20reached%20121%20GWh%20in,132%20GWh%20from%20Jan%202004%20to%20Mar%202023.

[19] https://clubofmozambique.com/news/mozambique-to-export-us5-million-a-month-of-electricity-to-malawi-report-289680/

From November, Mozambique will earn USS5 million a month from the export of 50 megawatts of electricity from Tete province to Malawi.

The revenue could reach up to US$10 million per month if Malawi agreed to import 100 megawatts, but the foreign exchange shortage faced by the Lilongwe government is hampering the deal.

Kankwamba Kumwenda, chief executive officer of ESCOM (Electricity Supply Corporation of Malawi), acknowledged recently that the payment method for imported electricity will be a challenge for Malawi, a country with limited foreign exchange reserves, to meet all its needs outside the country.

We note that 50 megawatts for $5 million over one month is 36,000 MWh of electricity at a price of $0.14/kWh. Thus, the national utility is spending $0.14 per kWh in foreign currency to import electricity for customers who are paying as little as 71.35 MWK per kWh in local currency.[20] Currently, at market exchange rates, the 71.35 MWK paid by small domestic customers is approximately $0.02 per kWh. This means that currently the national electric company loses about $0.12 per kWh in foreign currency for each grid kWh of eCooking that occurs with small, domestic grid-connected customers.

This implies that—at least at the current time—any expansion of eCooking on the grid in Malawi will likely exacerbate Malawi's ongoing foreign currency supply crisis.

Given these three considerations, KLLC will for the time being maintain a strategy and focus of supplying primarily off-grid solar eCooking systems without grid integration.

4. 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 less than $0.10 per watt, exceeding predictions.[21] This 3X decline in solar panel prices has allowed the capacity of OGSECS to increase by more than 4X from 150Wp to >600Wp. The higher capacity OGSECS can as of August 2024 provide an average of 1 kWh/day of efficient, electric cooking for approximately 40% of the daily food requirement of a household of 5 people.

Since August 2024, KLLC has promoted the subsidized sale of OGSECS in earnest and has sold more than 500 systems in the last year. But when sales are subsidized, ultimately the sales volume is constrained by the subsidy budget and the amount of subsidy per product sold.

After the completion of this current research project, KLLC will receive financing from US philanthropic donors for a 2025/6 impact financing budget of $40K for both OGSECS and solar pumping sales. To administer that subsidy in the most impactful way possible, KLLC will in partnership with a US non-profit project—Solar4Africa.org—to administer the subsidy budget through an Impact Bond mechanism.

To the extent that KLLC can minimize the subsidy required to bridge the affordability gap for OGSECS in rural Malawi, this will help maximize the number of new OGSECS systems that

[20] https://www.escom.mw/tariffs-and-charges/

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

can be procured with the $40k of Impact Bond financing. In effect, the volume of OGSECS sales relative to Impact Bond financing will be an empirical measure of how much KLLC will be able to bridge the affordability gap in practice.

Through the research presented here, KLLC in partnership with Solar4Africa.org has created a mechanism to efficiently finance and manage the affordability gap for off-grid solar eCooking access in rural Malawi. This research result is not just theoretical but will be implemented—at least at small scale—in the coming year.

We believe that the integrated solar pump and OGSECS solution for Women's Group customers shows special promise for generating a large amount of economic and social benefit for rural Malawians given a constrained affordability subsidy budget. Especially as it enables credit-based purchasing where the solar equipment purchase is paid for (with a profit) by the new income that the solar equipment enables via irrigated agriculture.

As we move forward, KLLC and Solar4Africa.org are committed to sharing their continued learnings in this regard with the international eCooking research community. Consequently, even after the completion of this project we shall publish further research reports and data that will be shared.[22]

Stay tuned!

ABBREVIATIONS

The following abbreviations are used in this report:

COGS	Cost of goods sold
EPC	Electric pressure/multi cooker
ESMAP	Energy Sector Management Program
IEA	International Energy Agency
GNI	Gross national income
kWh	Kilo-watt hour
LCOE	Levelized cost of electricity
LFP	Lithium iron phosphate (a type of battery chemistry)
LTO	Lithium titanate (a type of battery chemistry)
MPPT	Maximum power point tracking charge controller
MTF	Multi-tier framework [3]
MWK	Malawi Kwacha
OGSECS	Off-grid solar-electric cooker system
SAS	Stand-alone solar PV system
SDG7	Sustainable development goal #7
SSA	Sub-Saharan Africa
VEB	Verified Economic Benefit credits
Vmp	The maximum power voltage (of a solar panel)
Wh	Watt-hours
Wp	Peak watt output of a solar panel at standard test conditions

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

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[9] Bhatia, M., & Angelou, N., Beyond connections: energy access redefined. World Bank, 2015.

5. Appendices

Appendix A: Affordability threshold calculation

World bank data provides both average per-capita gross national income (GNI) and national income share by household income quintile. This allows for a binning of SSA population by income quintile and by country, and an estimation of the average income for each income quintile in each country where:

$$I_{quint} = I_{Avg} \times (QuintShare/20\%), \quad (1)$$

Where Iquint is the average income of the population in the income quintile, and where the population of the quintile is 20% of the country's population.

Note that GNI is in current USD and is calculated by the Atlas method. This is because this is the income value that is most representative of the international purchasing power of household income with respect to imported products like solar equipment and appliances.

The per capita electricity demand is estimated as approximately E_{demand}= 0.5 kWh/capita/day = 182.5kWh/capita/yr. This demand assumes efficient cooking with an EPC. This is a low estimate and as such will imply a somewhat high affordability threshold. Many households may need a somewhat lower electricity cost than what is estimated here in order to comfortably afford the use of solar electric cooking for all of their cooking needs.

With the above assumptions and inputs, then for each quintile, the affordable electricity cost threshold is estimated as:

$$C_{affordable} = 5\% \times I_{quint} / E_{demand}, \quad (2)$$

Figure A.2 shows the cumulative distribution of SSA population below an affordability threshold as a function of the $/kWh electricity cost of OGSECS cooking electricity. The figure illustrates that more than 500 million Africans need electricity to cost less than $0.20/kWh to be affordable for clean cooking. Of this population, approximately 250 million Africans need electricity to cost less than $0.12/kWh for it to be affordable for them to cook on off-grid solar electricity.

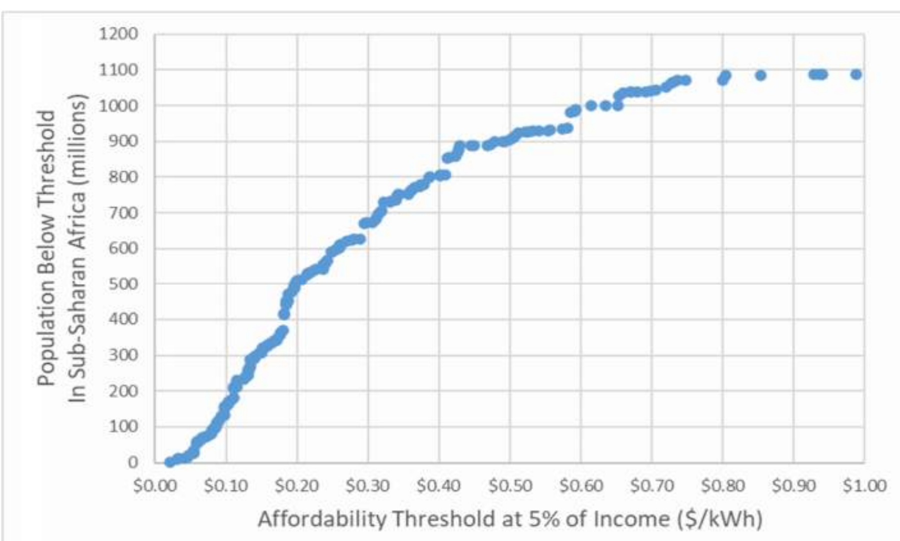

Figure A.2. Cumulative distribution of SSA population at different electricity access affordability thresholds. At each threshold value, the vertical access provides the cumulative population that requires a lower $/kWh cost in order for the electricity to be affordable (i.e. cost less than 5% of income).

This affordability analysis indicates that if SAS electricity LCOE is in the range of $0.25 to $0.35 per kWh as indicated by Egli, et al., then hundreds of millions of Africans are unlikely to be able to sustainably afford this cost as it will exceed 5% of the international purchasing power of their income. More than 600 million Africans have an affordability threshold lower than $0.25/kWh if their solar electricity access is going to be sufficient to include their solar e-cooking demand.

Appendix B: Distribution cost model

Introduction

A key aspect of providing cost-efficient access to off-grid solar electricity for cooking is designing a system that has an optimum balance of system components that are sized appropriately for their specific roles in supplying and regulating energy flows to cooking demand. We use a standard metric of system investment cost per unit solar panel capacity, i.e. $/Wp (Wp = peak watt). And we note that the relevant cost is the delivered cost of the system, thus the system cost is not simply a sum of the component costs. Instead, the delivered system cost is a sum of many costs including: system components purchased from manufacturers, shipping, taxes, import fees, storage, security, wholesale distribution, retail distribution logistics, sales and marketing, installation, etc. We note that most of these costs scale with the amount, size and cost of the different components being distributed with the off-grid solar electric cooking systems (OGSECS). We compile and calculate these costs for the specific case of distributing OGSECS at medium-scale (i.e. thousands of systems per year) in Malawi where containers of components are purchased from manufacturers and then shipped to Malawi, stored in a container yard, and then distributed to a network of village shops.

Cost calculation

Table B.1 illustrates the cost calculation for the OGSECS system. Delivered costs are placed into four categories: (1) Procurement and import expenses, (2) Wholesale storage and distribution, (3) Retail distribution and sales, and (4) Post-sales costs. All costs are indexed relative to the per-Wp costs of the solar panel. For example, if the factory door price of the MPPT is $0.05/W and if there is 0.9 watts of MPPT capacity for every 1.0 watts of solar panel capacity, then the MPPT cost is 0.9 × $0.05 = $0.045 is the cost of the MPPT per Wp of solar panel capacity.

Table B.1: Example cost calculation for OGSECS system

Cost Category	Component Cost	Solar Panel	MPPT	EPC	LTO Battery	Small LFP Battery
Procurement & Import	Factory Door Price	$0.100	$0.045	$0.038		$0.107
Procurement & Import	Shipping	$0.033	$0.005	$0.012		$0.037
Procurement & Import	Procurement Capital	$0.013	$0.005	$0.005		$0.014
Procurement & Import	Duty/Taxes/Delivery Fees	$0.020	$0.022	$0.033		$0.036
Procurement & Import	SUBTOTAL	$0.166	$0.077	$0.088	$0.260	$0.194
Wholesale	Storage Costs	$0.011	$0.002	$0.004	$0.013	$0.013
Wholesale	Security	$0.003	$0.000	$0.001	$0.003	$0.003
Wholesale	Distribution Management	$0.018	$0.008	$0.009	$0.028	$0.021
Wholesale	Wholesale Delivery	$0.027	$0.012	$0.014	$0.041	$0.032
Wholesale	SUBTOTAL	$0.059	$0.022	$0.029	$0.085	$0.069
Retail Distribution	Sales Commissions	$0.056	$0.025	$0.029	$0.086	$0.066
Retail Distribution	Retail Shop (Rent & Maintenance)	$0.017	$0.007	$0.009	$0.026	$0.020
Retail Distribution	Demonstration & Promotions	$0.006	$0.002	$0.003	$0.009	$0.007
Retail Distribution	Balance of System Wiring & Materials	$0.008	$0.004	$0.004	$0.013	$0.010
Retail Distribution	SUBTOTAL	$0.088	$0.038	$0.045	$0.134	$0.102
Post-sales Expenses	Repairs and Replacements	$0.012	$0.004	$0.006	$0.017	$0.014
Total Non-Admin	SUBTOTAL	$0.325	$0.141	$0.168	$0.496	$0.380
Post-sales Expenses	Project Administration & Reporting	$0.098	$0.042	$0.050	$0.149	$0.114
Post-sales Expenses	SUBTOTAL	$0.109	$0.046	$0.056	$0.166	$0.128
All	TOTAL	$0.423	$0.183	$0.219	$0.645	$0.493

As part of the supplemental materials of this study, the details of these calculations are provided in spreadsheet form as part of an integrated component and operational cost model for OGSECS.

System cost model parameters

In order to calculate all of the different cost components in Table B.1, values farther down in the distribution chain are generally dependent on costs incurred earlier in the distribution chain. We use cost model parameters that are generally applied to previous costs to calculate subsequent distribution costs. These parameters are shows in Table B.2 below.

Table B.2: System cost model parameters

System Cost Model Parameters		
Solar Panel price (factory door)	$0.100	/Wp
Solar Panel duty/tax/arrival fees	15%	of price + shipping
Shipping cost (panels)	$0.033	/Wp
Shipping cost (MPPTs)	10%	of MPPT cost
Shipping cost (EPCs)	31.7%	of EPC cost
Shipping cost (LFP Battery)	35.0%	of LFP Battery cost
Cost of procurement capital	20%	per annum
Procurement time	0.5	years
EPC price (factory door)	$0.046	/Wp
EPC sizing (Wepc/Wpanel)	71.4%	of panel size
EPC duty/tax/arrival fees	65%	of price + shipping
MPPT cost	$0.045	/Wp
MPPT sizing	85.7%	of panel size
MPPT duty/tax/arrival fees	45%	of price + shipping
LTO Battery cost (delivered)	$0.650	/Wh
LTO Battery capacity	0.343	Wh/Wp
LFP Battery cost (factory door)	$0.100	/Wh
LFP Battery capacity (LTO + LFP)	0.914	Wh/Wp
LFP Battery capacity (LFP only)	1.829	Wh/Wp
LFP duty/tax/arrival fees	25%	of price + shipping
Storage costs	35%	of shipping costs
Security costs	25%	of storage costs
Distribution management	10%	of cost of goods
Wholesale delivery	15%	of cost of goods
Sales commissions	25%	of wholesale goods cost
Retail shop rent and maintenance	30%	of commissions
Demonstration and promotions	10%	of wholesale goods cost
Balance of system wiring & materials	15%	of wholesale goods cost
Repairs and replacements	20%	of wholesale goods cost
Project Administration & Reporting	30%	of all other costs

We now discuss each of the cost parameters in Table B.2 in turn.

- The solar panel per Wp price is a high estimate from recent procurements of solar panels and is consistent with reports from Bloomberg New Energy Finance [B-1].
- Solar panel duty tax and arrival fees reflect the actual taxes and fees charged in Malawi.
- Shipping costs reflect the fact that is costs approximately $12,000 to ship a 40HQ container of solar panels from China to Malawi and that such a container can hold 365.5 kWp of solar panels.
- MPPT shipping costs are listed as 10% because they are small and can easily fit in any container of mixed goods.
- Shipping costs of EPCs are listed as 31.7% of EPC costs as a 40HQ container of EPCs that cost $37,800 can be shipped for $12,000 from China to Malawi.
- LFP shipping costs are assumed to be a relatively high at 35% of battery costs.
- Procurement capital is given a value of 20% as it is often taken from operating capital of a business which can have a high opportunity cost.
- The procurement time is given at 0.5 years because it includes payment, production, loading the container, shipping the container from a seaport in China to a seaport in Africa, shipping the container via land freight from a seaport to Malawi, customs clearance and delivery to the wholesale warehousing location.
- The EPC price is given as $0.046/W of EPC power as a 500 watt EPC can cost $21 at the factory door.
- For our model calculations the EPC sizing is given at 500W/[Solar Panel Size].

- Malawi has relatively high import taxes for EPCs, currently at about 65% total for customs, VAT, and other taxes.
- In our model calculations we set the MPPT sizing as 600W/[Solar Panel Size]
- MPPT import taxes and fees are set at 45%.
- The cost of a custom LTO battery assembled in Malawi is $77.38/120Wh ~ $0.65/Wh [B-2].
- The LTO battery capacity relative to the solar panel is simply the battery capacity in Wh divided by the solar panel capacity in Wp.
- The LFP battery cost is obtained from recent price quotes.
- Solar battery duty tax and arrival fees are less than those for EPCs and electronics in Malawi.

The remainder of the table lists the assumptions regarding other cost components relative to preceding cost estimates. Storage costs are a fraction of shipping costs, because it is possible to purchase the container that products are shipped in and store the products in the purchased container. Similarly, security costs scale as the storage costs as the number of guards that need to be hired scale as the number of storage yards or sites that are used.

The remaining cost factors in the table are self-explanatory, though significant research is possible to understand how these factors can vary in different contexts, countries and for different distribution organizations.

Estimation of OGSECS cost trends

By making assumptions or estimates of historical changes in component costs, it is possible to estimate the effective delivered system cost in previous years.

We complete this estimation exercise by using the historical cost input values shown in Table B.3:

Table B.3: Inputs for historical system cost estimation

	Cost Components				Results			
	Panel			LFP	High Overhead		Low Overhead	
Year	$/W	Shipping	LFP $/Wh	Shipping	Batt-free	100Ah LFP	Batt-free	100Ah LFP
2015	$0.55	$7,000	$0.38	5.37%	$1.99	$4.15	$1.53	$3.19
2016	$0.46	$7,000	$0.29	7.04%	$1.73	$3.38	$1.33	$2.60
2017	$0.32	$7,000	$0.22	9.28%	$1.32	$2.58	$1.02	$1.98
2018	$0.29	$7,000	$0.18	11.34%	$1.24	$2.26	$0.95	$1.74
2019	$0.22	$8,000	$0.16	14.58%	$1.05	$1.98	$0.81	$1.52
2020	$0.20	$9,000	$0.14	18.75%	$1.01	$1.84	$0.78	$1.42
2021	$0.24	$10,000	$0.13	22.44%	$1.14	$1.93	$0.88	$1.49
2022	$0.26	$15,000	$0.12	36.46%	$1.28	$2.10	$0.98	$1.62
2023	$0.17	$11,000	$0.11	29.17%	$0.95	$1.65	$0.73	$1.27
2024	$0.10	$12,000	$0.10	35.00%	$0.77	$1.43	$0.59	$1.10

When the historical cost data provided in Table B.3 is input into the cost model, the estimates of historical system prices are as shown in Figure B.1.

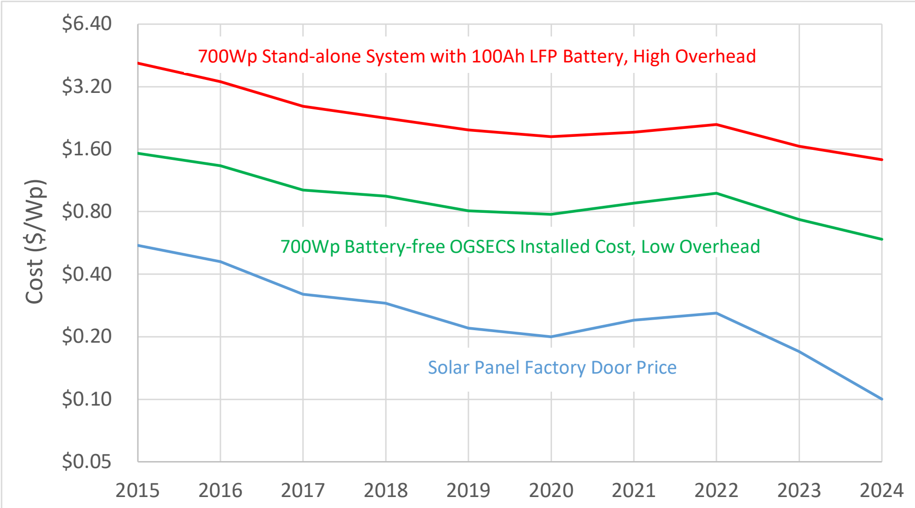

Figure B.1: Solar panels costs and cost outputs of the component-based cost model for 2015 through 2024. Costs are in nominal USD and note that the vertical axis has a logarithmic scale.

Summary

In this study, a transparent component-based model for the delivered cost of OGSECS is provided. The model shows that the fully over-headed, delivered cost of the system can be from 3 to 5 times the factory door cost of key system components. The cost of battery capacity in a battery-enable OGSECS can be more than half of the cost of the system. Thus, a battery-free OGSECS can be about half the cost per Wp of panel capacity than a fully battery-enabled OGSECS. This means that OGSECS that are either battery-free or that have only a small battery can provide a highly affordable entry-level system for off-grid solar electric cooking access.

This creates the possibility of affordable incremental acquisition of a larger-capacity system, where initially a battery-free OGSECS is purchased, and then over a period of years additional battery and solar panel capacity is added until the OGSECS can satisfy the entire energy demands of a low-income off-grid household. This allows incremental purchasing of a high-capacity off-grid solar system without incurring the cost of creating a consumer credit finance system.

Appendix B References

B-1. Q3 2024 Global PV Market Outlook (2024) Available Online: https://about.bnef.com/blog/3q-2024-global-pv-market-outlook/ (accessed on 30 December 2024)

B-2. Selvin, S.; Van Buskirk, R. Making a 10-year lifetime Solar eCooking Battery for Rural Africa. (27 November 2024) Available online: https://mecs.org.uk/recording-of-the-webinar-making-a-10-year-lifetime-solar-ecooking-battery-for-rural-africa/ (accessed 22 January 2025)

Appendix C: OGSECS simplified operational simulation model

Introduction

The operational simulation model described in this appendix provides capacity utilization estimates for an off-grid solar-electric cooking system (OGSECS) and also allows estimation of the per kWh levelized cost of electricity.

The e-cooking simulation model balances energy and current flows from the solar panel to the cooking loads through OGSECS components to estimate the fraction of solar panel output utilized, the charging and discharging of the batteries, the time spent cooking, and the fraction of cooking demand satisfied by the system.

The simulation model can simulate three different OGSECS battery configurations: (A) a battery-free version, (B) a variant with a small-capacity lithium titanate (LTO) battery, and (C) a variant with both a small LTO battery and a larger capacity lithium iron phosphate (LFP) battery.

Simplified modelling of solar resource and cooking demand

The operational simulation model uses simplified modelling of both the solar resource and demand. The model results are particularly sensitive to the total solar electricity output of the solar panel, and of the total quantity of energy demanded for cooking, but results are less sensitive to the fine details of exactly how much demand or electricity output occurs as a particular hour of the day.

Modelling the solar resource and panel output

To model the solar resource, the model approximates the variability of the solar resource with three values whose average corresponds to an average photovoltaic (PV) resource inferred from solar resource maps for Malawi provided by ESMAP [C-1] (p. 59). These resource maps indicate a median solar PV power generation potential of 1600 kWh/kWp annually which corresponds to 1600/365 = 4.38 hours per day (h/day) of equivalent rated output. Chisale et.al estimate the coefficient of variability (standard deviation divided by mean) of the daily solar resource in Malawi as approximately 25% [C-2] (p. 10). In our modelling we model resource variability with three values: the average resource, the resource plus 1.5 standard deviations (i.e. +37.5%) and the resource minus 1.5 standard deviations. These three values for Malawi are 4.38 h/day, 4.38 × 1.375 = 6.02 h/day and 4.38 × 0.625 = 2.74 h/day.

In addition, in our systems the panel output passes through an MPPT controller, which we estimate at 90% efficiency, thus the power provided by the panel through the MPPT corresponds to 6.02 x 0.9 = **5.42 h/day**, 4.38 x 0.9 = **3.94 h/day**, and 2.74 x 0.9 = **2.46 h/day**.

We model the solar panel output as following a sin curve from 6 AM to 6 PM with a peak resource at noon. Note that a resource with 1 Wp at noon, corresponds to a total output of 24/π watt-hours per day of output which is equal to **7.64 Wh/day**. Thus, the high, medium and low solar panel output values listed in the previous paragraph represent 71%, 52% and 32% of the maximum rated output of the solar panels over the course of a day.

System operation is calculated for these three solar panel output levels and then the system output is averaged to provide the estimated average system operational results.

Modelling cooking demand

Cooking demand is modelled as a series of cooking events. During a cooking event, the cooker operates at its maximum power level or at a level that corresponds to the available power from the solar panel or battery until the energy requirement of the cooking event is satisfied. Then the cooker shuts off until it is time to start a subsequent cooking event.

Field tests of OGSECS cooking energy use appears to indicate that OGSECS cooking event energy intensities ranging from at least 200Wh to 500Wh on average per event [C-3] (Figure 5), and on average the number of dishes cooked per household per day is approximately five [C-3] (p. 31).

For this study we model OGSECS operation for systems that generally have higher power than the field tests cited above. This is because with declines in solar panel costs it is now feasible to provide OGSECS with large solar panels that can satisfy a larger portion of total household demand. We will therefore model a range of demand profiles that range from 4 dishes per day to 6 dishes per day, where the energy intensity per dish ranges from 300Wh/dish to 500Wh/dish. The three demand profiles modelled here are consequently: (A) a low demand profile of four dishes per day of 300Wh each for a total of 1.2 kWh/day, (B) a medium demand profile of five dishes per day of 400Wh each for a total of 2.0 kWh/day, and (C) a high demand profile of six dishes per day of 500Wh each for a total of 3.0 kWh/day.

Another important feature that needs to be specified in a cooking demand profile is the time spacing between cooking events. Empirical data from OGSECS operation clearly shows a spacing in time between cooking events [C-3] (Figure 15). There are at least two reasons for this spacing: (1) cooks often need time to prepare the next dish after a first dish is finished cooking, and (2) when a dish is cooked in an insulated cooker, most energy is used heating up the dish, and much of the cooking can occur while the dish sits at boiling temperature with minimal added energy input. Thus, even when a cooked dish is quickly removed from the cooker and replaced, the energy profile of the cooking event can have a gap between periods of power draw because minimal power is drawn when a dish is cooking at a temperature slightly below boiling.

To account for the spacing between cooking events—or between periods of power draw—the operational model assumes a minimum time elapses between cooking events. In the model calculations presented here, it is assumed that a typical time spacing is 1 hour, though spacings of 0.5 and 1.5 hours are also examined and reported below in a sensitivity analysis that examines the degree to which the model results are sensitive to this assumption/input.

System configurations and power flow accounting

Figures C.1, C.2, and C.3 show the OGSECS system configurations for the three OGSECS configurations respectively: (1) a battery-free system, (2) a system with an LTO battery, and (3) a system with both an LTO and LFP battery.

In the battery-free configuration, the solar panels are connected to the input of a maximum power-point tracking (MPPT) solar controller whose output is connected to a direct current (DC) electric pressure/multi cooker (EPC) [C-4]. The MPPT adjusts the current and voltage of the output to obtain the maximum output from the solar panels. The EPC has an operating voltage that ranges from 10 to 24 volts and has two operating modes, a low-power mode where the cooker has a resistance of 2.3 ohms, and a high-power mode where cooker has a resistance of 1.15 ohms.

The configuration with an LTO battery is shown in Figure 2. In this configuration, the solar panels connect first to an MPPT which provides a 90% efficient conversion of the solar panel supply to the input ports to a custom LTO battery [C-5]. A separate output port provides power to the cooker at what is assumed to be the peak power requirement of the cooker of 500 watts. Both the inputs and outputs of the LTO battery have an effective resistance, which results in additional losses relative to the battery-free case. The model keeps track of the state of charge (SOC) of the battery and switches the output of the battery on and off to regulate the power to the cooker when the power input from the solar panels is less than 500 watts for an extended period and the battery SOC is near zero.

The configuration with both an LFP and LTO battery is shown in Figure 3 below. In this configuration, the LFP battery acts as an energy storage buffer between the MPPT and the LTO battery. The LFP battery is connected in parallel to the input leads of the LTO battery which are connected to the output of the MPPT. The LTO battery connection to the cooker is the same as in the previous case.

In the following sub-sections, we describe the power balancing and energy flow equations for modelling each configuration.

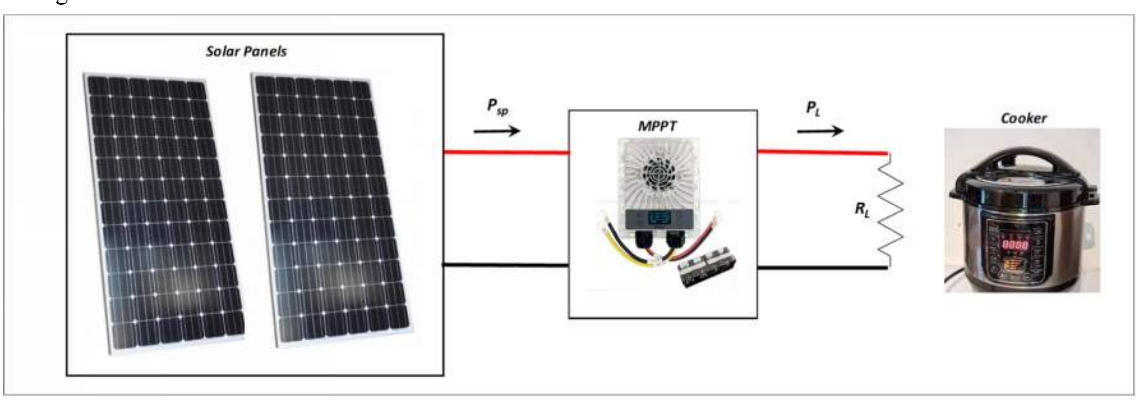

Figure C.**1**: Battery-free system configuration.

Battery-free configuration

For the battery-free configuration shown in Figure 1, the power flow from the solar panel is effectively controlled by the load. When the load is on, and if the potential solar panel output is greater than the peak load of the cooker, then the power flow to the load is equal to the cooker peak load. When during lower sunlight conditions the solar panel output is lower than the peak load of the cooker, the MPPT adjusts the voltage of the output until the load is equal to approximately 90% of the peak power output of the solar panel. Under very low sunlight conditions, when the peak solar panel output is below the minimum power of the cooker, the cooker shuts off.

We note that the cooking load in our case can have two settings: (1) High power (i.e. low resistance = 1.15 ohms) and (2) low power (i.e. higher resistance = 2.3 ohms). The operating voltage range of the cooker is from 10V to 24V. And because power = P = V^2/R where V is the voltage and R is the resistance, the power ranges for high power and low power are 87W to 500W for high power and 44W to 250W.

It is simple and straightforward to model these operating conditions in a spreadsheet in order to calculate cooking time and daily energy used in cooking given the cooking demand profiles described previously.

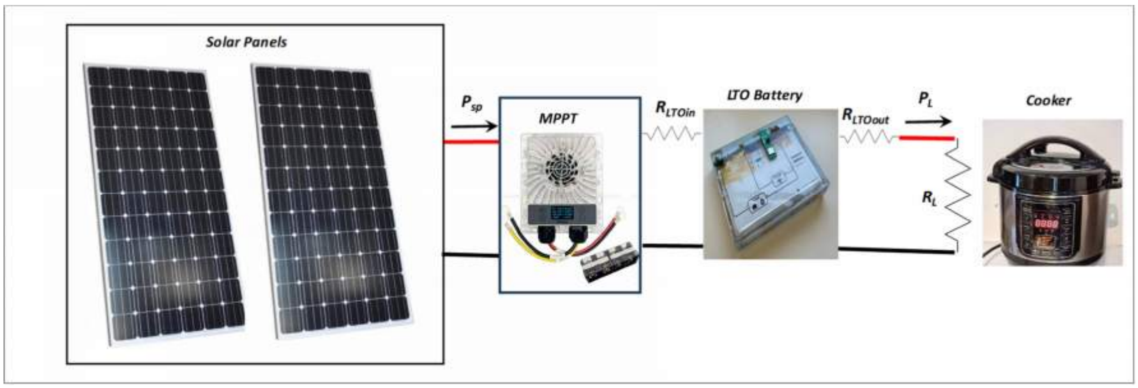

Figure C.**2**: Configuration with LTO battery.

System with LTO battery

The system with an LTO battery is shown in Figure 2. Note that because the battery utilizes the LTO battery chemistry, its charge and discharge rate can be higher than 4C. C represents the capacity of the battery and a discharge rate of 4C means that the discharge rate is four times the battery capacity in one hour. Thus a 20 amp-hour (Ah) LTO battery can charge and discharge at a peak rate that is higher 80 amps (A) [6].

In this case, the LTO battery acts as a buffer between the solar panel and the cooker. When the battery is less than fully charged, it accepts any power that is provided by the solar panel. And if the battery is not yet fully discharged, it can provide any power that might be needed by the load.

The operational simulation re-calculates the state of charge (SOC) of the battery every time step (which is set as 15 seconds in our calculations), and then determines whether the input and output ports of the battery are on or off based on the battery SOC. When the SOC is below 0%, the output is turned off, and when the SOC is above 100%, the input is turned off. The voltage of the battery is a function of the SOC with $V_{LTO}(SOC=0\%)$ = 11.0V and $V_{LTO}(SOC=100\%)$ = 13.2V.

Again, it is simple and straightforward to calculate the energy flows in a spreadsheet, and a spreadsheet with these calculations is provided with these supplemental materials. Example model calculations are provided subsequent sections.

The one non-trivial calculation is the estimating the current input to the LTO battery. For this we have the following equations:

$$I_{LTOin} \times R_{LTOin} = V_{MPPT} - V_{LTO} = P_{MMPT}/I_{LTOin} - V_{LTO}$$

$$I_{LTOin}^2 + (V_{LTO}/R_{LTOin}) \times I_{LTOin} - (P_{MMPT}/R_{LTOin}) = 0$$

$$I_{LTOin} = -(V_{LTO}/R_{LTOin}) + \sqrt{[(V_{LTO}/R_{LTOin})^2 + 4\times (P_{MMPT}/R_{LTOin})]}$$

Where I_{LTOin} is the current into the battery, V_{LTOin} is the voltage of the battery, R_{LTOin} is the resistance for current flowing into the battery and P_{MMPT} is the solar power output by the MPPT.

System with LTO + LFP batteries

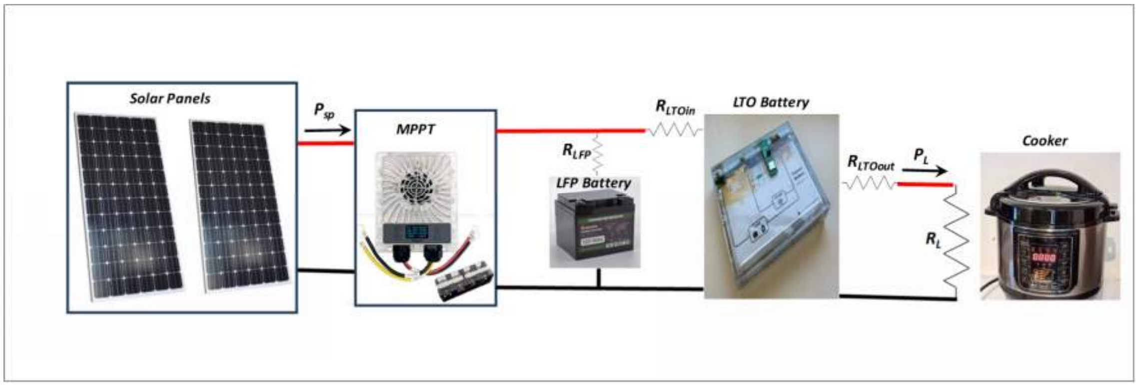

Figure C.**3**: Configuration with LTO and LFP battery.

The third system configuration is shown in Figure C.3 and has in addition to the LTO battery, an LFP battery connected in parallel with the LTO battery to the MPPT output wires. We assume that the LFP battery has a battery management system where if the battery voltage is either less than 12.0V or higher than 13.45V (corresponding to an SOC of 0% and 100% respectively) the battery shuts off to protect the battery.

Note that there are four possible states for the power flow from the MPPT to the batteries: (1) both the LTO and LFP battery are connected, (2) only the LTO is connected, (3) only the LFP is connected, and (4) neither the LTO nor the LFP are connected (usually when both the LTO and LFP are fully charged).

If I_{MPPT} is the current output of the MPPT, then the for the three non-zero current cases, we have:

$$I_{MPPT} = -b + \sqrt{[b^2 - 4\times c]}$$

where for case #1:

$$b = V_{LTO}/R_{LTOin} + V_{LFP}/R_{LFP}$$

$$c = -P_{MMPT} \times (1/R_{LTOin} + 1/R_{LFP})$$

where for case #2:

$$b = V_{LTO}/R_{LTOin}$$

$$c = -P_{MMPT}/R_{LTOin}$$

and where for case #3:

$$b = V_{LFP}/R_{LFP}$$

$$c = -P_{MMPT}/R_{LFP}$$

Where I_{MPPT} is the current from the MPPT, V_{LTO} is the voltage of the LTO battery, V_{LFP} is the voltage of the LFP battery R_{LTOin} is the resistance for current flowing into the LTO battery, R_{LFP} is the resistance for current flowing in and out of the LFP battery and P_{MMPT} is the solar power output by the MPPT.

Example operational simulations

In this section we illustrate the results of the operational model for the three different system configurations.

Battery-free configuration

Example simulations for the battery-free OGSECS with an 800Wp solar panel is shown in Figure C.4 for the medium cooking demand scenario.

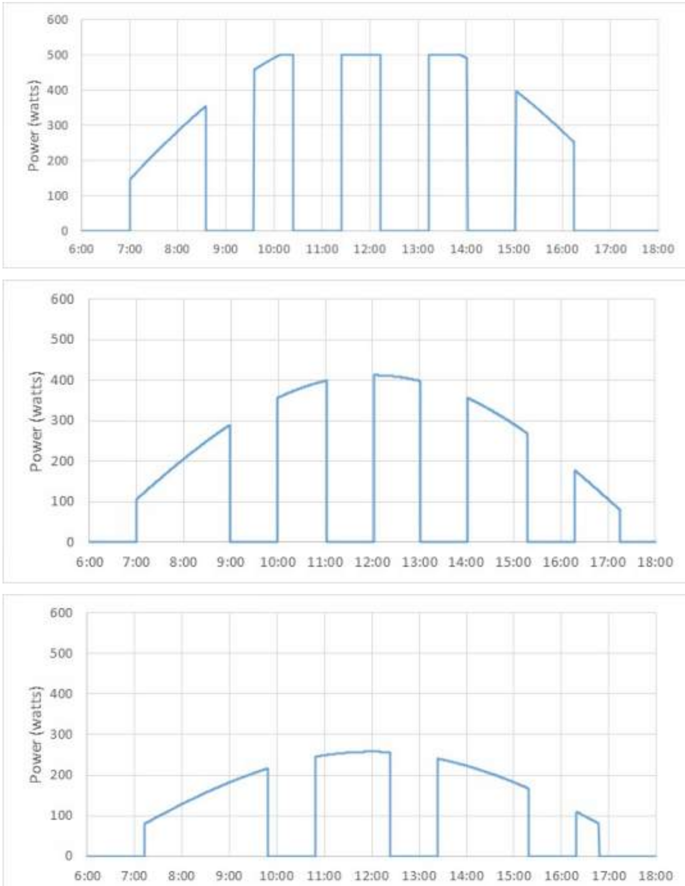

Figure C.**4**: Operational simulation for battery-free OGSECS with 800Wp solar panel. The top graph is for high sunshine day, the middle graph is for a medium sunshine day, and the bottom graph is for a low-sunshine day.

Under high-sunshine conditions, all five dishes are fully cooked, though the dishes at the beginning of the day and at the end of the day take longer because of the low power output of the solar panel at those times. The middle three dishes are cooked at power rates that are equal or close to the maximum power of the cooker of 500 watts. For high sunshine, the average power-on time for each dish is 1.05 hours and 46% of the total available solar power is utilized.

Under low-sunshine conditions, only three dishes can be cooked, with the average power-on time for each dish being twice as long at 2.11 hours and with a peak cooking power of only 257 watts. A larger fraction of the solar resource is utilized at 63% but only 62% of the cooking demand is satisfied.

Under medium sunshine conditions, the results are roughly halfway between the high sunshine and low-sunshine cases.

System with LTO battery

Example simulations for the OGSECS with a 240Wh LTO battery and a 600Wp solar panel are shown in Figure C.5 for the medium cooking demand scenario. When the battery has charge, it supplies the load at full power, and when the battery is discharged, it regulates power to the cooker by switching the output terminals to the load on and off so that on average the power to the load matches the input power from the solar panel.

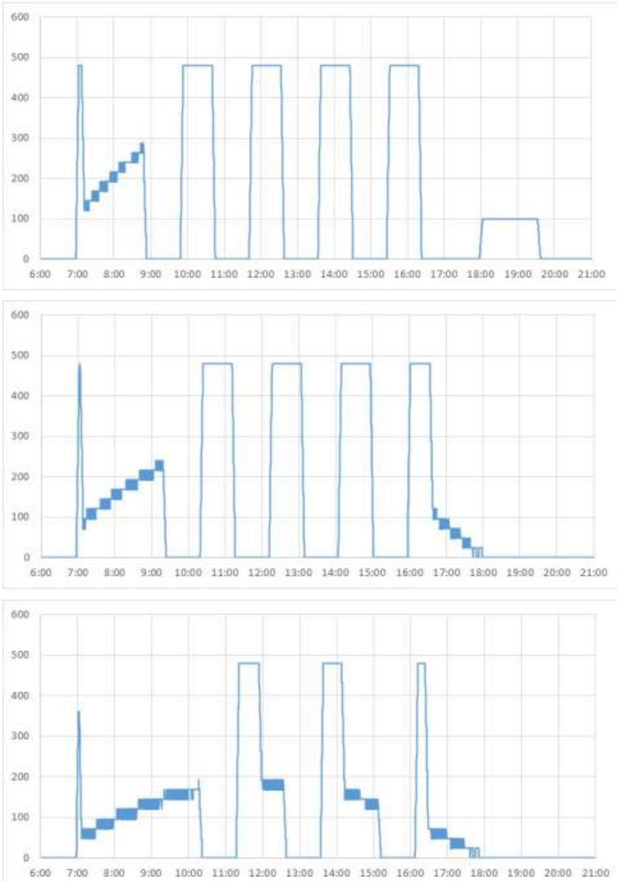

Figure C.**5**: Operational simulation for an OGSECS with a 240Wh LTO battery and a 600Wp solar panel. The top graph is for high-sunshine day, the middle graph is for a medium-sunshine day, and the bottom graph is for a low-sunshine day. The top graph illustrates the existence of an after-hours non-cooking load that can be served by the battery in addition to satisfying cooking demand on a high-sunshine day.

Under high-sunshine conditions, all five dishes are fully cooked, though the dishes at the beginning of the day and at the end of the day take longer because of the low power output of the solar panel at those times. The middle three dishes are cooked at power rates that are equal or close to the maximum power of the cooker of 500 watts. For high sunshine, the average power-on time for each dish is 1.07 hours and 66% of the total available solar power is utilized. The LTO battery cycles 2.9 times per day in this case.

Under low-sunshine conditions, only a little over three dishes can be cooked, with the average power-on time for each dish being more than twice as long at 2.31 hours. Almost all of the solar resource is utilized at 94% but only 69% of the cooking demand is satisfied. The LTO battery cycles 2.0 times per day.

Under medium sunshine conditions, almost all five dishes and 98% of cooking demand is satisfied, with an average power-on time per dish of 1.43 hours. About 83% of the available solar resource is used in this case, but after satisfying the cooking demand, there is no remaining available electricity storage for other nighttime loads. The LTO battery cycles 3.2 times per day in this case.

System with LTO + LFP batteries

Figure C.6 shows the load output results for a 600W system with both a 240 Wh LTO battery and a 50Ah 12.8V LFP battery. This system has enough electricity storage to store some energy from day-to-day on average. Thus, in these simulations we assume a starting energy storage of the batteries that equals the average of the ending energy storage of the batteries. On a high-sunshine day, there is enough solar panel energy to both supply the full cooking demand and to fully charge the batteries. On a medium-sunshine day there is enough solar panel energy to supply cooking demand and provide some charge to the batteries. On a low-sunshine day, there is not enough solar panels energy for the cooking demand, but some of the initial battery charge from the previous day (on average) can help supply the cooking demand.

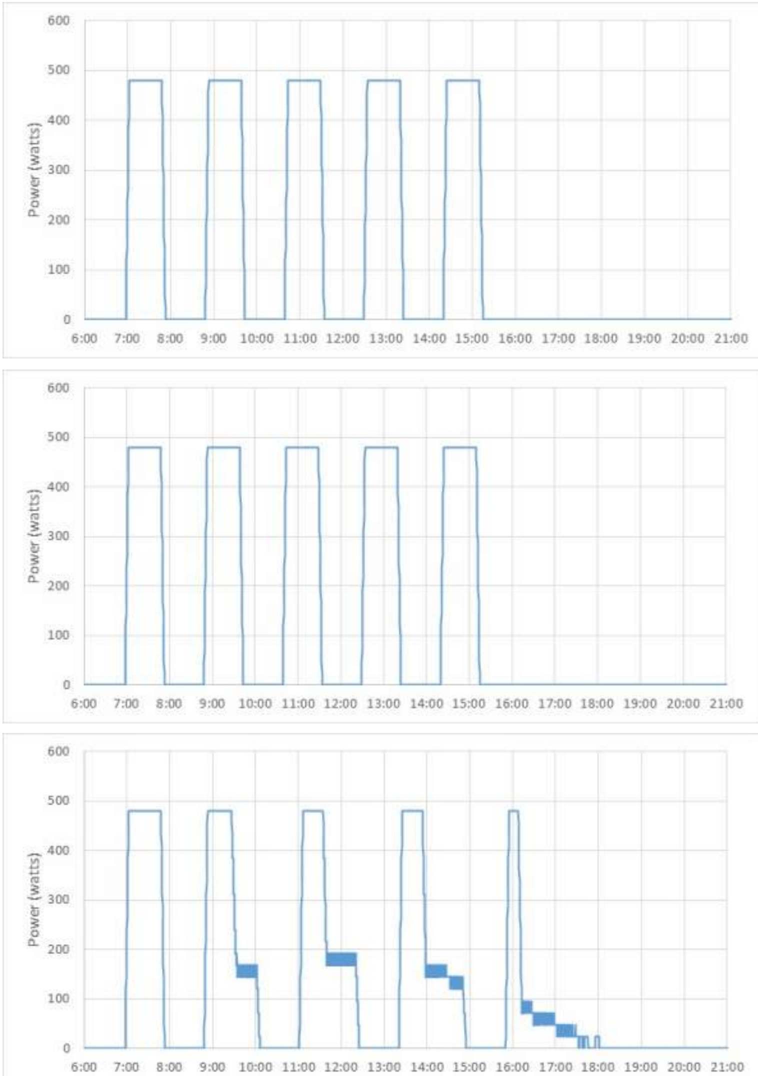

Figure C.**6**: Operational simulation for an OGSECS with a 240Wh LTO battery a 640Wh LFP battery and a 600Wp solar panel. The top graph is for high-sunshine day, the middle graph is for a medium-sunshine day, and the bottom graph is for a low-sunshine day. The simulation estimates the initial charge state on an average day as 66% SOC for the LTO battery and 53% SOC for the LFP battery. This allows the first dish of the day to be cooked at full power for all sunshine levels.

Under high-sunshine and medium-sunshine conditions, all five dishes are fully cooked at full power. For high sunshine, the average power-on time for each dish is 0.84 hours. Meanwhile 59% of the total available solar power is utilized for cooking on a high-sunshine day and 82% is utilized for cooking on a medium-sunshine day.

Under low-sunshine conditions, only a little over four dishes can be cooked, with the average power-on time for each dish being almost twice as long at 1.54 hours. In this case, all of the solar resource is utilized, while a significant amount of the cooking energy requirement is supplied by inter-day energy storage, and 91% of cooking energy demand is satisfied.

For the high-sunshine case the LTO battery cycles 2.6 times, and the LFP battery cycles 0.75 times. For medium sunshine case, the LTO battery cycles 3.7 times and the LFP cycles 0.86 times. For the low-sunshine case, the LTO battery cycles 3.1 times and the LFP cycles 0.30 times.

Combining simulation results with the component-based cost model

The component-based cost model provides estimates of the $/Wp investment cost of an OGSECS for different configurations and component sizes. Meanwhile the operational simulation model provides the average amount of daily utilized energy for high, medium and low sunshine conditions. Therefore, to calculate the levelized cost of electricity (LCOE), we multiply the investment cost per Wp by an annual cost recovery factor (CRF) to estimate the annualized investment cost per Wp. Similarly, we take the average daily utilized energy divided by the Wp of the solar panel capacity and multiply it times 365 days/year to estimate the annual kWh of energy use per Wp of capacity. The ratio of these two values provides an estimate of LCOE.

Different system components have different lifetimes: specifically, we assume a 10-year lifetime for the solar panels and MPPT and a five-year lifetime for the EPC. We multiply each component cost by its corresponding CRF to get the annualized cost for that component.

Sensitivity analysis of model outputs

In this section we perform a sensitivity analysis of key model outputs as a function of model assumptions and inputs parameters. A system feature that is easy to vary is the total capacity of the solar panels in the system. Meanwhile our key metric is the per-kWh LCOE. Thus typically, we will illustrate simulation model results as a curve that represents the LCOE as a function of the solar panel capacity in the system with the capacity of the MPPT and EPC generally fixed at 600W and 500W unless otherwise specified.

We first illustrate the sensitivity with respect to cooking demand scenario, and then we look at sensitivity with respect to cooker peak power.

Cooking demand scenario sensitivity

Figure C.7 illustrates the sensitivity results for a 240 Wh LTO OGSECS system with respect to the basic cooking demand scenario of either 4 dishes at 300 Wh per dish, 5 dishes at 400 Wh per dish, or 6 dishes at 500 Wh/dish. The key take-away from the results is that the system appears to be over-sized for the low-demand scenario, thus the LCOE is relatively high for the low demand case. We note that the LCOE drops by more than 30% going from the low-demand to the medium-demand scenario for systems with a solar panel larger than 600Wp.

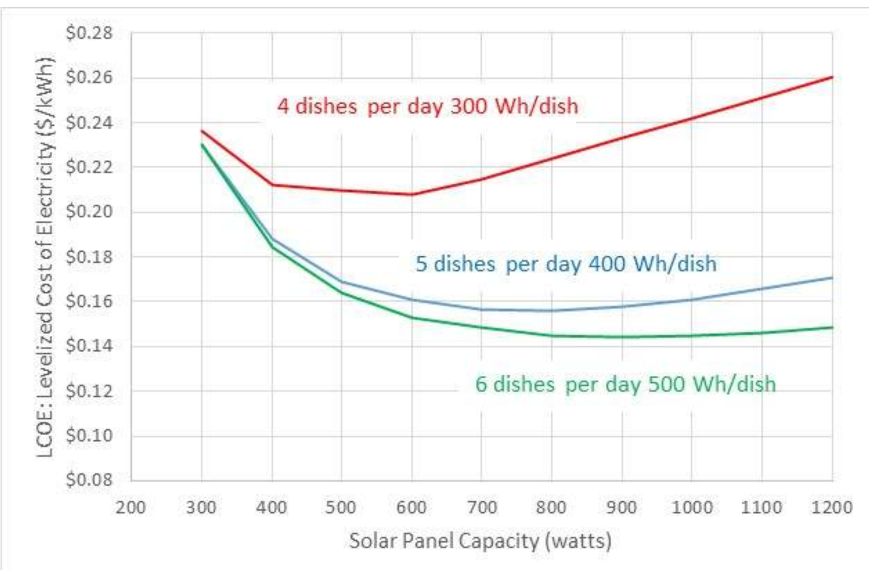

Figure C.7: Sensitivity of LCOE with respect to demand scenario for a 240 Wh LTO OGSECS for systems with different solar panel capacities.

We note that for both the medium-demand scenario and high-demand scenario has approximately the same LCOE. This is because the system only has enough capacity to satisfy the medium-demand, and for the high-demand scenario, a significant portion of demand is not satisfied.

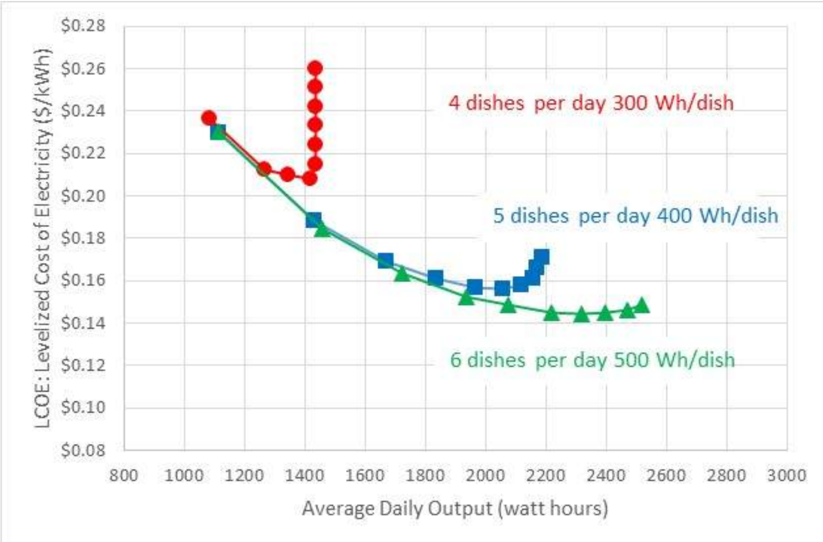

Figure C.**8**: The same as Figure C.7, but now the horizontal axis is the average daily power output of the OGSECS. Note that they key factor that influences a decreasing LCOE is increasing system output that is utilized by the customer. This includes both cooking demand and any excess nighttime energy that may be remaining in the battery after sunset that may be used either for other loads or for early morning cooking the following day. Symbols represent systems with different solar panel capacity, with capacity starting at 300Wp and increasing in increments of 100Wp from left to right.

Figure C.8 illustrates how a key factor influencing LCOE is the total utilized system output. As utilized system output increases from 1100 Wh/day to 2500 Wh/day, LCOE decreases from $0.23/kWh to less than $0.15/kWh, a 35% decline.

Sensitivity with respect to time between cooking events

Figure C.9 shows the impact of changing the spacing between cooking events for an OGSECS with a 240 Wh LTO battery for the medium demand scenario of five 400 Wh cooking events

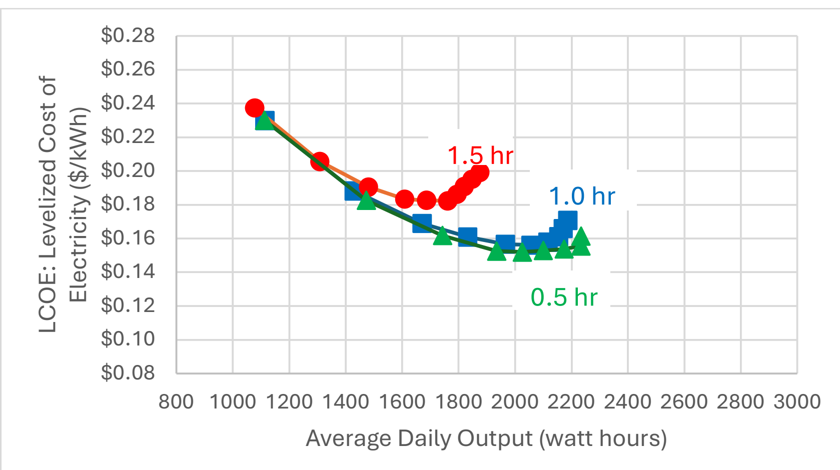

Figure C.**9**: Sensitivity analysis of changing the time spacing between cooking events. The baseline case is 1.0 hours between cooking events. There is essentially no change from decreasing this time spacing, yet increasing the spacing results in less power output from the OGSECS.

The sensitivity analysis shows that there is essentially no change from decreasing the times between cooking events lower than 1 hour for the medium demand scenario. But when the time between cooking events increases from 1 hour to 1.5 hours, the average daily energy use decreases by about 15%, and the corresponding LCOE increases by a corresponding 18%.

Sensitivity with respect to cooker peak power

A key characteristic of the cooker in an OGSECS system is its peak power. A high-powered cooker will be able to cook dishes more rapidly and will satisfy demand more quickly. This has an impact on the usable daily output of the OGSECS and the corresponding LCOE as shown in Figure C.10 below.

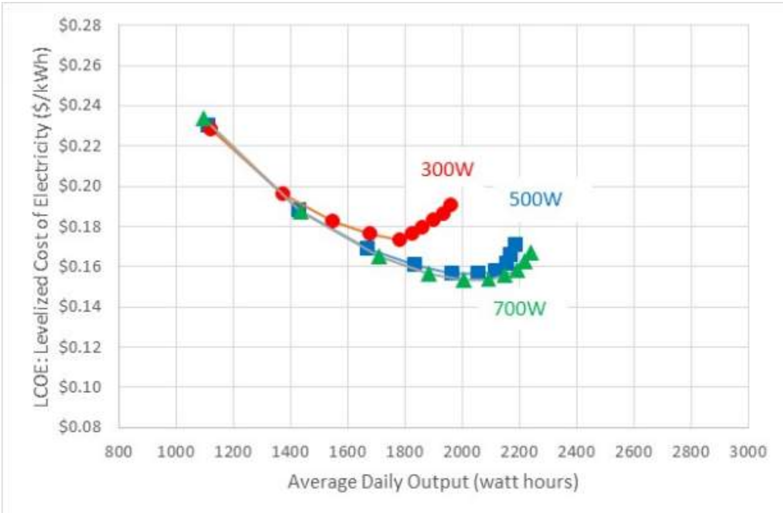

Figure C.**10**: Sensitivity analysis of changing cooker peak power. There is a significant increase in OGSECS output going from 300W peak cooker to a 500W peak cooker, but little improvement is seen increasing further to 700W.

The sensitivity analysis of impact of changing the peak power of the cooker assuming that the unit cost o the cooker does not change. The minimum LCOE for a system with a 300W cooker is $0.173/kWh compared to $0.156/kWh for an OGSECS with a 500W cooker, an 11% increase,

Summary

The operational simulation model takes the characteristics of different OGSECS configurations, applies a particular cooking energy demand scenarios and then estimates how much of this demand can be supplied by the OGSECS system.

Combining the results of the operational simulation model with the results of the component-based delivered system cost model allows an estimate of the OGSECS LCOE as a function of system characteristics such as solar panel and other operating parameters of the system. The LCOE is most sensitive to average utilized daily system output. Thus, optimizing user behaviour for high levels of system utilization is THE key factor in obtaining very low LCOE values for such stand-alone solar systems in the rural African context.

Appendix C References

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Appendix D: Initial Impact Bond Agreement

Introduction

A revised version of this Impact Bond Agreement will be implemented from October 2025 through December 2026.

Core Agreement

This agreement is between Solar4Africa.org (the Impact Lender, S4A) and Kachione LLC (the Implementer, KLLC), where S4A agrees to provide up to $40,000 in financing for creating and measuring solar system benefits for low-income rural Malawians.

The financing is in the form of an "Impact Bond" (the Bond) where S4A provides a line of credit for solar equipment procurement that can be repaid either in cash, or as Impact. The interest on Bond funds utilized by KLLC is charged at a rate of 1%/month, compounded monthly. Impact is credited at a rate of $1 of repayment for every $10 of Verified Economic Benefit (VEB) that is verified for qualified KLLC customers and their community.

An addendum to this agreement specifies the methods that KLLC can use to create the VEB that KLLC can use to repay all or part of the Bond funds borrowed by KLLC.

Any Bond funds drawn by KLLC must be repaid in full with interest within 24 months of the withdrawal date of the funds. Any repayment made by KLLC (either in cash or in VEB impact) will be credited against the principal and interest of those funds with the earliest withdrawal date.

Any use or withdrawal of Bond funds will be documented by a communication between the directors of KLLC and S4A that will function as a withdrawal receipt. S4A will keep a record of all such receipts and shall provide a quarterly accounting update of the line of credit that includes amount withdrawn, amount repaid, interest charged, net balance of utilized funds, and net credit line remaining and available for withdrawal.

S4A at its discretion may notify KLLC, of an increase in credit line when additional funds become available for the financing scheme.

Outline of VEB Crediting Method

A VEB, or Verified Economic Benefit, shall be estimated through measurement or estimation of kWh of off-grid solar electricity use for certified KLLC customers.

KLLC customers that are eligible to be certified for VEB repayment shall be customers that have bought a solar product from KLLC after January 1, 2025 where the following documentation is available:

1) A purchase receipt
2) Name and phone number of a valid contact.
3) Village, T/A & GPS coordinates of where the solar system is kept.
4) Verification of solar system use either through a phone call or visit from staff or contractors.

KLLC shall provide S4A with a list of customers that it proposes to be certified. KLLC shall periodically update the list of certified customers. S4A shall certify the customers after verifying that sufficient information has been provided for each customer and that they qualify.

At the expense of S4A, S4A shall conduct random verification checks of certified customers as necessary to estimate a verified to certified ratio (***RV2C***). The ***RV2C*** is the ratio of the number of customers that pass a verification check to the total number of certified customers for which a verification check was attempted.

The loan repayment credit that KLLC can claim shall be $1 for every $10 of estimated VEB times the ***RV2C***.

VEB shall be estimated using an impact factor (***ImpF***) that is expressed in units of USD per measured kWh, where ***VEB = ImpF x MkWh***, where ***MkWh*** is the measured or estimated kWh of solar system use.

ImpF is a product of three factors:

1) the Usage to Measured kWh ratio (***RU2M***),
2) the Benefit per kWh of usage (***BpU***), and
3) the Benefit Certainty Factor (***BCF***).

where:

ImpF = ***RU2M*** x ***BpU*** x ***BCF***

ImpF can vary with customer characteristics, type of solar equipment being used, type of kWh measurement that is made, and the sampling and measurement protocol for collecting measurement data.

S4A shall provide KLLC with the ***ImpF*** values that it can use for different customer types, solar system types, kWh measurement or estimation methods and different data collection protocols.

Initial per-KWh Crediting Schedule

This section provides a rough estimate of the VEB-based crediting schedule for different certified customers VEB estimates and measurements. Two key factors influence the variation in crediting rates. First, for the more difficult measurements, it is likely that there is unmeasured system use that occurs, thus ***RU2M*** is larger. Secondly, for the more approximate measurement methods, there is greater uncertainty that the estimates or measurements accurately depict use, thus ***BCF*** is smaller.

There are four measurement protocols that will be used:

1. Verification of typical system use through interviews and field verification that the equipment shows normal wear and tear.
2. Metered use, where the meter data is collected via phone or WhatsApp communications.
3. Metered use with a visit of monitoring staff who can verify proper system and meter operation.
4. High-time-resolution metering with a data logger.

There are two solar systems that can earn VEB's for this contract. A solar-electric cooking system, and a solar-pumping system. The solar pumping system provides at least twice as much economic benefit per kWh as the solar cooking system.

Crediting Schedule

For the solar cooking system:

- Unmetered usage estimate: $0.05/kWh
- Phone-verified metered estimate: $0.10/kWh
- Field-verified metered estimate: $0.15/kWh
- Datalogger-verified estimate: $0.25/kWh

For the solar pumping system:

- Unmetered usage estimate: $0.10/kWh
- Phone-verified metered estimate: $0.20/kWh
- Field-verified metered estimate: $0.30/kWh
- Datalogger-verified estimate: $0.50/kWh

Appendix E: Power Meter and LTO Battery Log data

Introduction

KLLC has monitored OGSECS energy use utilizing two completely independent measurement and data collection techniques.

The least expensive and simplest monitoring method is to use a cumulative power meter, specifically a PZEM-031. KLLC purchases the electronics unit and then adds input and output leads and encases the meter electronics in clear epoxy resin for durability and ease of installation. The resulting meter is illustrated in Figure E.1. The delivered cost of this meter is approximately $10.

The PZEM-31 measures and displays four quantities: instantaneous voltage, current, and power along with cumulative energy. Even as the power flowing through the meter turns on and off, the meter has a small memory that stores the previous energy reading when it turns off. When the meter turns back on, the cumulative energy reading begins counting from the previous reading after it turns on. The cumulative energy can be reset with a reset button. The cumulative energy reading is displayed in units of watt-hours (Wh) when the measurement is between 0 Wh and 9999 Wh inclusive and displays in units of kilowatt hours (kWh) from 10 kWh to 9999 kWh of cumulative energy.

Figure E.1: A PZEM-031 meter that has been encased in clear epoxy resin in Malawi. The energy measurement is in Wh. After 9999Wh, the units switch to kWh.

As described in the *Empowering Efficiency Phase II* report [7], KLLC is assembling both 5-cell and 8-cell LTO batteries which have operating voltages of 11V-13V and 17V-21V respectively. The batteries have a custom, programmable battery management system (BMS) that can record high-time-resolution operational data on an SD card. This data aids both the diagnosis of technical issues with battery operation and use, and it can be used to verify solar system usage behaviour.

LTO battery technical challenges and improvements

At the end of the *Empowering Efficiency Phase II* project the LTO battery operational and data collection capabilities and features were adequate but less than ideal. Some of the technical issues that had room for improvement at the end of that earlier project were as follows:

- 12V LTO batteries did not have the power capacity to operate cookers at desirable levels of power (i.e. ~300W).
- 18V to 12V converters for powering 12V loads (like lights and cell phone charging) were found to be somewhat unreliable.

- Data file management was primitive: i.e. a blank file needed to be present on the SD card for the BMS software to write data to the card, and any interruption of data recording would lead all data writing to stop until the SD card was removed and re-inserted.
- Standby power use was sufficiently large to discharge the battery within a few days.
- Charge port and discharge port controls were allowing battery discharge through the charge port and battery charging through the discharge port; and
- The battery would turn off due to an over-discharge condition too quickly when the battery is highly loaded.

Thus, several technical improvements in LTO design and operation were explored in the present project, including the following:

- Adding thermally conducting epoxy to the power electronics to decrease operating temperatures and increase the current and power capacity of the battery.
- Programming of more sophisticated data recording and data file management with no need for a blank file on the SD card. In addition, both the battery serial number, data recording start time, and data recording end time are recorded in the file name. Furthermore, implementation of an automatic re-start of data recording when data recording is interrupted.
- Replacement of the battery voltage indicator with LED charge indicator lights to decrease standby energy use.
- Implementation of a sleep mode in the operation of the battery when battery cells drop below 1.85V/cell to help avoid over-discharge of cells from standby power use.
- Use of a battery cell resistance estimate and current measurements to adjust the determination of the over-discharge voltage when the battery is heavily loaded.
- Both battery voltage and charge port voltage are now logged in the SD data recording. When the battery is fully charged, the battery is disconnected from the charge port and the charge port voltage may be very different from the battery voltage. This allows the battery to record the voltage of the solar panel, parallel loads or the MPPT output voltage when the battery is fully charged.

Implementation of these technical improvements in LTO battery operation and design was completed in early August 2025.

Collection of power meter data

KLLC began collecting meter data from customers at the end of July 2025. As shown in Figure 9 of the main report above, most regular customers are not actively prioritizing and utilizing the cookers in their system. This is likely because these customers purchased the system in order to obtain a subsidized price for the solar panel. KLLC plans to solve this issue going forward by decreasing the subsidy for regular customers and signing a sales agreement with the customers where the solar panel is on loan, with future loan payments subsidized only if cooker use is clearly verified.

As of the writing of this report, KLLC is starting to have technicians visit OGSECS customers to conduct a “Cooker Use Check” where proper functioning of the cooker system with meter is verified, The customers are asked some simple questions about system use, and the cumulative energy reading on the meter is recorded by the visiting technician.

A copy of selected columns of the raw Cooker Use Check data is provided in a data file posting at:

https://www.researchgate.net/publication/397091136_Cooker_System_Cumulative_Energy_Use_Data_LTO_Battery_Log_Data_for_Selected_OGSECS_Customers

LTO battery deployment and collection of log data

As described in the main report, in early 2025, KLLC notice a fairly high level of diversion of subsidized cooking system equipment to primarily non-cooking uses for a substantial fraction of regular customers. And since making LTO batteries affordable also involves a subsidy for many customers, KLLC was hesitant to distribute large numbers of LTO batteries to cooking system customers until it could be verified that the customers were using the cooker system primarily for cooking.

In addition, discussions with customers clearly indicated that if the LTO battery could also be used for lighting and phone charging, this would be a much-desired improvement in the perceived benefits of the battery. In Malawi, 12V solar lights and phone chargers are inexpensive and readily available in the market. This means that lights and phone chargers can be most easily used with the 12V LTO battery.

Therefore, in August 2025, KLLC pursued the strategy of adapting the 12V LTO battery for use with both cooking and solar lights. As part of this strategy, it implemented an initial test deployment with a set of 20 Women's Group customers that had high levels of verified cooking system usage with their battery-free OGSECS. In order to use the 12V LTO battery for cooking. In this test deployment, a 12V to 18V DC/DC converter was added to the system to provide higher voltage to the cooker. At 18V, the cooker operates at approximately 300 watts while cooking. At 12V, the cooker operates at approximately 120W.

During and after deployment of the 12V LTO batteries three problematic issues arose: (A) The standby power the DC/DC converter drained the battery and prevented it from supplying lights at night (so a switch was added), (B) the converter or battery had apparent durability issues, and (C) a drained battery would sometimes reach a low voltage that was outside the operating range of the MPPT, which would prevent the MPPT from providing large amounts of charge current for recharging the battery.

These LTO battery challenges helped motivate KLLC to organize a series of the parallel system tests at the KLLC workshop which were used to evaluate the relative performance of a fairly large variety of system configurations: with and without battery, with and without MPPT, and with and without DC/DC converters. These parallel system tests were undertaken in late September 2025. The results of these tests are described in the "Workshop OGECS test results" section of the main report.

Two key conclusions of the workshop test results are guiding future OGSECS deployment plans as of October 2025.

The first guiding conclusion is that two cookers are better than one, especially in a battery-free system. Thus, for the 20 Women's Group customers who had the problematic LTO battery deployments, the 12V LTO batteries and DC/DC converters were removed, and a second cooker was added to their system.

The second guiding conclusion is that best battery for cooker use is an upgraded 18V LTO with the BMS power electronics embedded in thermally conducting epoxy. As of October 2025, KLLC is in the process of assembling 100 such batteries for future deployment with primarily Women's Group customers. KLLC will also import solar lights and phone chargers that can operate at a wide range of input voltages so that they can be connected to the 18V

LTO batteries without a DC/DC converter. The addition of the lights and phone chargers will help assure that the 18V batteries provide additional much-desired benefit to customers.

Meanwhile, the 12V LTO batteries can be redirected for use in systems with smaller 12V solar panels that power lights, DC/AC inverters, and 12V cooking appliances like small 12V rice cookers, insulated water heaters or thermoelectric food coolers/warmers. 12V cooking appliances of up to 200W can probably be easily accommodated by the 12V LTO batteries.

Access to selected field data

During the abortive deployment of 12V LTO batteries with DC/DC converters for cooker use, LTO battery data was collected. We compiled an illustrative example of some of the data collected during the field deployment. The raw data is available on ResearchGate along with a spreadsheet of the cumulative meter data that has been collected to date. The link for the posted data is: https://www.researchgate.net/publication/397091136_Cooker_System_Cumulative_Energy_Use_Data_LTO_Battery_Log_Data_for_Selected_OGSECS_Customers

The file names of individual battery data logs and notes regarding the posted files are provided in Table E.1 below.

Table E.1: Details of posted customer energy use data (with identifying customer information removed).

File Name	Notes
0_RawCustomerMeterData_20251030	Readings of cumulative meter data
Log_5S-dv12-00007_start2508161121_end2508210607 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00007_start2508210612_end2508300615 - Battery Data	DC/DC converter installed on 2025-08-27
Log_5S-dv12-00007_start2508300623_end2509050727 - Battery Data	Apparent normal use
Log_5S-dv12-00007_start2509050802 - Battery Data	Looks like stopped using cookerafter 2025-09-09
Log_5S-dv12-00011_start2508161055_end2508201525 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00011_start2508201539_end2508281536 - Battery Data	Looks like continuing over-discharge and undercharging issues
Log_5S-dv12-00011_start2508281541 - Battery Data	Looks like cooker was operated mostly in low-power mode
Log_5S-dv12-00014_start2508161051_end2508210613 - Battery Data	Looks like some over-discharge issues
Log_5S-dv12-00014_start2508210624_end2508290735 - Battery Data	Installation successful on 2025-08-27
Log_5S-dv12-00014_start2508290755 - Battery Data	Cooker use stopped on 2025-09-19
Log_5S-dv12-00018_start2508161122_end2508200243 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00018_start2508211023_end2508271133 - Battery Data	Looks like continuing over-discharge and undercharging issues
Log_5S-dv12-00018_start2509120707_end2509231604 - Battery Data	Low levels of cooker usage
Log_5S-dv12-00018_start2509231604_end2510091021 - Battery Data	Only occasional cooker usage
Log_5S-dv12-00018_start2510091121 - Battery Data	Mostly used for lights at night
Log_5S-dv12-00021_start2508161120 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00022_start2508161116_end2508211126 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00022_start2508211131_end2508271447 - Battery Data	Continuing over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00022_start2508271503 - Battery Data	MPPT stopped working properly at low battery voltage
Log_5S-dv12-00026_start2511050702 - Battery Data	Battery used only for lights
Log_5S-dv12-00042_start2508210244_end2508230219 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00049_start2508161049_end2508210556 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00049_start2508271024 - Battery Data	Looks like DC/DC converter was removed after 2025-09-10
Log_5S-dv12-00053_start2508161103_end2508211142 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00053_start2508211149_end2508281217 - Battery Data	Looks like over-discharge/low battery voltage/MPPT issue
Log_5S-dv12-00053_start2508281227 - Battery Data	Looks like durability/oprational issues
Log_5S-dv12-00061_start2508161126_end2508211331 - Battery Data	Operating withouth DC/DC converter, or on low power
Log_5S-dv12-00061_start2508211336_end2508271120 - Battery Data	DC/DC converter installed on 2025-08-27
Log_5S-dv12-00061_start2508271126_end2510170756 - Battery Data	After some time, customer used battery mostly for lights
Log_5S-dv12-00079_start2508161144 - Battery Data	Short-time recording (2.5 days of use)
Log_5S-dv12-00079_start2508201638_end2508271035 - Battery Data	Looks like DC/DC converter installed on 2025-08-27
Log_5S-dv12-00079_start2510081907 - Battery Data	Battery only used for lights