Cooking Support on Mini-grids (COSMO): Synthesis report

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Working paper for comment

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Executive Summary

The conclusion of this synthesis report is that eCooking is feasible and cost-effective in many mini-grid contexts and can enable cost savings for consumers and increased profitability for mini-grid operators. Its benefits are particularly evident when it is integrated into mini-grid planning from the start. Comprehensive and realistic technical and financial modelling assessing different levels of eCooking penetration and usage is essential for determining mini-grid upgrade requirements and resulting financial feasibility.

Mini-grids can be an effective means of electrifying remote areas beyond the reach of the national grid. However, they often suffer from low per capita electricity demand, struggling to generate sufficient revenue from electricity sales for financial sustainability. Using electricity for cooking (eCooking) presents a possible solution for increasing demand while also providing customers with health benefits, increased convenience, time savings, and even cost savings depending on cooking fuel costs. This is particularly important for solar powered mini-grids which often have high levels of unused power, especially during the peak daylight hours.

The "Cooking Support on Mini-grids" (COSMO) competition seeks to strengthen the utilisation of mini-grids for electric cooking (eCooking). Phase 1, now complete, funded seven projects to develop business plans for integrating eCooking into planned or existing mini-grids. Awardees were qualified mini-grid developers with experienced, multi-disciplinary teams, who worked for 6 months on these projects, conducting technical and financial modelling of introducing eCooking to mini-grids, as well as exploring social and economic aspects of eCooking adoption at both household and community levels. Phase 2 contributes finance for the implementation of their plans in 4 of the 7 winners, and these funds will be dispersed during 2024 to 2026. Due to the commercial sensitivities of the case studies, we have anonymised the developer teams and refer to each case by its country of presence.

The report summarises technical results on how eCooking loads in Phase 1 were modelled among the 7 participant teams, and their effects on a mini-grid load profiles, design, and financial sustainability, both for integrating eCooking into mini-grid planning for unbuilt systems, and adding eCooking to existing communities. A wide range of assumptions were made around eCooking penetration levels, usage levels, and usage characteristics. Table 1.1 presents key technical modelling aspects of the studies, including assumed eCooking penetration and demand, community demand increase, and resulting upgrade requirements.

Table 1.1: Key technical modelling findings across the studies.

	Study	Customers	eCooking %	Daily average eCooking demand (kWh/HH/day)	% increase total demand	PV capacity % increase	Battery capacity % increase
New Build	Project 1 Portfolio	2,605	50	0.73	157	33	23
	Project 2 Portfolio (case study)	28 mini-grids (2,000)	10	1.94	34	47	0
	Project 3 Portfolio (case study)	30,000 (150)	50	0.36	45	N/A Assumed 0	N/A Assumed 0
Existing	Project 4	84	26	0.65	34	50	21
	Project 5	3,783	7	30% increase	2	0	0
	Project 6	124	85	3.24	N/A	104	70
Hydro	Project 7	533	71	0.96	220	N/A	N/A

Reading the table – a high percentage of ecooking is considered good in column 4, as is increased total demand in column 6. Since batteries are often a significant expense, the need to not increase battery size is considered good in column 8.

Generally, it was found that introducing eCooking increased household electricity demand, and in turn, community-wide demand (both considered a good thing by developers), as well as increasing peak community demand (which was not always considered helpful). For most studies, upgrades to mini-grid infrastructure (solar PV capacity, battery storage capacity) were required to accommodate the increased peak demand. The outcomes are context specific, and it is clear even from Table 1.1, that for instance, for Project 6 to upgrade a small grid to accommodate eCooking for about two thirds of its consumers, it would have to double the PV panels and increase the battery size by about two thirds. The introduction of eCooking in this context would significantly increase the CAPEX. However, in contrast a significantly larger network of grids in Project 1 reaching almost 25 times the households of Project 6, would require only a one third increase in PV Panels and 20% increase in batteries. The resulting impact on the mini-grids would be a very significant 150% increase in demand.

However, does this increase in demand translate into increased revenues and overall financial security? Table 1.2 presents key aspects of the financial modelling conducted by the developers, providing percentage increases in key indicators where possible, and monetary figures where no baseline scenario was presented.

Table 1.2: Key financial modelling results across the studies.

	Study	Project period (years)	CAPEX % or USD$ increase	OPEX % or USD$ increase	Revenue % or USD$ increase	NPV % or USD$ increase	Payback period
New Build	Project 1 Portfolio	15	6.7	71	157	485	-56% (9 years to 4)
	Project 2 Portfolio	24	9	14	25	20	+18% (11 years to 13)
	Project 3 Portfolio	22	0	0	45	IRR +3%	-33% (9 years to 6)
Existing	Project 4	10	USD 31,250	-34	182	213	+125% (4 years to 9)
	Project 5	10	0	5.7	4	IRR +1.95%	2 years (no change)
	Project 6	10	USD 71,782	USD 15,704	USD 79,917	USD -53,563	18.4 years
Hydro	Project 7	N/A	USD 240,313*	USD 2,932	224%* (up to USD 24,557)	reduces	increases by 10 years or more

*while revenue greatly increases, the extra CAPEX (on transformers and wiring, not generation) is disproportionately high and greatly reduces its attractiveness.

While increases in demand translated into increased revenue, some of the key financial metrics were also very context specific. Project 1, cited above as increasing its demand by 157%, does indeed project a corresponding increase in the revenue (of 157%). A relatively small increase in CAPEX (6.7%) albeit with a relatively high increase in OPEX (71%) means the extra revenue makes the whole mini-grid portfolio much more viable than without eCooking. The payback period reduces from 9 years to 4 and there is a very substantial increase (nearly 500%) in the Net Present Value (NPV) of the development. For Project 3 there is a very detailed investment model, and while increased revenue could reduce the payback period (with existing investment offers), the developer felt that the relatively modest inclusion of eCooking would ensure more favourable investment terms.

However, that good news example potentially masks complexity. Other systems such as Project 2, found that introducing a more modest penetration of eCooking (10%), would require similar upgrades on the CAPEX (9%) (although a modest increase in OPEX (14%)) but would generate much less extra revenue than in Project 1. This output of the financial modelling is confounded by a planned reduction in tariff. Overall, the NPV only increased by 20% and the payback period actually extended by 2 years. Project 4, with its small existing grid, 26% eCooking penetration and low value CAPEX upgrade, reduces its OPEX, has greater revenues (182%) but increases its payback from 4 years to 9 years.

The studies range from 7% to 81% penetration of eCooking and there is no direct correlation between that penetration and financial viability. Increases in CAPEX and OPEX vary across all the studies and again there is no simple relationship between such upgrades and financial stability. As expected, each mini-grid analysis was context specific. What we can see is that in all cases the introduction of eCooking increases revenue. Such an increase in revenue varies from modest to significant and does not always result in a lower period of time to reach payback. It does however generally enable increased NPV and/or Internal Rate of Return (IRR).

Of the projects described above, four have been taken on to Phase 2 where MECS will contribute finance to the building or upgrading of the mini-grid based on Phase 1. If these projects succeed in including eCooking, they will help 28,000 people to access renewable energy and include Tier 5 stoves as part of their daily experience. Assuming only one meal a day is cooked with the mini-grid, then 2,300 tonnes of wood per year would be saved, over 10,000 tonnes of CO2 equivalent emissions and approximately 70,000 hours of women time saved per year and released for other activities (Based on the BARHAP model). The BARHAP model does include fuel stacking, but it was not possible to say how many Disability-Adjusted Life Years (DALYs) would be saved per year, by that partial use of eCooking. Nevertheless, the net social benefit could be monetised at $26,000 per year – and that is an externalised benefit that none of the financial modelling above took into account.

The following specific findings were identified from the technical and financial modelling:

Adding eCooking to existing mini-grids can appear challenging due to upgrade requirements, whereas integrating high eCooking penetration into mini-grid portfolio planning from the beginning can greatly improve the business case.

As discussed above, in Project 1, assuming 50% eCooking penetration, with two or more EPC usages per day, eCooking reduced the payback period for the unbuilt project from 9 years to 4 years, and tripled the IRR. The increased CAPEX for PV and battery storage upgrades were modest at $300K on a $2.8m project development. Therefore, vastly increased energy sales from eCooking can outweigh increased capacity requirements, and enable profitability relatively quickly.

Similarly, integrating eCooking into mini-grid portfolio planning increases revenues and reduces average tariff for cost-recovery, and improves the case for investment. Higher levels of eCooking reduce payback periods.

In Project 2, eCooking increased revenues and NPV for the unbuilt mini-grid portfolio, and improved the proposition for investors due to larger CAPEX and therefore ticket size. It also enabled better equity payments, and a reduced average tariff. However, the tariff is still required to reduce further according to regulations, requiring extra support, with carbon finance suggested. The payback period increased due to increased CAPEX, OPEX (higher replacement costs), reduced tariff, and increased equity payments, although a higher penetration of eCooking would likely reduce the payback period.

It is more difficult to upgrade an existing mini-grid after adding eCooking, due to high CAPEX, compared to integrating eCooking into original planning. A contributing factor is needing to reduce daytime tariff to incentivise eCooking, reducing potential revenue from other daytime electricity usage if not targeted at cooks. However, it is still possible to generate a higher NPV over a sustained period.

In Project 4, there was an increase in payback period from 4 years to 9 years, due to the relatively high CAPEX of the mini-grid system upgrades, compared to zero in the baseline scenario, as the mini-grid was already in operation. However, even with only two years of operation beyond the payback period, there was a modelled three-fold increase in the NPV, showing that eCooking can vastly increase profitability in the long term.

If staying within mini-grid load capacity limits, eCooking increases revenue and therefore IRR, but penetration is limited to low levels, so returns are modest.

In Project 5, modelling showed that only 200 HHs (out of 3,000) could adopt eCooking, which would result in a very small increase in IRR.

Projects should not consider very high eCooking penetrations immediately if the CAPEX required for upgrades is too high, while providing eCookers free of charge harms the financial viability of the project and may not generate ownership.

In Project 6, the scenarios integrated 105 eCookers into a community of around 124 HHs, and customers were not charged for eCookers, contributing to a high payback period for the mini-grid, alongside assumptions of unrealistically high eCooking durations and levels of coincidence across households.

eCooking can improve load factor and revenue of struggling micro hydropower (MHP) mini-grids, and grid interconnection can enable energy sales and reduce mini-grid upgrade requirements, meeting demand during peak load periods.

In Project 7, introducing eCooking at high penetration led to an almost 50% increase in revenue. However, distribution system upgrade (transformers) costs and grid connection costs were very high, vastly outweighing increased revenue, so a high level of support was required.

Time-of-use (ToU) tariffs could be used to encourage customers to schedule their eCooking during daylight hours when solar radiation is abundant, reducing reliance of stored battery power, and saving customers money. Some consumers showed willingness to shift their cooking to daytime to the midday period, especially if incentivised to do so, while others said this would be inconvenient/impossible. Demand-side management measures beyond ToU tariffs would be required, such as community engagement/campaigns, SMS alerts to users, timer switches, power limiting, etc. Piloting is required to test practical willingness to cook during the day, and associated DSM measures.

Encouraging daytime eCooking means that higher levels of fuel stacking is likely, and even expected, both in the evenings and in the daytime (when solar insolation is insufficient to meet daytime eCooking demand).

EPCs are very suitable for contexts where the energy supply is limited because they use little energy and consume full power for only a short preheat period of around 15 minutes (and then intermittently during the cooking phase), although induction cookers can also cook efficiently if operated carefully i.e., simmering on low power and using a lid.

eCooking modelling assumptions heavily affect outcomes and must be carefully designed, including accounting for inevitable fuel stacking. Assumptions should consider: starting with a conservative initial number of eCookers especially if introducing to an existing mini-grid; short high-power periods for EPC cooking, moderate levels of coincidence of eCooking across households due to diversity in cooking timings, a low 'after diversification maximum demand' (ADMD) and moderate cooking durations to take into account fuel stacking (reducing the number of eCooking dishes per meal). eCooking load profile modelling should be improved, increasing resolution from hourly (HOMER default), to capture realistic levels of coincidence between cookers being used, and therefore more realistic total demand of eCooking. If hourly resolution is essential, eCooking profiles should consist of averages and ADMD of higher resolution data, to represent moderate coincidence levels.

Mini-grid modelling should also consider employing higher resolution computation than hourly, to capture realistic eCooking coincidence levels, and short spikes in demand from short-duration usage of appliances and machines in mini-grid communities. Generally, HOMER modelling may oversize PV and battery capacity requirements for upscaling eCooking, if high levels of coincidence are specified in hourly eCooking profiles, leading to higher system costs than necessary. Or, put another way, higher penetrations of eCooking may be possible for given mini-grid capacities.

Diesel is expensive, supply chains are vulnerable, maintenance requirements are high, and the transport of diesel fuel requires significant logistics support, especially in rural communities with poor infrastructure. Transitioning from including diesel generators to 100% renewables for new mini-grids is now viable with resilience measures including allowing ~5% capacity shortage, enabling economically sized PV and battery storage capacities.

The second part of the Phase 1 reports synthesised the more qualitative aspects of the business plans, on cultural cooking context, financing, awareness raising, eCooking training, after sales services, and eWaste management, generating the following findings:

In some contexts, consumers pay inflated prices for charcoal and firewood due to geographical isolation and transport costs, creating transferrable expenditure. There is a perception that most people in mini-grid communities collect fuel for no monetary cost, which was found to be untrue.

Focussing on charcoal, average monthly costs ranged from $9.94 to $24.75 across four contexts in Project 1 ($9.94), Project 6 ($10.29), Project 2 ($19.07) and Project 5 ($24.75). Firewood was the predominant cooking fuel in other contexts (Project 4, Project 7 and Project 3) but around one third of consumers were also regularly paying for LPG. Even when firewood is collected for free, reduced drudgery could free up time for income generation, increasing the feasibility of switching to eCooking.

To mitigate the upfront costs of eCookers, asset financing, subsidies, grant funding, and carbon financing should be explored. The mini-grid operator in Project 3 described a system whereby customers are provided appliances on credit according to their credit rating, with the amount of credit and specific terms tailored based on their historical consumption data. The system includes the potential for on-bill financing, described in this case as an option in the event of late repayment, through applying a surcharge to a customer's tariff.

Providing comprehensive after sales services in mini-grid communities is essential but difficult. Without local manufacturing plants with spare parts for repair of eCookers, and with many communities located in rural areas, the organisations explained that the initial focus would be on ensuring the quality and performance of the appliances, and providing comprehensive initial training and support to customers. Therefore, eCooking appliance standards and testing protocols must be introduced which ensure appliances are safe, easy to use, and cook local dishes effectively, reducing the need for repair.

Training local technicians and electricians to provide eCooking appliance repair services must be facilitated, because warranties might require customers to take their eCookers to faraway locations for fixing which is often unfeasible. Local repair centres and appliance shops could established and stocked with an inventory of spare parts, from which appliances could be sold, training provided, and repair services offered.

In Project 7, initial discussions with the eCooking appliance supplier suggested that the supplier would provide repair and maintenance training to one person from the community. In Project 3, the idea of local appliance shops was put forward, from which appliances could be sold, training could be provided at the point of acquisition, and repair services offered. In Project 1 and Project 3 there were plans to provide customers with helplines and email support as well as routine visits from operator technicians to troubleshoot issues.

The studies also touched briefly on household wiring, emphasising the importance of having electricians assess wiring according to standards and implement upgrades where necessary based on load assessments.

The studies highlighted the urgent need to rapidly accelerate progress in eWaste management as eCooking scales, with recycling capability currently limited, especially in remote locations. All studies emphasised the need to repair and reuse eCooking appliances as much as possible. Beyond that, the organisations planned to partner with recycling companies, set up collection points in the communities, raise awareness of eWaste so that cooks do not dispose of broken appliances, and partner with local electrical goods shops which could store spares from defunct appliances. Creative arrangements around eWaste management are required alongside accelerated development of repair and recycling facilities at local and national levels.

Acknowledgements

This synthesis represents work from a myriad of people. While there are 7 cases from 7 countries, each case had a team of people working on it. Due to the commercial sensitivities of the case studies, in this synthesis we have anonymised the developer teams and countries and refer to each case as Project 1, Project 2, etc. While we wish to refrain from naming specific authors or commercial developers, in these acknowledgements we wish to note everyone's contributions and thank them for their work.

ACRONYMS

ADMD - After Diversification Maximum Demand

AMI - Advanced Meter Infrastructure

BESS - Battery Energy Storage Systems

CAPEX - Capital Expenditure

COSMO - 'Cooking Support on Mini-grids' Challenge Fund

HOMER - Hybrid Optimization of Multiple Energy Resources modelling software

IRR - Internal Rate of Return

MECS - Modern Energy Cooking Services (UK Aid funded Programme of research)

MHP - Micro Hydropower

NPV - Net Present Value

OPEX - Operational Expenditure

PV - Photovoltaic Solar Panels for generating electricity

PVSyst - software that calculates energy yields for a given site taking into account solar irradiation and

Temperature through its meteorological database

SACCO - Savings and Credit Cooperative

TES - Thermal Energy Storage

Contents

2 Background

The Modern Energy Cooking Services (MECS) programme is implementing a 'Cooking Support on Mini-grids' (COSMO) competition, the latest in a series of challenge funds that the MECS programme has engaged with. Previous funds have prompted innovation, early research, and piloting, all of which seek to rapidly accelerate the transition from biomass to clean cooking, particularly modern energy cooking services, on a global scale. The "Cooking Support on Mini-grids" (COSMO) competition seeks to strengthen the utilisation of mini-grids for electric cooking (eCooking).

Phase 1 funded seven projects to develop business plans for integrating eCooking into planned or existing mini-grids. Awardees were qualified mini-grid developers with experienced, multi-disciplinary teams, who worked for 6 months on these projects, conducting technical and financial modelling of introducing eCooking to mini-grids, as well as exploring social and economic aspects of eCooking adoption at both household and community levels. This report outlines and summarises findings.

3 Methodology

Seven projects in a variety of contexts and across seven countries were supported. Most focussed on solar mini-grid systems, while Project 7 examined a micro hydropower mini-grid community. There was a mixture of mainland and island projects, providing valuable insights into each community dynamic.

Each of the awardees developed a business plan for integrating eCooking into a mini-grid or portfolio of mini-grids, either already in operation, or in planning. To do so, a variety of methodologies were used. Some projects included trialling of eCooking appliances in communities, while others focussed on surveys and modelling. Methodologies employed included:

- Surveys
- Interviews
- Focus groups
- Mini-grid performance monitoring (using data loggers)
- Household/cooker smart meters
- Market assessment of cookers
- Testing of cookers
- Cooking demonstrations, trainings
- Deployment and monitoring of cookers

This report synthesises the findings of the phase 1 projects, which are detailed in Table 3.1 below:

Table 3.1: Details on the seven COSMO Phase 1 projects

Project	Project Reference	Project Outline
Project 1	Developer 1 Utilization of AC Mini-grids for Electric cooking [1]	This project aims at generating an understanding which will help Developer 1 to design and operate profitable AC mini-grids which incorporate electric cooking. This will, involve collecting information and data which in end will help to answer the question of what sustainable mini-grids which include the e-cooking load could look like. Developer 1 was looking to collect data from different sources to validate some key assumptions on electric cooking and mini-grids profitability from different sources. At the end of the phase, Developer 1 had data and evidence for developing the detailed business plan, detailed modelling of the mini-grid, and a high-level implementation plan for either building a new grid or modifying an existing one.
Project 2	Developer 2 Validating eCooking in Planning and Operations of Solar Mini-grids [2]	Building on its 2019-2020 MECS-funded work, Developer 2 will integrate planning for eCooking into two solar mini-grids. Developer 2's initial findings were extremely promising for eCooking on its solar mini-grids, and this project will expand the feasibility work to both 1) build a new solar mini-grid and 2) expand an existing solar-diesel mini-grid with additional solar capacity, incorporating eCooking loads into the generation system design and operations planning. Specifically, Developer 2 • updated user expenditure data with new surveys of homes, businesses, and charcoal vendors, • conducted preliminary user engagement around optimal tariff and demand-side-management programs specifically for eCooking services, • conducted additional HOMER mini-grid generations system sizing runs + financial model scenarios based on various inputs for eCooking like overall adoption rate and time-of-use constraints, • conducted preliminary research around results-based financing for the gender+carbon+health benefits of the combination of eCooking and a "Feminist Electrification" approach to mini-grid development and operations, • reviewed available information on best appliances, engaged with suppliers, procure and trialed several different models of EPC to enable appliance selection, and • expanded research on optimal metering methods for EPCs. Developer 2 is planning to scale-up its mini-grid operations to serve more than 23,000 new connections in the next 4 years, and favourable eCooking findings will guide Developer 2's planning for those and other future grids. This project will help validate Developer 2's strong hypothesis that electric cooking on solar-powered mini-grids can

		significantly improve the customer experience, reduce climate impacts, and boost the mini-grid business model all at once.
Project 3	Developer 3 Mini-grid Ecooking Applications for Settlements (MEALS) [3]	Developer 3 is a renewable energy engineering and development company dedicated to increasing energy access via clean, reliable, and affordable electricity services to off-grid communities. Developer 3 appreciates the need for sustainable uses of electricity to enhance the benefits of rural electrification via solar mini-grids, and electric cooking represents an important means to reduce indoor air pollution (causing respiratory illness), avoid unsustainable biomass harvesting, and relieve women and girls from their disproportionate role providing labour for extensive collection of cooking fuel. In this program Developer 3 assessed the opportunity to promote clean, affordable, energy efficient ecooking devices, such as electric pressure cookers, alongside other appliances that will be retailed by a subsidiary in the mini-grid communities. This data-driven approach provided the foundation for an exciting and innovative option to modernize and improve cooking practices in Project 3 with consultation and engagement of communities that are experiencing electricity service for the first time.
Project 4	Developer 4 Mini grid resilience through integration of e-cooking loads [4] [5]	E-cooking has the potential to enhance the financial viability and sustainability of mini-grids by increasing demand. For the COSMO competition, Developer 4 proposed to use a mini-grid (13.5kWp PV, 38.4kWh battery storage) which was installed in 2015. This project is run by a co-operative with elected officers, and supported by the utility. The mini-grid catalysed local socio-economic growth with the electrical demand grown from 10kWh/d to over 28kWh/d. The recent survey (Nov 2019) in the mini-grid indicated that a significant number of customers are currently using LPG for cooking. Cooking cost varies across different types of fuels used, mainly dominated by LPG. Integration of e-cooking will open up the opportunity for replacing expensive LPG and environmentally damaging firewood collection in the community while increasing income of the mini-grid through utilizing the excess power generated in the daytime. COSMO funding, will enable the mini grid to accommodate e-cooking expansion coupled with the installation of smart customers meters (or smart meters with automated energy management features). This will enable Developer 4 to test various techno-economic approaches to identify the most suitable model that can be adapted by the planned deployment of 98 mini grids as well as others in the region.

Project 5	Developer 5 E-Pressure Cookers & Solar Mini-grid: Customer behaviors and Power plant performances for a bankable mini-grid' business model [6]	EPCs can significantly contribute to energy demand in mini-grids, improving the financial viability of mini-grids. EPC usage is cheaper for customers compared to conventional cooking fuels especially charcoal which is being used in island settings. Developer 5 has a 600 kWp solar hybrid mini-grid installed in an island and has a pipeline of 15 mini-grid in other islands, where forest cover has greatly been reduced due to cooking needs. Using its existing 600 kWp mini-grid, Developer 5 wanted to understand how its future mini-grids can be technically designed and financially modelled to ensure that EPCs can be sustainably used in its island mini-grids, both existing and future mini-grid projects. On the one hand, it is important to understand customer behaviours and adoption techniques needed for sustainable use of EPCs for mini-grid customers (e.g., tariff level, EPC pricing, usage patterns, etc.). On the other hand, the mini-grid should be able to accommodate EPC inclusion in its technical capabilities (e.g., power plant capacity, distribution line designs, acceptable variations, etc.) and improve its financial returns (quicker payback, better IRR, etc.). Working with a sample of 30 EPCs in its existing mini-grid, Developer 5 will research these customer behaviours and patterns, and the adaptations needed in its mini-grid. With its asset financing partner focusing on EPC distribution and its research partner focusing on all research aspects, Developer 5 will develop a mini-grid business plan and model for eCooking for its current and future mini-grids.

Project 6	Developer 6 Uptake of Modern Cooking Service on Mini-grids: Machine Learning of Redundant Energy for Cooking with Innovative Business Model [7]	In Project 6's context, fuelwood and charcoal represent 80% (national average) of the fuels used for cooking, resulting in high greenhouse gas and black carbon emissions with negative environmental impacts. Indoor air-pollution from the polluting cooking fuels also has negative health impacts on women and their children. In most off-grid communities, mini-grids have been found to be effective in providing energy access. As at the year 2022, 15 mini-grids have been developed in Project 6's context. The Government is planning an additional 35 mini-grids. One challenge of mini-grid deployment is the mismatch between consumer energy demand and energy generation from the PV mini-grids. Batteries are used to store energy in the daytime, and later used for energy supply in the night-time and early mornings. During the daytime sunshine hours, however, when the solar PV mini-grids are generating their maximum power, the demand is usually low because customers will be in their farms/market/businesses. This leads to excess unused energy generation from the mini-grids (redundant energy) when the battery is fully charged around noon time, and demand is low. Developer 6's preliminary investigation showed that redundant energy could support modern cooking using efficient pressure cookers. Previous work on a selected solar-home-system demonstrated the use of redundant energy for household cooking using pressurised solar electric cookers with phase change materials. In this phase, we explore the design requirements through machine learning and sustainable business models for implementing modern cooking on mini-grids.
Project 7	Developer 7 Enabling eCooking in a Micro Hydro Project [8]	Developer 7, a nonprofit umbrella organisation of micro hydro users, wants to enable electric cooking appliances to be sustainably used in homes and businesses in the mini-grid of a member organisation. The mini-grid is a community owned micro hydro power plant (MHP) with its own distribution system. The Generation Cooperative is cooperative registered to operate and manage the MHP. The 68 kW MHP supplies 503 consumers which are mostly domestic consumers with some commercial consumers such as mills, hotels and restaurants. The MHP was initially developed with the objective of energy access and it has been challenging to gain financial sustainability. The financial sustainability of the MHP can be aided with increasing productive end use of the electricity generated such as ecooking. The cooperative will promote, import and sell and provide repair and maintenance facility of e cooking in the community. The project aims dual objective: socioeconomic advantages of cooperative.

4 Review of technical results and modelling

This section focusses on the technical and financial modelling reported by the studies, presenting their eCooking modelling, mini-grid modelling, and financial analysis, and extracting key findings.

The technical models of new mini-grids or upgrades of existing ones were mostly based on operation strategies that maximise the use of PV energy, by adapting the effect of the electric cooking load to the solar energy profile, i.e., during daytime. Existing cooking practice patterns were generally established based on historical data and surveys.

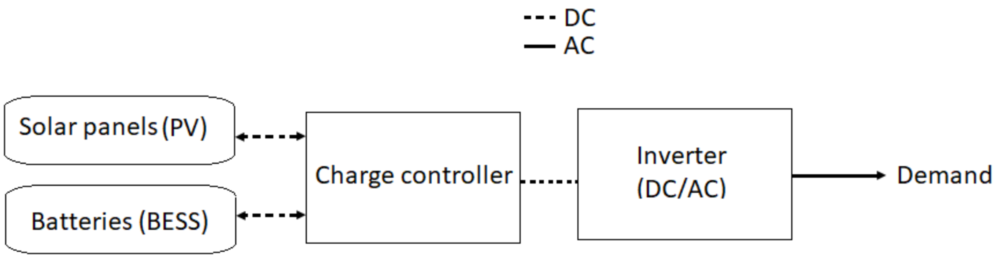


Figure 4.1: Typical solar mini-grid configuration.

Depending on assumptions and demand-side management (DSM) approaches adopted, the increase in average daily demand and peak demand from introducing eCooking required changes in design and operation of the mini-grids. All studies considered a combination of solar PV and Battery Energy Storage Systems (BESS) (see typical configuration in Figure 4.1) except the micro hydropower (MHP) focussed study.

Commonly used electrical devices and appliances in the mini-grid communities included lights (bulbs), mobile phones, TVs, fans, refrigerators and irons. For eCooking, some studies described the benefit of providing a range of eCooking appliances, or multiple. In Project 1, EPCs were the favoured eCooker. EPCs are very suitable for contexts where the energy supply is limited because they use little energy and consume full power for only a short preheat period (and then intermittently during the cooking phase), although induction cookers can also cook efficiently if operated carefully i.e., simmering on low power and using a lid. Induction cookers were favoured in Project 7 in a survey of 200 households, although lack of familiarity with eCooking appliances may also affect opinions.

The tariffs in the mini-grid communities were set based on a number of factors such as adherence to relevant regulations, tariff caps, financial modelling, negotiation with the regulator, and community consultation. In some countries such as that of Project 2, the regulator plays a key role in setting and approving the average tariff. In other countries like that of Project 1, the regulator sets the cap/maximum tariff that should not be exceeded. However, mini-grid operators in both Project 2 and Project 1 do have the freedom to adjust the tariff structure according to their plans to encourage the use of electricity. In Project 1, operating and maintenance costs and risks were considered during tariff-setting, such as mini-grid infrastructure repairs and reserves for emergency replacements. In other contexts, such as MHP mini-grids in Project 7's context, the mini-grid operator often agrees the tariff with customers. The community can change the tariff considering operating costs and energy sales, although this can be difficult due to social pressures. Lastly, the mini-grid operator in Project 4 was allowed to set the tariff for experimental purposes as a pilot case.

The following sections analyse each study in turn, under thematic groups. The headline findings from each study are presented, followed by a bullet point summary of their technical and financial modelling, followed by further details and explanations.

4.1 Integrating eCooking into mini-grid planning

Two studies, Project 1 (Developer 1, D1) and Project 2 (Developer 2, D2), focussed on unbuilt mini-grid portfolios, exploring the effects of integrating eCooking into communities from the very beginning.

4.1.1 Project 1

Adding eCooking to existing mini-grids can appear unfeasible due to upgrade requirements, whereas integrating high eCooking penetration into mini-grid portfolio planning from the beginning can drastically improve business cases.

In Project 1, assuming 50% eCooking penetration, with two EPC usages per day, reduces the payback period for the unbuilt project from 9 years to 4 years, and triples the IRR, despite increased CAPEX for PV and battery storage upgrades. Therefore, vastly increased energy sales from eCooking can outweigh increased capacity requirements, and enable profitability relatively quickly.

Bullet point summary:

- A portfolio of unbuilt mini-grids (12 small mini-grids with average of 217 customers/mini-grid) serving 2,605 customers of which 60% are residential.
- The average usage of the EPC per customer was assumed to be 30 minutes for lunch and dinner preparations, which was equated to a daily usage of 0.5 kWh, bringing a total of 15 kWh additional demand per customer each month.
  - More detail on the thinking behind these assumptions would have been useful, to understand whether 30 minutes usage for lunch and dinner means 15 minutes for lunch and 15 minutes for dinner, or 30 minutes for lunch or dinner.
- The average energy consumption without eCooking was assumed to be 7 kWh per customer per month, increasing to 18 kWh including eCooking, for every customer (100% eCooking penetration).
- This equates to an 11 kWh increase, translating to 0.37 kWh per day, or 0.5 kWh for 22 days per month.
- 0.37-0.5 kWh corresponds to 1-2 dishes cooked in the EPC [9], a reasonably conservative assumption.
  - As this is an average, an equivalent assumption would be 50% of customers using an EPC 2-4 times per day, consuming 0.73-1 kWh per day, or 22 kWh per month for cooking, while 50% remain without eCooking. Other equivalents include 3-6 usages per day for a third of customers, or 4+ usages per day for 25% of customers.
- Overall, even though the minigrids are unbuilt and eCookers could theoretically be adopted by all ~200 customers in each community, providing the infrastructure was specified to support this, such high uptake seems unlikely, so 50% eCooking penetration may present a more realistic scenario.
- The effect of including electric cooking load in the minigrid model resulted in the following load profile characteristics:
  - More than double the total daily average energy demand from 608 kWh to 1,563 kWh, an increase of 157%.
- HOMER modelling was conducted, leading to calculated upgrade requirements across the portfolio of:
  - Increase of 33% in total PV installed capacity from 299 kWp to 397.5 kWp.

- Increase of 23% in total battery energy storage capacity from 667 kWh to 821 kWh.
- However, for most of the mini-grids in the portfolio, only PV capacity upgrades were required, with the assumption that DSM will enable confinement of eCooking to daytime.
- Including electric cooking in the financial model resulted in the following:
  - Increase of 157% in total revenue, from USD 17,559,932 to USD 45,088,695.
  - Reduction of payback period from 9 years to 4 years due to increase in revenues, with the tariff capped at $0.75/kWh.
  - Increase of almost 485% in NPV, from USD 815,711 to USD 4,772,180, across the 15-year project period, and three-fold increase in the IRR, from 11% to 30%.
  - Increase of 10% in average cost per connection from USD 1,009 to USD 1,077 with 10% of residential customers adopting eCooking.
  - An increase of 6.7% in CAPEX costs from USD 2,629,703 to USD 2,806,849 due to increased sizes of mini-grid components such as PV, battery storage, inverter, etc, leading to the above increase in cost per connection.
  - An increase in total OPEX of 71%, from USD 7,243,490 to USD 12,370,678, due to increased energy sales and higher component (e.g. batteries) replacement costs.
- The study also provided valuable information on the relative costs of mini-grid components, reporting that the battery modules and inverter were the highest cost components.

Detailed summary:

The study focussed on an unbuilt (planned) mini-grid portfolio of 12 small mini-grids, serving a total 2,605 customers, of which 60% are residential, with an average of 217 customers per mini-grid.

"Customers will receive 24-hour, AC, and grid-equivalent electricity. This will allow customers to have lights at night, charge their phones, power small appliances (TVs, radios, fridges, etc), and power productive loads (mills, hair clippers, motors, etc). Each community will receive a self-sufficient, smart mini-grid with at least 19 kW of power generation capacity, depending on the number of connections. Technology will consist primarily of solar PV and battery storage. Mini-grid technology and distribution is deployed at the village level grid, and do not require MV lines or transformers to deliver power to the villages."

Load modelling

The study began by estimating expected electricity demand before and after the introduction of eCooking. The expected load profile for the communities was assessed by analysing data from 13 existing mini-grids, as shown in Figure 4.2, which presents the average daily load profile of each site.

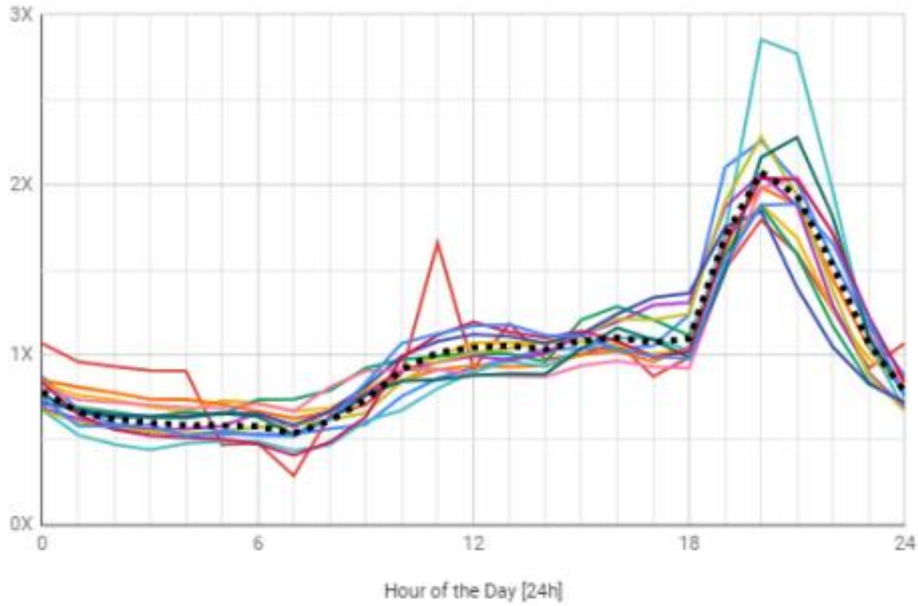


Figure 4.2: Average normalised daily load profiles of mini-grids in Project 1 context. Developer 1, 2023 [1].

The data showed that the peak load occurs in the evening, around 8pm, when appliances and lighting are most utilised. The peak load is around 300%-500% of the daily average load, informing the sizing of peak mini-grid output capacity. The expected monthly average electricity demand per customer was set at 7 kWh.

To estimate electricity demand with some level of eCooking, surveys were conducted (of 200 participants across different communities) to understand cooking behaviours, finding that cooking in rural areas mostly occurs: (i) 8-10 am, breakfast, (ii) 12-2 pm, lunch, and (iii) 4-5 pm, dinner preparations. The latter finding, of dinner mostly being prepared between 4pm and 5pm, is surprising, especially given that the community-wide peak load occurs around 8pm, suggesting that peak activity including eating would occur around this time and therefore closely follow dinner preparation in the preceding hours of 5pm onwards. Piloting would be required to ratify the findings on most common timings of cooking.

The following assumptions on eCooking electricity consumption were then implemented: "The Electric Pressure Cooker has a power rating of 1 kW and we are expecting the average usage of the EPC per customer to be 30 minutes for lunch and dinner preparations. With this assumption, the EPC customer is likely to have a daily usage of 0.5 kWh which brings a total of an additional 15 kWh additional demand per customer." It is unclear whether 30 minutes usage for lunch and dinner means 15 minutes for lunch and 15 minutes for dinner, or 30 minutes for lunch or dinner. EPC cooking actually only draws continuous rated power for the preheat period, which is often around 15 minutes, so the assumptions would be reasonably accurate in terms of energy consumption for one EPC dish cooked for lunch and one EPC dish cooked for dinner, with fuel stacking (using other stoves such as charcoal, firewood, LPG, etc) for other dishes for each meal, and for breakfast cooking.

The expected monthly EPC electricity consumption was then suggested as follows: "The historical data indicates that in a typical grid without the e-cook, the average starting consumption per customer is average of 5 to 7 kWh. With the inclusion of e-cooking, we are expecting the initial consumption to grow to an average of 20 kWh the minimum being 18 kWh." The final numbers chosen were 7 kWh without eCooking, and 18 kWh with eCooking, actually equating to an 11 kWh increase, translating to 0.37 kWh per day for 30 days in a month, or 0.5 kWh per day for 22 days per month. Although it is possible the EPC would not be used every day, using it for only 22 days per month could be seen as low, but is of course dependent on community-specific culture. More detail behind these assumptions would have been beneficial to understand the rationale here. Regardless, 0.37-0.5 kWh eCooking electricity consumption per day corresponds to 1-2 dishes cooked in the EPC per day, with the median EPC energy consumption across relevant MECS studies around 0.32 kWh (0.073 kWh per capita, average of 4.3 people per household) [9].

The way in which the demand profile was constructed, in terms of timing of cooking, coincidence of EPC usage across HHs, resolution of load profile, was not explained. The study proposed that eCooking would smooth out the daily load profile, increasing demand during meal times, and not increasing the peak evening load further: "These characteristics change the non-electric cooking scenario load profile and made the overall demand more or less evenly distributed during the day throughout late evening with four peaks: morning (breakfast), mid-day (lunch), evening (dinner) and night (around 8:00 pm)." This hypothesis requires piloting to evaluate, as it may be likely that people want to cook dinner later than 5pm and that cooking dinner would therefore align with the community-wide peak activity.

Two measures were put forward for encouraging users to cook during certain time windows, both of which require testing to understand their effectiveness:

- "Peak shaving: D1 will encourage EPC users to shift their cooking activities to off-peak hours when electricity demand is lower, mostly during day hours-off peak periods. This will be achieved by having a low tariff structure through the time of use tariff structure across the EPC customers. D1 will do campaigns and consumer education to promote off-peak cooking practices while discouraging the on peak usage of EPC through a high tariff structure."
- "Smart scheduling: Our call center will provide EPC users with real-time information about the grid's electricity availability and suggest optimal cooking times to distribute the load evenly. Smart scheduling can be facilitated through SMS alerts that provide users with personalized cooking schedules based on the energy availability of the mini-grid."

Interestingly, the study appears to compare 0% eCooking in the baseline scenario with 100% eCooking in the eCooking scenario, as the average electricity consumption for all 2,605 customers increases from 7 kWh to 18 kWh. It seems unrealistic that every customer in every mini-grid in the portfolio would adopt eCooking at the same time, but the modelling is useful for understanding what the effects would be. Furthermore, the assumption of 0.37-0.5 kWh EPC energy consumption per day, approximately one or two dishes, is somewhat conservative, as one would hope customers would want to use their EPC at least once per main meal. Therefore, as we are dealing with averages, an equivalent assumption would be 50% of customers using an EPC 2-4 times per day, consuming 0.73-1 kWh per day, or 22 kWh per month for eCooking, while 50% remain without eCooking. These levels of eCooking penetration and usage may be more realistic than 100% penetration and one EPC dish per day.

Overall, including electric cooking load in the mini-grid portfolio model more than doubled the total projected daily average electricity demand from 607.8 kWh to 1563 kWh, an increase of almost 157%. The precise effect of eCooking on the load profile and daily peak demand were not reported, beyond the aforementioned hypothesis of it smoothing out the load across the day.

Mini-grid upgrade modelling

HOMER software was then used for each mini-grid in the portfolio to calculate PV and battery capacity requirements, and economic factors, with and without eCooking. Assumptions on peak demand specified in the load profiles inputted to HOMER were not provided. Peak demand is very important in dictating mini-grid infrastructure capacity requirements. Monthly variation in electricity demand was discussed, and reported to be significant, due to events such as harvests and celebrations, with an additional buffer in mini-grid capacity recommended to cover it.

The modelling showed that integrating eCooking would require an:

- Increase of 33% in total PV installed capacity from 299 kWp to 397.5 kWp.
- Increase of 23% in total battery storage capacity from 667 kWh to 821 kWh.

The upgrade requirements above are totals across the portfolio. The modelling found that 8 out of 12 of the mini-grids would require increased PV capacities, of which only two would require increased battery storage, and only one would require increased inverter capacity. Details on the HOMER modelling were not provided, so it is unclear why some mini-grids were reported to require no upgrades. The fact that only two systems needed increased battery storage suggests the implementers believe that DSM measures will enable confinement of eCooking to daytime.

Financial modelling

Financial analysis was conducted to assess the mini-grid portfolio business case. The modelling set the start date of construction as January 2024, with deployment in January 2025. Integrating eCooking resulted in the following:

- Increase of 157% in total revenue, from USD 17,559,932 to USD 45,088,695.
- Reduction of payback period from 9 years to 4 years due to increase in revenues, with the tariff capped at $0.75/kWh.
- Increase of almost 485% in NPV, from USD 815,711 to USD 4,772,180, across the 15-year project period, and three-fold increase in the IRR, from 11% to 30%.
- Increase of 10% in average cost per connection from $1,009 to $1,077 with 10% of residential customers adopting eCooking.

The latter increase is due to an increase of 6.7% in CAPEX costs, from $2,629,703 to $2,806,849, due to increased sizes of mini-grid components such as PV and battery storage. There was also an increase in total OPEX of 71%, from USD 7,243,490 to USD 12,370,678, due to increased energy sales and higher component (e.g. batteries) replacement costs. The study reported confirmation $1.3 million of grant funding through results-based financing (RBF) from Rural Electrification Agency (REA).

Figure 4.3 shows that the payback period shortened by more than 50% to 4 years from 9 years. This huge reduction stems from the significant increase in electricity sales as a result of inclusion of eCooking.

(a)

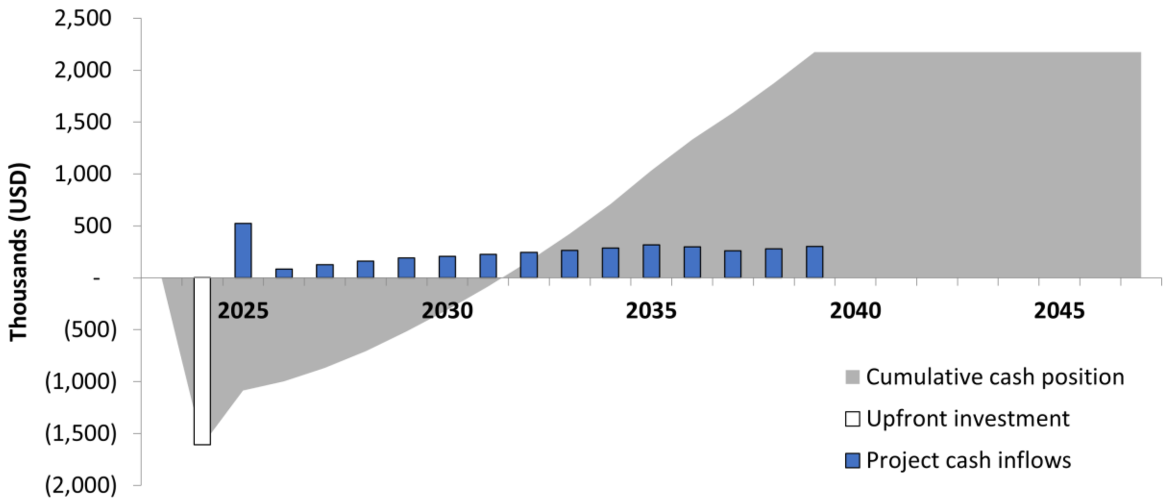
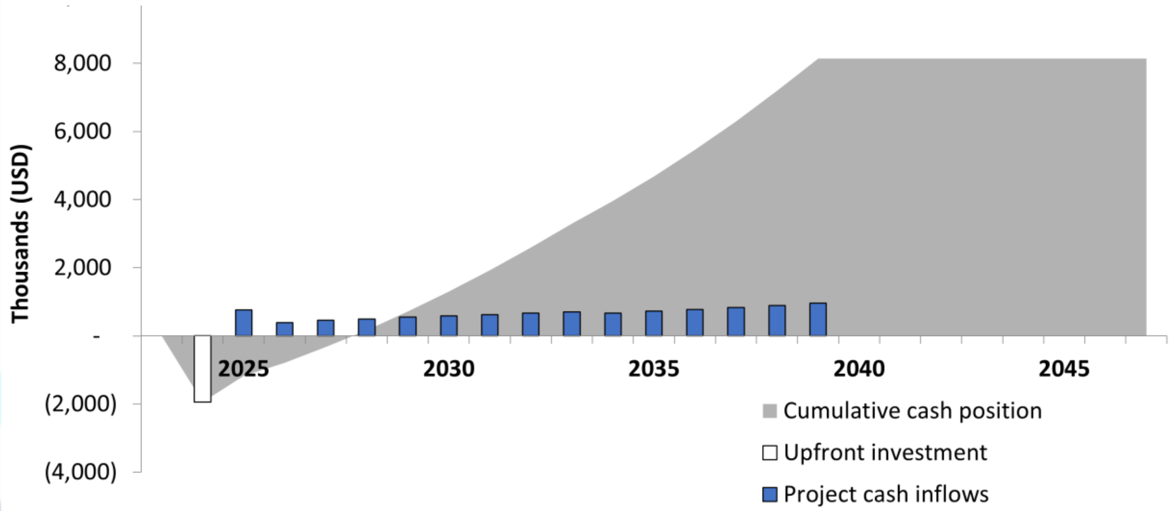


Figure 4.3: Cashflow analysis and payback period for Project 1 (a) without eCooking (b) with eCooking. Developer 1, 2023 [1].

(b)



The study also provided valuable information on the relative costs of mini-grid components. Table 4.1: Representative costs of 32 kWp mini-grid power system from Project 1. Developer 1, 2023 [1].Table 4.1 depicts representative costs for a 32 kWp system, showing that the battery modules and inverter are the highest cost components. The costs are exclusive of taxes and vary depending on size of the site.

Table 4.1: Representative costs of 32 kWp mini-grid power system from Project 1. Developer 1, 2023 [1].

Power System	Cost Exclusive of Taxes	Units	32KWp Power System	Lifetime
Panels	220	*USD/kWp*	6,996	25
Panel Frames	160	*USD/kWp*	5,088	25
PV BOS	120	*USD/kWp*	3,816	25
Battery Inverter	269	*USD/kVa*	13,450	25
Outdoor Inverter Cabinet	3350	*USD/#*	3,350	
Inverter Cabinet Foundation	25	*USD/#*	25	25
Battery Modules	1633	*USD/batteries*	14,697	10
Battery BOS	800	*USD/#*	800	25
Outdoor Battery Cabinet	3350	*USD/#*	3,350	
Battery Accessories	900	*USD/#*	900	25
Battery Cabinet Foundation	13	*USD/#*	13	25
Labor	5075		5075	
			57,560	

4.1.2 Project 2

Integrating eCooking into mini-grid portfolio planning increases revenues and reduces average tariff for cost-recovery, and improves the case for investment. Higher levels of eCooking reduce payback periods.

In Project 2, eCooking increased revenues and NPV for the unbuilt mini-grid portfolio, and improved the proposition for investors due to larger CAPEX and therefore ticket size. It also enabled better equity payments, and a reduced average tariff. However, the tariff is still required to reduce further according to regulations, requiring extra support, with carbon finance suggested. The payback period actually increased due to increased CAPEX, OPEX (higher replacement costs), reduced tariff, and increased equity payments, although a higher penetration of eCooking would likely reduce the payback period.

Bullet point summary:

- Large mini-grid portfolio, of 28 solar mini-grids, of which only two are already built.
- One unbuilt community was chosen as a case study. A commune, it has 12,486 inhabitants and could comprise around 2,000 households.
- The report does not specify the number of customers expected to be connected to the case study mini-grid. Nor is the number of customers for each other mini-grid in the portfolio presented.
- Load modelling representative of the usual procedure was illustrated for the case study, while financial modelling was conducted for the entire portfolio.
- Typical electricity demand was presented, followed by the average daily profile with DSM measures implemented, shifting evening loads to daytime. This reduced the evening peak from 46 kW to less than 30 kW, while increasing the midday peak from 55 kW to 75 kW, thereby maximising use of available solar energy and minimising expensive battery storage requirements.
- eCooking penetration of 10% was then assumed. Electrical energy consumption (1.94 kWh per HH per day) and load profiles observed in a previous study were utilised to model eCooking loads, as well as a peak multiplier approach based on historical data.
- For the case study, 10% eCooking resulted in a 34% increase in average daily energy consumption, from 771 kWh to 1036 kWh, and a 60% increase in peak demand, from 101 kW to 162 kW.
- Modelling user HOMER was conducted to understand upgrade requirements for PV and storage, which were determined as follows:

    - An increase of 47% in PV installed capacity, from 270 kWp to 398 kWp, to accommodate the inclusion of eCooking.
    - No upgrade requirement for battery storage, due to the assumption that demand-side management approaches could shift evening demand to daytime, so that the increased solar capacity can meet eCooking and other loads during the day.
- Building on the case study, financial modelling assessing the effect of integrating eCooking into all 28 mini-grids in the portfolio generated the following results:
    - Increase of 25% in operating revenue (US$22.9 million) due to the additional electricity consumption from eCooking.
    - Increase of two years in payback from 11 to 13 years. However, as there is a 20-year window for repayment of the sub-debt, this is not seen as a negative result.
    - Increase of 20% in project NPV (net present value) from US$18.1M to US$21.7M.
    - Increase of 9% in total CAPEX for the portfolio (US$3.5 million increase).
    - Increase of 14% in OPEX over the 24-year horizon (US$4.8 million) entirely due to components replacement costs for equipment of greater capacity, such as batteries, inverters, etc.
    - Reduction of 10% in average tariff level required for viability, from $0.69/kWh to $0.63/kWh, due to increased revenue.

Detailed summary:

Project 2 focussed on a mini-grid portfolio of 28 solar mini-grids, of which only two are already built. One unbuilt community was chosen as a case study. A commune, it has 12,486 inhabitants and could comprise around 2,000 households. It is likely that fewer connections are planned, as the mini-grid may focus on the city rather than the entire commune. The report did not specify the number of customers expected to be connected to the case study mini-grid. Nor was the number of customers for each other mini-grid in the portfolio presented.

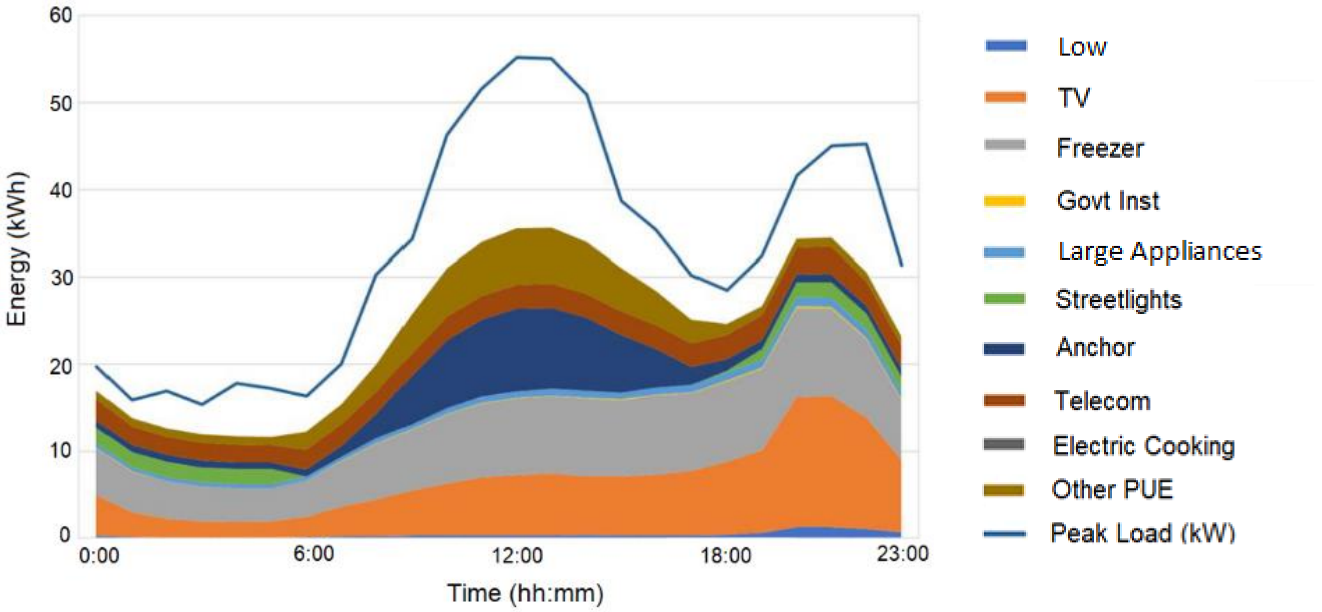
Load modelling

The study used the case study to present the typical process for mini-grid modelling, first without eCooking and then with eCooking integrated. Figure 4.4 presents the expected daily load profiles of the case study, including how DSM (b) and the inclusion of eCooking (c) affect demand.

The aggregated profiles can be considered the average hourly energy consumption over a given day in Year 5 of mini-grid operation, while peak load is considered the maximum expected consumption at any point in Year 5 of operation. (Year 5 allows customers to grow into their more expected consumption patterns as it takes time to adjust to new electricity access (e.g., purchasing, appliance access and utilisation, business growth, etc.))

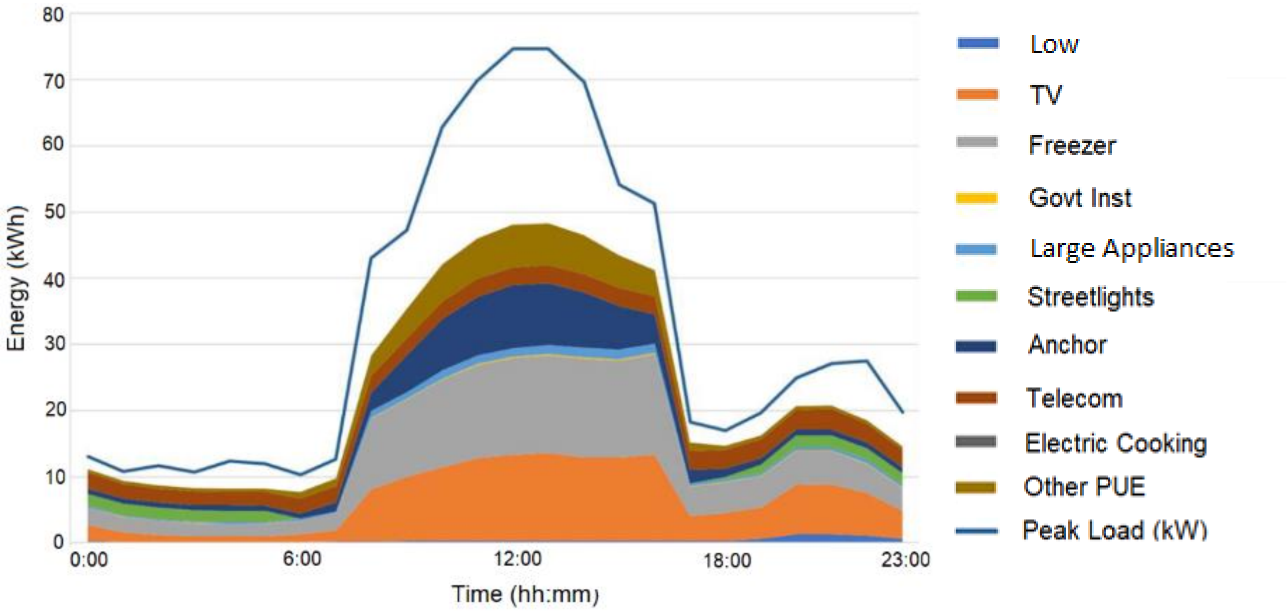
The types of loads considered in the typical aggregated load profile (a) included customers expected to use only minimal lighting and phone charging (Low), small appliance use (TV), standard appliance use (Freezer), larger appliance use, government institutions, streetlights, anchor customers, telecom towers, and other types of productive uses (PUE) of electricity (pumps, motor-based equipment, etc.).

Typical residential and small business customers (Low, TV and Freezer) are expected to experience daily peak consumption in the evening hours, while telecommunication customers maintain a relatively steady load, and anchor customers and other PUE customers focus their operation primarily during the daytime hours.



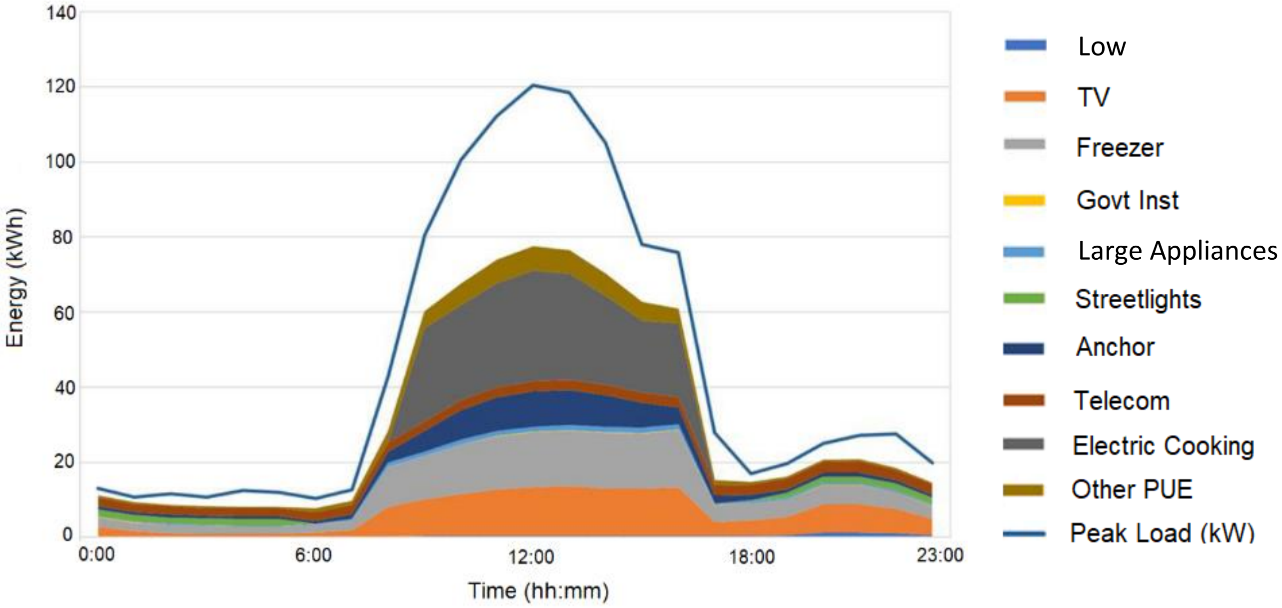
60
50
40
30
20
10
0
Energy (kWh)
0:00
6:00
12:00
18:00
23:00
Time (hh:mm)
Low
TV
Freezer
Govt Inst
Large Appliances
Streetlights
Anchor
Telecom
Electric Cooking
Other PUE
Peak Load (kW)

(a)



80
70
60
50
40
30
20
10
0
Energy (kWh)
0:00
6:00
12:00
18:00
23:00
Time (hh:mm)
Low
TV
Freezer
Govt Inst
Large Appliances
Streetlights
Anchor
Telecom
Electric Cooking
Other PUE
Peak Load (kW)

(b)



(c)

Figure 4.4: Case study community average daily load profile and contributions: (a) current situation, (b) with 50% of evening load shifted to midday, and (c) plus eCooking at 10% penetration. Developer 2, 2023 [2].

The DSM approach adopted was to shift some of the evening load, 50% in this case, to daytime hours. Figure 4.4 (b) shows the new expected load profile after implementing 50% load shifting initiatives for some of these customer types (TV, Freezer, Large Appliances and other PUE). Evening peak consumption decreased, such that the overall load profile better aligned to potential solar production, as a result of the load shifting. Reduction in nighttime loading, and daytime loads more closely following the curve for solar availability, led to a reduction in battery capacity requirements (one of the costliest considerations in system design). The shift increased the midday peak demand from around 55 kW to approximately 75 kW and reduced the evening peak from 46 kW to less than 30 kW.

Lastly, Figure 4.4 (c) demonstrates how the load profile is expected to look with 10% of customers cooking with electricity in the middle of the day. The midday peak increased significantly with the inclusion of eCooking from around 75 kW to around 120 kW, enabling maximised usage of PV capacity and reducing the need for upgraded battery storage.

Modelling of eCooking demand integrated into Figure 4.4 (c) was conducted using historical data and load profiles, and employing a peak multiplier approach. Figure 4.5 presents average load profiles for EPCs and induction cookers in a previous study by the developer. Presumably, these are normalised by the number of customers whose data is included in the profiles.

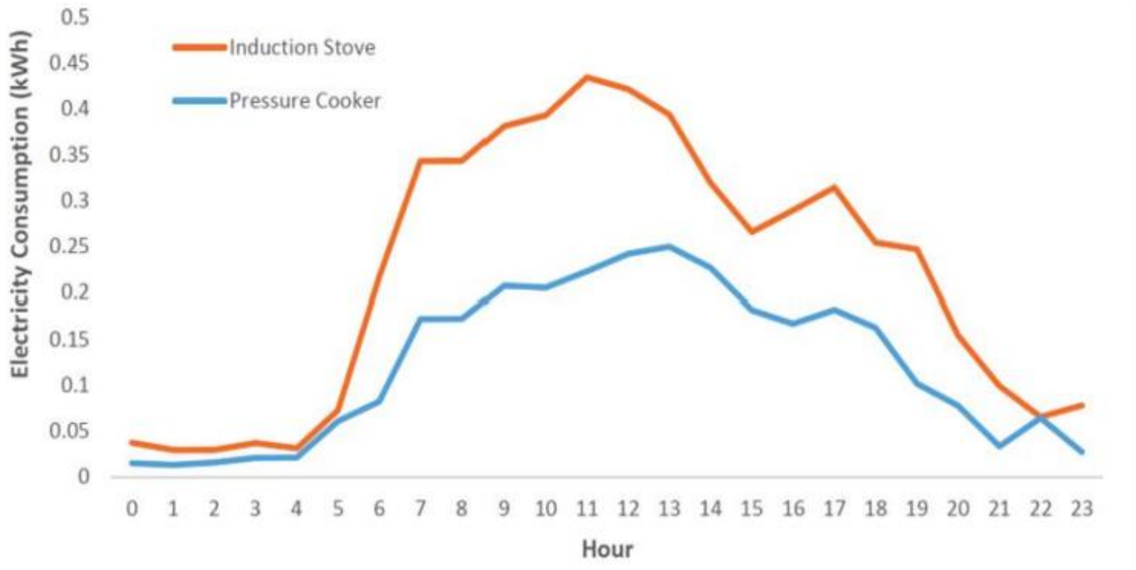


Figure 4.5: Average hourly load profiles for EPCs and induction cookers from a previous study. Developer 2, 2023 [2].

For this study, average eCooking consumption depicted in Figure 4.5 was reduced by 40% to reflect the shift away from free electricity for cooking in the previous study to actual cooking tariffs, and the shift to just EPCs rather than EPCs and induction stoves. This led to Figure 4.6, below, in which the blue line represents the assumed average load profile for the COSMO study, again normalised by the number of HHs. Daily average eCooking demand per HH per day was assumed to be 1.94 kWh, based on data from the previous study. This seems high, for EPC usage, as each dish cooked in an EPC generally consumes less than 0.5 kWh [9]**.**

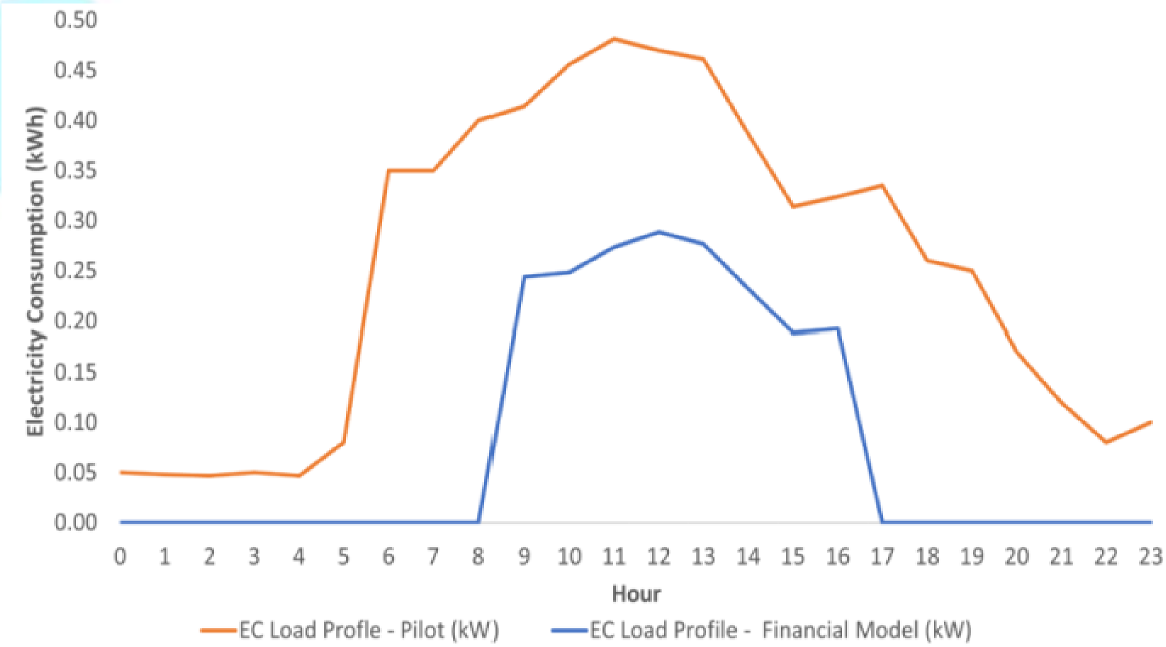


Figure 4.6: Adjusted average eCooking load profiles for study in Project 2. Developer 2, 2023 [2].

As evident, the study assumed that eCooking could be confined to daytime hours, with peak eCooking occurring during the middle of the day. This assumption was partly based on previous findings of the implementers, whose previous study found that 61% of eCooking load occurred between 9 AM and 4 PM, and asserted that this was the natural consumption pattern without any additional price signals or customer training to influence shifting/alignment. However, Figure 4.5 and Figure 4.6 show that a lot of cooking in the previous study occurred in the early morning and late afternoon, outside of peak solar generation hours.

The study detailed DSM measures used to encourage daytime cooking, including: community engagement initiatives (e.g., energy literacy, energy efficiency training); tariff rate structuring (e.g., time of use pricing, lower tariff); and tariff load limit structuring (e.g., power limits). Further information on the latter two measures was provided: "All customers have time of use rates that offer lower cost electricity during the day and more expensive rates at night. This incentivizes customers to shift their electricity consumption from when generation costs are high (e.g., production from batteries and gensets currently, and just batteries in the future) to when generation costs are lower (e.g., production from solar). Customer tariffs also include power limits which help to control the timing and shape of their ultimate electricity consumption." There are also plans for further, innovative DSM approaches in the future, including reactive community engagement, reactive load management and reactive demand management. All DSM measures require testing to quantify the actual willingness of cooks to cook during daytime hours.

Alongside the above approach on using eCooking data and profiles from a previous study, peak load modelling for eCooking "utilised a peak multiplier with respect to historical data to develop an expected peak multiplier relative to average load for each hour of the day. The average peak multiplier when considering the electric cooking window of 8am to 5pm is a 147.9% increase above average (a multiple of x1.479). This approach was taken as a proxy for diversification factor, coincidence factor, and other similar approaches, and is perceived to meet sizing needs, but there is always opportunity to incorporate additional methods in future sizing considerations."

Details on this approach described above were not provided. Furthermore, as mentioned, the number of customers connected to the case study mini-grid and the total number connected across the portfolio were not specified, only that the eCooking scenario evaluated 10% eCooking adoption. These omissions make it difficult to fully evaluate the eCooking modelling, except to say that assuming 1.94 kWh per day per HH is optimistic in terms of correlating to high levels of eCooking each day, of around 4-8 EPC dishes depending on foods cooked and cooking practices. Therefore, 10% eCooking adoption at 1.94 kWh per day could also represent 5% eCooking adoption at around 1 kWh per HH per day, equating to 2-4 EPC dishes.

The study provided its own evaluation as follows: "Given the lack of available data of actual consumption with electric cooking at the tariff rate ultimately selected (in the previous study electricity for cooking was provided free of charge to prioritise research outcomes), there is an understood risk associated with the average consumption values assumed. That said, a combination of factors helps to mitigate this risk:

1. High interest among customers is expected to materialise, with only 10% of customers nominally being signed up with one EC device per customer as the target for initial rollout. Initial pilots demonstrated significant interest from the communities.
2. Actual implementation of electric cooking will incorporate a staged rollout, where consumption within the designed tariff structure will be monitored and future stages would be adjusted accordingly.
3. Use of time-of-use load limits, linked to time-of-use pricing, allows for reactionary decision making that can be adjusted to meet project and customer needs."

The first two points are sensible, while the latter requires testing. Nevertheless, the study found that 10% eCooking adoption at 1.94 kWh per HH per day led to the following results for the case study community:

- Increase of 34% in average daily energy consumption – from 771 kWh to 1036 kWh.

- Increase of around 60% in peak demand, from 101 kW to 162 kW, with the peak occurring during the middle of the day.

Mini-grid upgrade modelling

Modelling user HOMER was conducted to understand upgrade requirements for PV and storage to accommodate eCooking. Table 4.2, below, presents the results for the case study.

Table 4.2: Impact of eCooking on case study mini-grid in Project 2. Developer 2, 2023 [2].

Metric	With Electric Cooking	Without Electric Cooking	Change due to Electric Cooking
Energy Consumption (kWh/day)	1036.49	771.27	+34%
Peak Power (kW peak)	162	100.85	+61%
Solar PV (kWp)	398	270	+47%
Energy Storage (kWh)	475	479	-1%

As shown, there was no upgrade requirement for battery storage, due to the assumption that DSM approaches could shift evening demand to daytime, so that the increased solar capacity could meet eCooking and other loads during the day. The study reported that other mini-grids in the portfolio would require some increase in energy storage, but generally solar PV satisfied the majority of the need. A capacity shortage of 5% was permitted as follows: “This shortage in energy demand met across the systems was determined as sufficient for sizing generation systems large enough to supply energy needs but not too large so that the expected revenue cannot adequately meet project economic viability.”

The study also explained that fuel stacking in the evenings and on days with little solar insolation was expected: “Given the baseline abundance of charcoal and other cooking means, setting the expectation with customers that they should maintain backup supplies for their cooking needs can be readily managed. This allows for only meeting mid-day cooking needs on days that align with excess solar and [for eCooking to] be the first load to curtail when the system requires.” This is realistic, as fuel stacking with eCooking is inevitable because people often want to cook two or more dishes at the same time, prefer traditional stoves for certain dishes, experience power cuts, etc. The health benefits of a part-transition to eCooking require investigation to understand the effects of different levels of biomass cooking on indoor air pollution. However, a part-transition to eCooking will benefit health to some degree, as well as freeing up time, potentially reducing cooking fuel costs, and increasing electricity sales for improved mini-grid financial sustainability.

It is possible that peak capacity requirements are overstated by HOMER. The load addition due to eCooking may be higher than in reality, due to the hourly resolution of load modelling, which cannot capture varying levels of coincidence of usage of eCookers and their short high-power periods, and how these factors would in fact lead to relatively low peaks compared to the maximum possible peaks if all eCookers are ‘on’ at the same time. Also, as mentioned, 1.94 kWh per HH per day is already high. For these reasons, upgrade requirements may not be as high in reality as reported by HOMER, or higher levels of eCooking may be possible with the specified upgrades.

Financial modelling

Financial modelling was conducted assessing the effect of integrating eCooking into all 28 mini-grids in the portfolio, over a 24-year period. "The main financial and regulation requirements were:

- to maintain a minimum equity IRR of 12% and senior debt loan maturity of 12 years and sub-debt maximum term of 20 years.
- a project size of $46 million in total CAPEX costs to unlock pledged funding sources and meet co-financing requirements.
- a maximum weighted average tariff rate across all customers of US$0.56/kWh (2019 dollars, adjustment for inflation is permitted) as part of the concession negotiations with the energy regulator.

The results were as follows:

- Increase of 25% in operating revenue (US$22.9 million) due to the additional electricity consumption from eCooking.
- Increase of two years in payback from 11 to 13 years. However, as there was a 20-year window for repayment of the sub-debt, this was not seen as a negative result.
- Increase of 20% in project NPV (net present value) from US$18.1M to US$21.7M.
- Reduction of 10% in average tariff level required for viability, from $0.69/kWh to $0.63/kWh, due to increased revenue.
- Increase of 9% in total CAPEX for the portfolio (US$3.5 million increase).
- Increase of 14% in OPEX over the 24-year horizon (US$4.8 million) entirely due to components replacement costs for equipment of greater capacity, such as batteries, inverters, etc.
- Increase of 12% in total low-interest sub-debt secured for the project ($0.9 million) due to increase in the total CAPEX requirements.

Although the payback period increased, due to increased CAPEX, OPEX (higher replacement costs), reduced tariff, and increased equity payments, this was planned by the implementers, and it would likely reduce with higher penetrations of eCooking. The benefits of eCooking were clear to the study authors: "Electric cooking enhances the microgrid financial model by increasing total low-interest debt accessible by raising CAPEX and "ticket size" for large institutional investors, increasing operational revenue, reducing average tariff required for cost-recovery, and enabling better equity payments for investors while still preserving debt repayment windows."

The average tariff was required to reduce further according to regulations. Adjusting for inflation, the study anticipated that the regulated tariff at grid launch would be $0.60/kWh, short of the $0.63/kWh require for cost recovery in the eCooking scenario. Therefore, the study asserted that "cost recovery would depend on either (i) regulatory adjustment after at least 1 year of operation, which is a complex and uncertain process or (ii) additional revenue streams. Offering electric cooking services when there is excess grid capacity that would otherwise go unsold could be a way to increase projected revenues, as could exploring pathways for results-based financing and small donor crowd-financing to help bring down the cost of electricity for electric cooking. Carbon finance could also be an elegant way to increase revenues while keeping costs low for customers and keeping the weighted average tariff charged to the end-customers below the regulated limit. Carbon financing might be able to deliver upwards of $0.1/kWh."

4.1.3 Project 3

Project 3 provided details on mini-grid modelling and financial modelling, but not separated into with and without eCooking. eCooking load modelling was explained and is summarised here.

Bullet point summary:

- An unbuilt mini-grid portfolio comprising 10 villages with an estimated 30,000 people who will receive energy services through this project. Combined, these mini-grids will provide just over 1 MW of grid-quality electricity.
- The case study existing mini-grid served a community of 150 households. Load modelling assumed that 50% of the mini-grid residential customers would adopt eCooking and use it for cooking for one meal every other day (on average), a conservative assumption. This was based on historical electricity consumption data and some key assumptions about the use of eCooking device (typified by an instant pot with 0.85 kW – 1 kW power rating and an average usage of 1 hour per meal).
    - These are reasonable assumptions, although they seem quite conservative, and it would be hoped that consumers would use their eCookers much more than once every other day.
    - On the other hand, if being used for one dish, or even two, 1 hour of usage is actually high, as an assumption, because the EPC only draws high-power continuously for a short preheat period of around 15 minutes per dish.
- The effect of eCooking on community electricity demand was estimated using the above assumptions, applying them to historical data in order to estimate demand growth.
- It was assumed that eCooking will increase electricity consumption by 45% on top of the projected demand, although the rationale for this assumption was unclear.
- The latest data estimated current daily average electricity demand as around 0.8 kWh per HH, with eCooking adding 45%, or 0.36 kWh, per day.
- No modelling on upgrade requirements was presented as the grid was designed oversized and able to take the extra demand. Details on financial modelling were not provided. However, the comprehensive financial model, when run with a 45% increase in revenue, suggests a 3% increase in IRR.

Detailed summary:

The case study mini-grid served a community of 150 households. Modelling assumed that 50% of the mini-grid residential customers would adopt eCooking and use it for cooking for one meal every other day (on average), a conservative assumption. “This was based on historical electricity consumption data and some key assumptions about the use of eCooking device (typified by an instant pot with 0.85 kW – 1 kW power rating and an average usage of 1 hour per meal).”

The model demonstrated that the introduction of eCooking has the potential to modify the demand curve by shifting it upwards by 45% and this is likely to result in accentuating morning and evening peaks due to the timing and duration and power consumption draw of the eCooking devices. Details on the rationale for this figure of 45% were not presented.

Collected data showed the underlying trend in the community's electricity consumption, which was increasing over time at a year-on-year growth rate of close to 40% as customers familiarise with electricity services and acquire appliances, as seen in Figure 4.7. “The 45% eCooking line indicates the expected increase in electricity consumption with the introduction of eCooking. The 45% increase in consumption and mini-grid revenues would be achieved if the assumptions are valid, i.e. that 50% of customers use an EPC for one meal every other day." The latest data (April 2023) in the graph estimated current daily average electricity demand as around 0.8 kWh per HH, with eCooking adding 45%, or 0.36 kWh, per day.

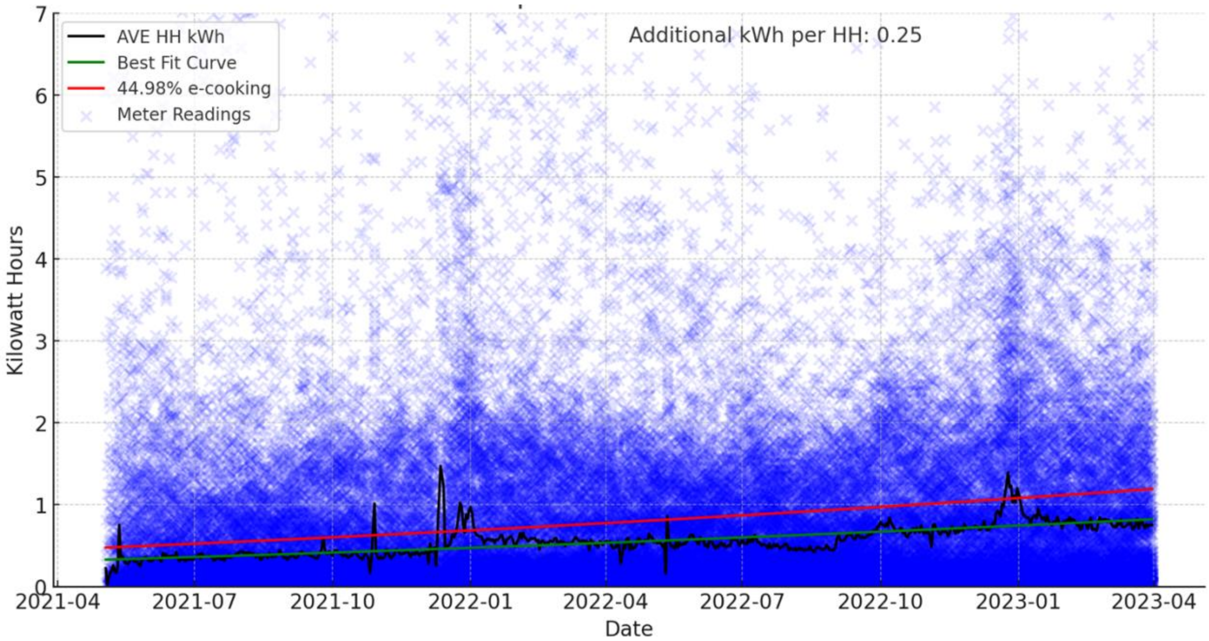


Figure 4.7: Case study community demand, average demand, load growth model and eCooking load model. Developer 3, 2023 [3].

Figure 4.8 below uses line-fitting to project future demand: "The eCooking curves are ~45% above the polynomial and linear best fit curves, representing the potential increase in electricity consumption if eCooking were introduced."

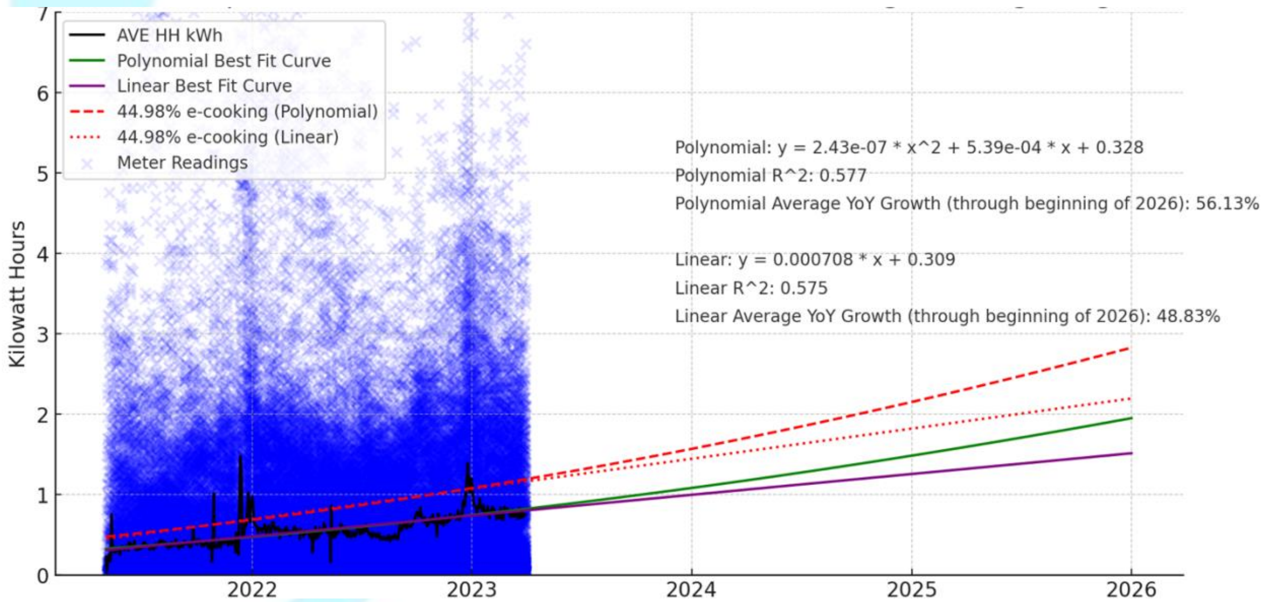


Figure 4.8: Project community demand and demand plus eCooking using linear and polynomial line-fitting. Developer 3, 2023 [3].

"The actual future trend is likely to be influenced by a variety of factors, including changes in population, economic conditions, energy efficiency improvements, etc. These should be taken into account when using forecasts for planning or decision-making purposes. Whether growth is linear or polynomial, the introduction of eCooking, as represented by the red lines, could lead to a significant increases in electricity consumption."

The report did not unpack details on mini-grid technical and financial modelling, however, the very comprehensive financial model that includes investment interest rates and was designed to show changes in investment conditions, interest rates, etc, when run with a 45% increase in revenue suggests a 3% increase in IRR. The developer in their report suggest that this more favourable return would actually be used to negotiate a reduction in terms for the borrowing, and that consequently the whole model would change (favourably). Due to the overdesign of the mini-grid electric networks, the introduction of cooking loads is not anticipated to have a negative impact on the network, and there is no need for increased CAPEX nor noticeable increase to OPEX. The mini-grid electric networks have been intentionally designed with excess capacity, providing sufficient headroom to accommodate the adoption of clean electric cooking appliances without overloading the system. This design approach ensures that the network can handle the additional demand associated with cooking loads without compromising its reliability and stability.

4.2 Adding eCooking to existing mini-grids

The following studies focussed on existing mini-grids, exploring the effects of introducing eCooking to mini-grid communities.

4.2.1 Project 4

It is more difficult to upgrade an existing mini-grid after adding eCooking due to high CAPEX, compared to integrating eCooking into original planning. Another contributing factor is needing to reduce daytime tariff to incentivise eCooking, reducing potential revenue from all daytime electricity usage if not targeted at cooks. However, it is still possible to generate a higher NPV over a sustained period.

In Project 4, there was an increase in payback period from 4 years to 9 years, due to the high CAPEX of the mini-grid system upgrades, compared to zero in the baseline scenario, as the mini-grid was already in operation. However, even with only two years of operation beyond the payback period, there was a modelled three-fold increase in the NPV, showing that eCooking can vastly increase profitability in the long term.

Bullet point summary:

- The mini-grid was originally installed in 2015 and consists of a 15 kWp PV array, 47.7 kWh lithium-ion battery and 15 kVA inverter feeding a single phase low voltage distribution network.
- In 2023, there were a total of 84 customer connections. The non-electric cooking load scenario peak demand occurred in the evening leaving significant unused power generation during the day.
- Based on the survey focusing on electric cooking, 17 e-cookers of different capacities were selected for 12 customers.
- In the modelling, most of the eCooking took place during the afternoon hours, while a few cooking sessions were also included during the early morning hours and in the evening.
- Including electric cooking load in the mini-grid model, increased the electricity demand to 54.5kWh/d (42kWh existing load + 12.5kWh e-cooking load).
- Modelling upgrade scenarios, using HOMER, found that while the current system can support a maximum of 46 kWh/d load, including additional 15kWp PV and 10kWh storage capacity can support a 74 kWh/d load, enabling introduction of 5 more induction cookers.
- The inclusion of eCooking in the financial model, evaluated over 10 years, with smart meters for variable tariff implementation, indicates:

- Almost a three-fold increase in electricity sales revenues in the range from $22k to $63k even with a reduction in daytime tariff.
- An increase in payback period from 4 years to 9 years, due to the high CAPEX of the mini-grid system upgrades ($31,250), compared to zero in the baseline scenario.

- However, even with only two years of operation beyond the payback period, there is a three-fold increase in the NPV, from US$1,908 to $5,976, showing that eCooking vastly increases profitability in the long term.
- The upgraded scenario payback period was high because the original mini-grid plant construction costs were not considered as it is already in operation.
- The reduced daytime tariff also reduces potential revenue but incentivises daytime eCooking, reducing plant upgrade requirements.

Detailed summary:

Project 4 focussed on a small solar mini-grid, originally installed in 2015, which consists of a 15 kWp PV array, 47.7 kWh lithium ion battery and 15 kVA inverter feeding a single phase low voltage distribution network. In 2023, there were a total of 84 customer connections. The daily electrical demand was approximately 32 kWh based on measured consumption and customer surveys.

The non-electric cooking load scenario peak demand occurred in the evening, leaving significant unused solar power generation during the day, and a significant number of customers were found to use LPG for cooking. Therefore, the study identified that eCooking could "replace expensive LPG and environmentally damaging firewood collection in the community, while increasing income of the mini-grid through utilising the excess power generated in the daytime."

Figure 4.9 below provides a conceptual framework for integrating eCooking into the community and mini-grid system, showing that it can benefit both customers and operators.

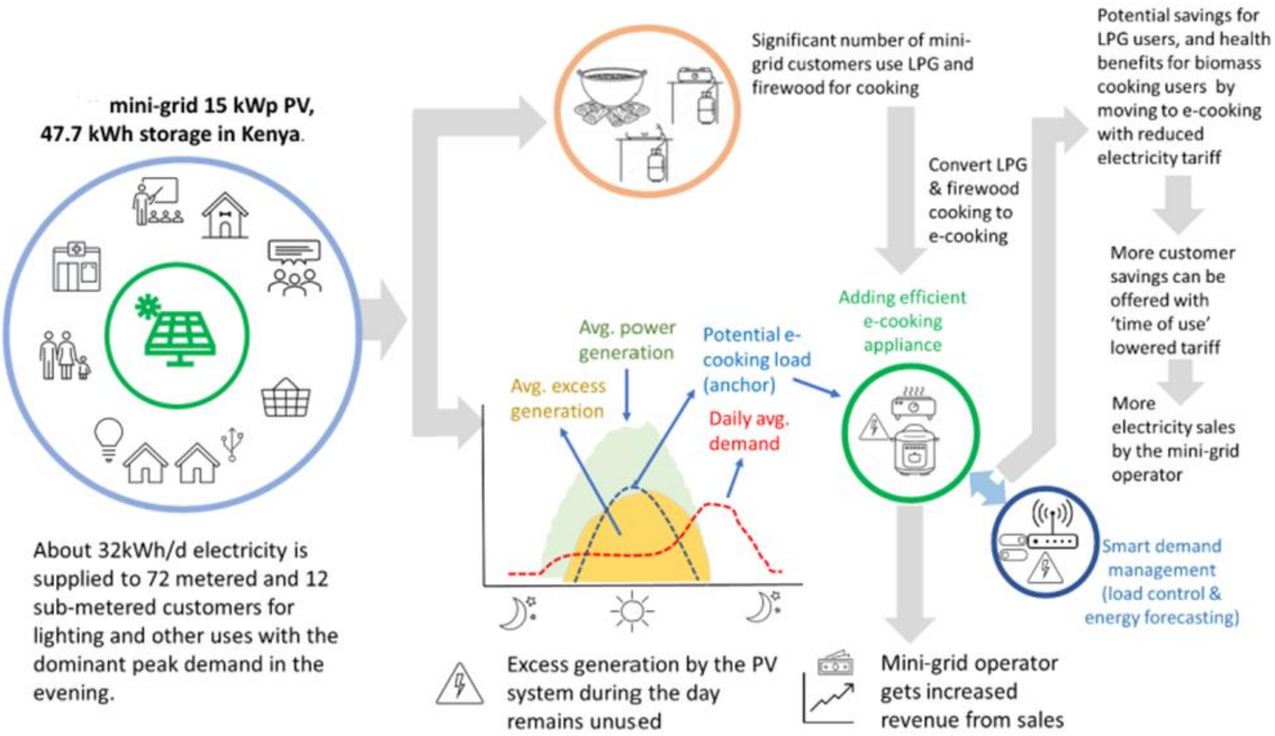


Figure 4.9: Conceptual framework including key processes and assumptions around boosting mini-grid revenue and saving customers money through integrating eCooking, Project 4. Developer 4, 2023 [4] [5].

Load modelling

For the modelling, "load profiles were developed using data from (i) remote monitoring of the current mini-grid performance, (ii) community surveys conducted in 2019 and 2023, (iii) evidence of load growth in our other mini-grids, and (iv) eCookers power rating data from manufacturers. For EPC power consumption the electricity consumption data was crosschecked with the findings from" [10].

Figure 4.10, below, shows the measured average half-hourly load profile of the community mini-grid system in 2018-2019.

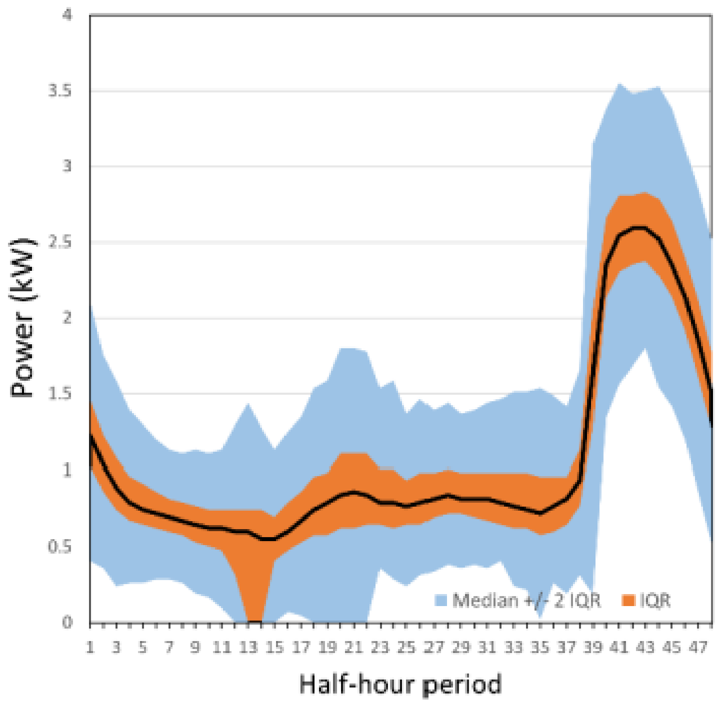


Figure 4.10: Monitored half hourly load profile of the community mini-grid showing evening peak and low daytime load (data source: developer's original research using monitoring data from 2018-19). Developer 4, 2023 [4] [5].

As evident from Figure 4.10, the peak load occurred in the evening, and was much greater than the off-peak load. Therefore, it was important for eCooking to occur before the evening peak demand: "Switching all cooking times between 10am and 2pm would help the powerplant to serve such loads without using the battery bank, and will create opportunities for customers to reduce cost by using cheaper variable tariff, when established."

The report investigated willingness to shift cooking practices to around the middle of the day. From the survey, 48% of 29 respondents who cook early in the morning (usually 6am – 8am) said they would be able to move morning cooking to around 9am, and 55% said they would be able to move their evening cooking towards the middle of the day (10am – 2pm). The following quotes illustrate varying attitudes to shifting cooking times:

➢ "Most of us, I included, cannot switch cooking breakfast too as late as 9 as we have children and spouses going to school and to work early in the morning. We are very comfortable cooking lunch before 2 pm."

➢ "I will not be able to shift my cooking schedule entirely because I have children who go to school very early in the morning and have to eat before they go".

➢ "We can boil our cereals early too, but we cannot cook supper as early as 2pm".

➢ "I leave my home for work the whole day and I get back much later than 2 pm. It is impossible for me to cook supper at 2 pm".

➢ "If I could spend lower than USD 1.15 a month we could try and cook supper earlier and warm it later in the evening".

➢ "I can consider that option since cooking will be affordable and within my budget".

The first two quotes show that delaying breakfast cooking can be impossible. The third and fourth quotes show reluctance to cook dinner as early as 2pm. The fifth quote considers cooking dinner early if it reduces costs, but suggests warming it later in the evening, which would presumably require biomass or gas stove usage. The sixth quote illustrates that reduced daytime tariffs can incentivise behaviour change. Therefore, piloting is required to test the effectiveness of reduced tariffs.

The study reported that a "variable tariff will be introduced in order to incentivise cooking during peak solar hours: typically 10:00-14:00, but depending on irradiance levels and battery state of charge. It is anticipated that the low rate is to be set at US$0.23/kWh and the higher rate at $0.38/kWh. It is assumed that targeted consumers will cook with electricity so that the mini-grid can achieve the returns projected. The key message here is make consumers aware that cooking with electricity can be a cheaper option."

An interesting point was made on incentivising transitioning to eCooking: "An upper bound on the tariff is the cost of LPG delivered heat, which for a 0.4 efficiency burner is around $0.58/kWh. A tariff of $0.23-0.38 would therefore leave room for cost saving and repayment of loan to buy an e-cooker."

Further plans for DSM to control eCooking loads in Phase 2 of the project were presented as follows: "A smart plug with time of use tariff (ToU) indications used for e-cooking devices will be employed that can be remotely switched off via GSM. This will also have synergy with e-mobility (battery charging) and other high loads that could be introduced on the mini-grid.

The proposed smart metering system will have a facility to limit current remotely at the premises level at times of high demand, controlled by a central hub. The software will include functionality for forecasting generation and for equitable queueing of e-cooking loads." Figure 4.11 below illustrates the plans.

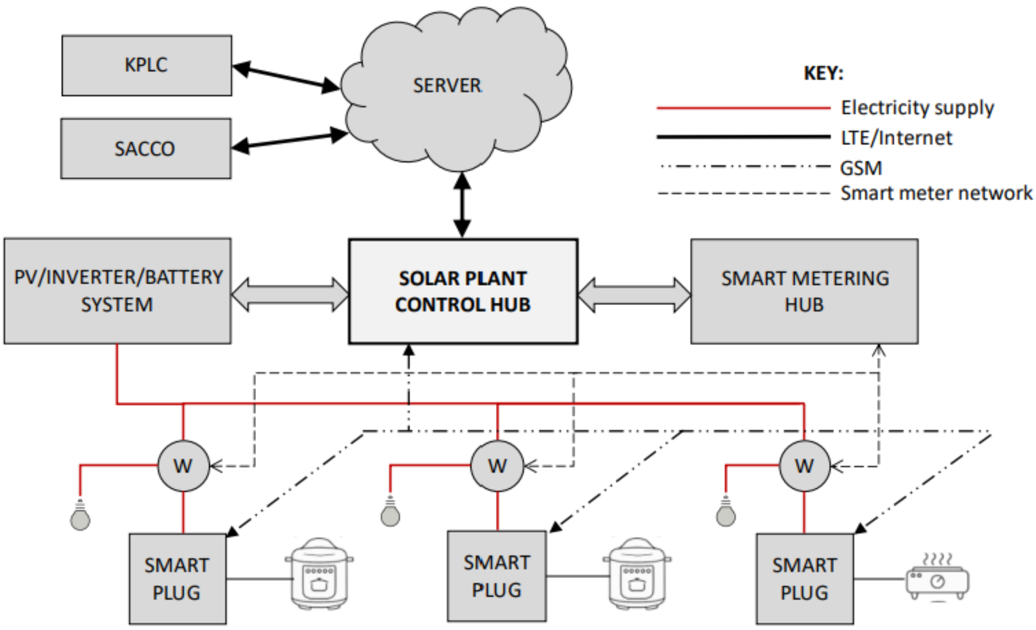


Figure 4.11: Planned smart metering system: "Control hub communicates with smart plugs, smart metering hub and PV plant. Also connects to cloud server to enable traceability and transparency of eCooking and other energy consumption." Developer 4, 2023 [4] [5].

The mini-grid average daily electrical demand was 32kWh. Based on experience of tariff reduction and load growth in another mini-grid in a similar context, the study anticipated that within the new lowered tariff environment electrical load would grow to around 42kWh/d, and indicated that the mini-grid's current capacity (15kWp PV, 47.7kWh lithium ion battery bank) would be able to support such load growth.

However, with eCooking integrated, it was anticipated that the mini-grid would require upgrading to accommodate the increased demand. It was also anticipated that the variable tariff would enable increased levels of eCooking without further upgrades, by shifting cooking away from the evening peak, when battery storage is required to power it. Figure 4.12, below, indicates how capacity upgrades and smart metering with variable tariffs could give headroom for increased demand growth in mini-grids, including eCooking.

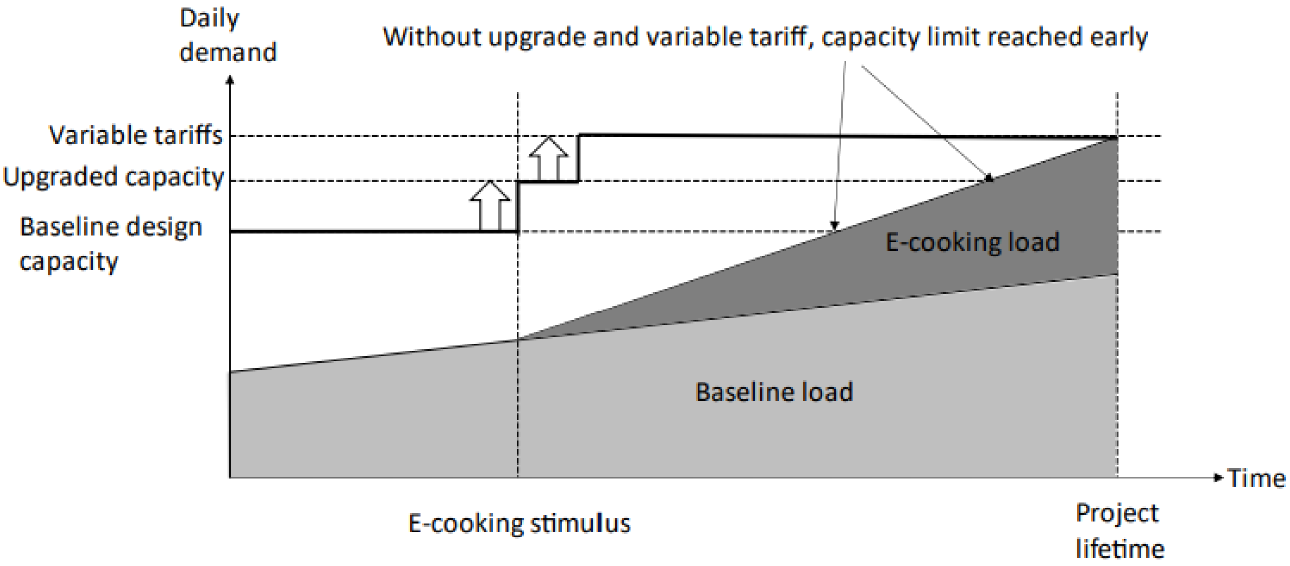


Figure 4.12: Conceptual model of growth in daily demand over time and the effect of adding eCooking, Developer 4, 2023 [4] [5].

Modelling of eCooking loads was conducted, to assess the effect of eCooking on demand, and required upgrades. "Based on respondents' cooking fuel type, time requirement and cooking habit, 17 e-cookers (12 EPCs and 5 Induction hobs) of different capacities for a combination of business and family uses were selected." Table 4.3 below presents details on the eCooking scenario.

Table 4.3: Proposed types and numbers of eCookers and target customers. Developer 4, 2023 [4] [5].

Type of e-cooker	Number of cookers	Capacity (l)	Power rating (kW)	Application	Comment
EPC	2	10	1.35	Business	
EPC	2	8	1.35	Business & family	
EPC	8	6	1.00	Family	
Single induction hob	3	5	1.00	Family	
Double induction hob	2	5	1.50	Business	
Total	**17**		19.4*	4 businesses and 8 families	

* Maximum possible power consumption at a time if all 17 cookers turn on at the same time. However, power consumption will drop to nearly half in around 15 min.

The note on maximum possible power consumption means that maximum coincidence cannot occur for long, because the EPC only consumes high power continuously for its preheat period of about 15 minutes. Maximum consumption of 19.4 kW is very unlikely to occur at all due to diversity in cooking timings.

Table 4.4 below presents eCooking modelling assumptions across the day, based on expected usage of eCookers by the potential customers, with approximate energy consumptions. Although most of the eCooking was confined to the afternoon hours as an anchor load for the mini-grid, a few cooking sessions were also included during the early morning hours and in the evening. It was also assumed that 4 of the 12 EPCs would be used twice in the afternoon session every day.

Table 4.4: eCooker usage assumptions and estimated power consumptions. Developer 4, 2023 [4] [5].

e-cooker type	Morning cooking 6-8am	Afternoon cooking 10am-2pm	Evening cooking 6pm-11pm
EPC	3 x 50 min sessions	16* x 50 min cooking sessions	2 x 50 min sessions
Estimated energy consumption**	**0.9 kWh** (@0.3kWh/session)	**5.6 kWh** (@0.35kWh/session	**0.6 kWh** (@0.3kWh/session)
Single induction hob	2 x 60 min cooking sessions	3 x 60 min cooking sessions	1 x 60 min cooking sessions
Estimated energy consumption	**1.2 kWh** (@.6kWh/session)	**1.8 kWh** (@.6kWh/session)	**0.6 kWh** (@0.6kWh/session)
Double induction hob	-	2 X 60 min cooking sessions	-
Estimated energy consumption		**1.8 kWh** (@0.9kWh/session ; both hobs)	-
Total	**2.1 kWh**	**9.2 kWh**	**1.2 kWh**

*assuming 4 EPC used twice [Total estimated e-cooking load 12.5kWh/d]
**Electricity consumption by the e-cooker (EPC and induction hob) may vary depending on their power rating, size and type of food cooked.

The assumptions presented here are interesting and seem realistic. It would be useful to have more insight into how energy consumption figures were calculated, although 0.3 kWh for EPC cooking per dish is reasonable and in keeping with MECS studies [9].

Overall, the study estimated electricity consumption of the 17 eCookers at 12.5 kWh/d. “This eCooking load will increase the mini-grid’s electrical demand to 54.5 kWh/d (42 kWh existing load + 12.5 kWh eCooking load). However, the current capacity of the mini-grid can support only up to 46 kWh/d with the maximum allowable 4% (precisely 3.8%) capacity shortage.” This maximum capacity shortage for PV-battery power system modelling was applied according to the “Multi-tier Matrix for Measuring Access to Household Electricity Supply.” [11]

Mini-grid upgrade modelling

Therefore, upgrading was required. The study used HOMER to determine upgrade requirements to “accommodate eCooking loads and any other growth in load. The optimum system capacity combination was found to be 30 kWp PV and 58 kWh lithium battery bank. This means there will be an upgrade requirement of 15 kWp PV and 10 kWh battery storage. With such an upgrade, modelling results indicate that on average there will be ~55% unused power in the daytime.”

The study conducted further modelling, increasing eCooking penetration: “Here we propose to add 5 more EPCs to be used in the peak sun hours only. Adding 5 more EPCs will add another ~1.7 kWh/d cooking load. This will increase total daily cooking load to 14.2 kWh and total mini-grid load will reach to 56.2 kWh/d. This means ~26% load of the mini-grid arises from eCooking. At this point, modelling outcomes show that there will be on average 52% unused power in the day time. However, we assume that by the second year of the mini-grid upgrade and tariff reduction there will be more electrical demand from other types of productive uses.”

Overall, the total PV capacity was doubled to 30 kWp, and the battery storage capacity was increased from 47.7 kWh to 58.3 kWh, to accommodate the overall 34% increase in mini-grid load from 42 kWh/day to 56.2 kWh/day. The average daily eCooking energy consumption across the 22 eCookers was 0.65 kWh. The study reported that the upgrades "will be able to support up to a total of 74 kWh/d electrical demand within the 4% capacity shortage limit." Table 4.5, below, outlines the modelling scenarios assessed.

Table 4.5: Modelling scenarios assessed with results including total average electricity demand, unused electricity and capacity shortage. Developer 4, 2023 [4] [5].

Mini-grid capacity	Load scenario	Unused electricity	Capacity shortage
Baseline capacity: 15kWp PV, 47.7kWh Li-ion battery bank	Current load, old tariff, no e-cooking load (32 kWh/d)	55%	0.2%
	Increased load, reduced tariff, no e-cooking load (42 kWh/d)	39%	1.8%
	Increased load, reduced tariff, no e-cooking load (46 kWh/d)	33%	3.8%
Upgraded capacity: 30kWp PV, 58kWh Li-ion battery bank	Increased load, reduced tariff, 17 e-cooking load (54.5kWh/d)	54%	0.4%
	Increased load, reduced tariff, 17 + 5 e-cooking load (56.2kWh/d)	52%	0.5%
	Increased load, reduced tariff, 17 + 5 e-cooking load, other productive uses load taking advantage of variable cheaper tariff (~74 kWh/d)	43%	3.6%

Figure 4.13, below, illustrates the battery bank state of charge (SoC) for the last scenario in Table 4.5, with the blue lines marking times of capacity shortage.

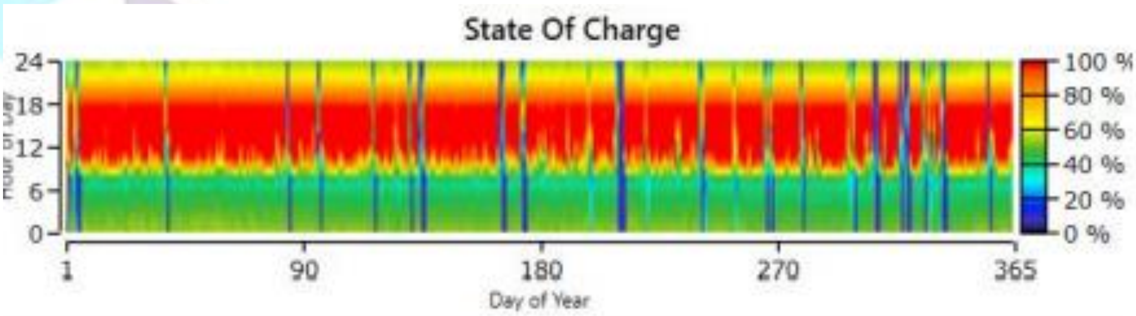


Figure 4.13: Battery bank modelled SoC across the year for the last scenario in Table 4.5. Developer 4, 2023 [4] [5].

The study provided details on the mini-grid upgrade design: "Given the objective of enhancing daytime demand for electricity, the approach taken in designing the upgrade was to maximise the potential of the existing inverter capacity by incorporating a 'grid-tied' inverter controlled by the off-grid inverters. These transformer-less units give a much greater capacity/dollar than the off-grid inverters (but only operate during the day). For effective control, grid-tied inverter capacity should not exceed off-grid inverter capacity [Victron] and therefore we settled on 15 kVA additional grid-tied inverter."

Figure 4.14, below "shows the additional components (highlighted in yellow) required to enhance the mini-grid plant to handle eCooking loads in addition to expected growth in demand."

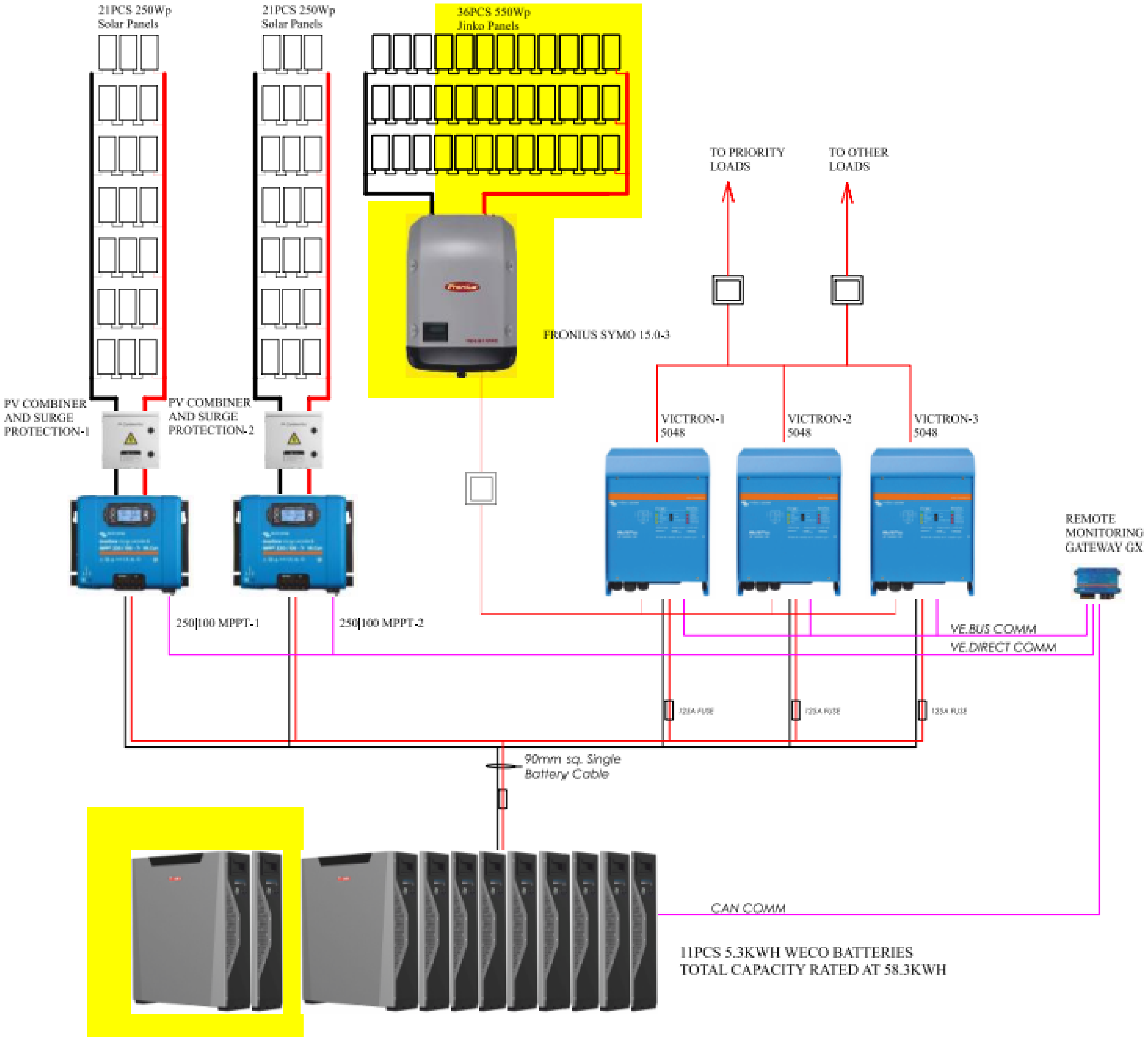


Figure 4.14: Upgraded mini-grid system to support increased loads. New components highlighted in yellow. Developer 4, 2023 [4] [5].

“In essence, approximately 20 kWp of the new total 30 kWp PV is allocated to a 15 kVA grid-tie inverter AC-coupled to the Victron off-grid inverters, with the existing 10 kWp DC-coupled via MPPT chargers to the battery, whose capacity is increased to 58.3 kWh.”

Financial modelling

The baseline and upgraded scenarios were assessed in terms of financial feasibility. An important assumption on system losses was made: “Under the baseline scenario, there are high technical and non-technical losses in the mini-grid (around 50% total generation), which would be reduced to around 10% in the upgraded scenario. In the upgraded scenario, this will be addressed in two ways, firstly by three-phasing the mini-grid network to reduce thermal losses. This will be undertaken by the utility and represents a subsidy to the project. Secondly, use of smart metering system, that will allow variable tariffs and secure mobile payments, removing most if not all of the non-technical losses.”

This estimated reduction in total system losses from 50% to 10% is high, and would require piloting to test its validity. It would also be important to understand any implications of loss reduction on mini-grid infrastructure, i.e. would distribution system upgrades be required to accommodate higher power transmission?

The study reported that "An outgoing item in the Upgraded scenario cashflow is an incentive payment to the SACCO who will be organizing the marketing, credit facility, sale and after sales of the eCookers. The payment will be a percentage (assumed 15%) of the daytime revenue from eCooking, giving the SACCO a motivation to increase sales and use during periods of solar generation."

The CAPEX of the upgraded system is shown in Table 4.6, illustrating the relative financial weight of each component.

Table 4.6: Capital costs of upgrading mini-grid to accommodate eCooking. Developer 4, 2023 [4] [5].

Item	Cost USD
15 kWp 550W Jinko Solar	7500
15 kVA Fronius Symo	5000
10.6 kWh WECO li-ion	5150
Smart Metering system	8100
Demand control devices	3000
Installation	2500
	31250

The cashflow comparison of baseline and upgraded scenarios is shown below, Table 4.7. Both scenarios assumed project life of 10 years and a discount rate of 5%.

Table 4.7: Cashflow analyses of the Baseline and Upgraded scenarios over a 10-year project period. Developer 4, 2023 [4] [5].

Baseline scenario

Year	CAPEX (USD)	OPEX (USD)	Generated (kWh/d)	Losses	Tariff (USD)	Sales (USD)	Discounted cashflow (USD)
1	0	1991	32.0	50%	0.29	1669	-323
2	0	1991	40.0	50%	0.29	2086	90
3	0	1991	42.0	50%	0.29	2190	180
4	0	1991	44.0	50%	0.29	2294	262
5	0	1991	44.0	50%	0.29	2294	249
6	0	1991	46.0	50%	0.29	2399	319
7	0	1991	46.0	50%	0.29	2399	304
8	0	1991	46.0	50%	0.29	2399	289
9	0	1991	46.0	50%	0.29	2399	276
10	0	1991	46.0	50%	0.29	2399	262
						NPV:	**1908**

Upgraded scenario

Year	CAPEX (USD)	OPEX (USD)	generated (kWh/d, high)	generated (kWh/d, low)	Losses	Tariff high (USD)	Tariff low (USD)	Electricity sales (USD)	Incentive to SACCO	Discounted cashflow
1	31250	1306	25.6	18.4	10%	0.36	0.21	4297	216	-28475
2	0	1306	29.1	20.9	10%	0.36	0.21	4883	246	3173
3	0	1306	32.5	23.5	10%	0.36	0.21	5469	275	3527
4	0	1306	36.0	26.0	10%	0.36	0.21	6055	305	3840
5	0	1306	39.5	28.5	10%	0.36	0.21	6641	334	4115
6	0	1306	43.0	31.0	10%	0.36	0.21	7227	364	4355
7	0	1306	43.0	31.0	10%	0.36	0.21	7227	364	4147
8	0	1306	43.0	31.0	10%	0.36	0.21	7227	364	3950
9	0	1306	43.0	31.0	10%	0.36	0.21	7227	364	3762
10	0	1306	43.0	31.0	10%	0.36	0.21	7227	364	3583
									NPV:	**5976**

The introduction of eCooking led to an almost three-fold increase in electricity sales revenues – from a total of $22,528 to $63,480, even with the specified reduction in daytime tariff. This resulted in a three-fold increase in the NPV, over the 10-year project period, from US$1,908 to $5,976.

It is important to note that this increase is not only due to the introduction of eCooking in the model but also the reduction of energy losses due to smart meters (from 50% to 10%). The reduction in OPEX from $1,991 to $1,306 also increased profitability – due to the installation of smart meters, the need for a full-time staff member to collect payments was removed.

The payback period for the project increased from 4 years to 9 years. This is due to the high CAPEX in the upgraded scenario, compared to zero in the baseline scenario, requiring 9 years of increased electricity sales to repay. However, as stated, the NPV over the 10-year period was higher in the upgraded scenario, even with only two years of operation beyond the payback period, showing that eCooking vastly increases profitability in the long term.

Replacement costs for mini-grid infrastructure such as batteries were not considered. As the mini-grid has been operating for 8 years, it is likely that the batteries would require replacement within the 10-year project period, in the baseline scenario, and possibly also in the upgraded scenario (within 10 years of usage). The study reported: "The expected lifetime of the main system components is greater than the project cashflow period of 10 years, so significant replacement costs should not occur in that timeframe."

The next two study summaries, Project 5 and Project 6, illustrate the results of introducing eCooking at very low and very high penetrations, respectively.

4.2.2 Project 5

If staying within mini-grid load capacity limits, eCooking increases revenue and therefore IRR, but penetration is limited to low levels, so returns are modest.

In Project 5, modelling showed that only 200 HHs (out of 3,000) could adopt eCooking, which would result in a very small increase in IRR.

Bullet point summary:

- D5's 600 kWp solar hybrid mini grid installed on an island currently serves around 3,783 customers, of which 80% are households (3,026).
- The mini grid system consists of a 600 kWp PV system, a 385 kWh lithium-ion battery, and a 200 kVA Gen-set.
- The results from an EPC eCooking pilot of 30 households in the community showed that the average electricity consumption for households with EPCs increased by 30%, per household.
- Modelling limited EPC penetration in the mini grid to a maximum of 200 customers due to capacity, though it was unclear how this conclusion was arrived at, and how the EPC cooking load profiles were created.
- For the assessed scenario of 200 households adopting eCooking (7% of the community), a small increase in overall electricity demand of only 2% was calculated. No upgrade to mini-grid infrastructure was required for this scenario.
- Adding 200 EPCs to the existing load mix would increase the generator run time from 2 hours per day to approximately 3 hours per day. This would translate to approximately 30% increase in diesel fuel cost,

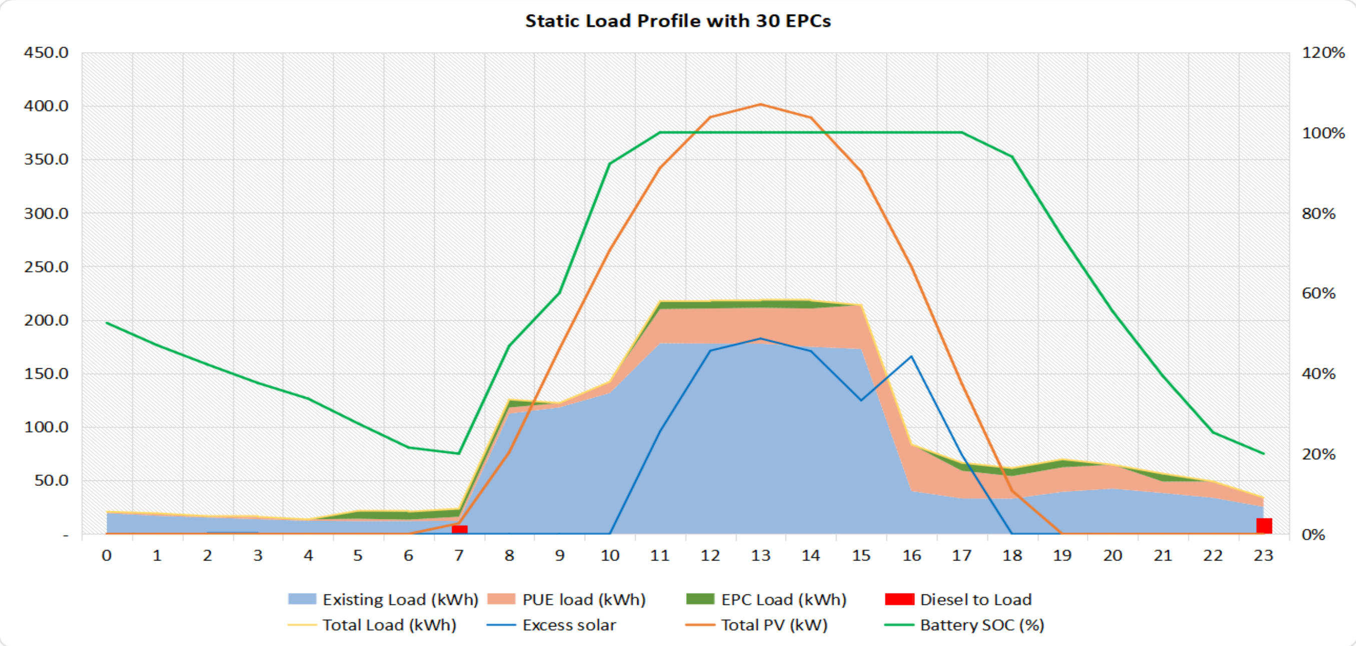
increasing OPEX. However, increased electricity sales meant that, overall, the IRR increased slightly, from 7.69% to 7.84%, with a payback period of two years.

- Diesel generator usage depended on exactly when eCooking occurs. Further details are required on how the eCooking load profiles were constructed.
- Increasing the number of EPCs beyond 200 pieces to, for example, 400 pieces would trigger a plant expansion of at least 50% for the battery bank and 16% for the solar panels. This would translate to an expansion of CAPEX of about USD 100,000.
- Load management techniques are planned to reduce gen-set running hours in a day e.g., lower daily tariffs for cooking to move people during day-time cooking.
- Additional scenarios should have been assessed, with higher penetrations of eCooking, and modelling of upgrade requirements, and their costings, to understand the economic viability of increasing electricity sales through eCooking to pay off investment in upgraded generation and storage infrastructure.
- Overall, the study showed that introducing eCooking increases revenue and profitability. The implementers anticipated an average monthly sales volume of approximately 20 EPCs, with expectations of steady growth as more people become aware of the benefits and advantages of e-cooking, which would further increase revenue.

Detailed summary:

The study focussed on a 600 kWp solar hybrid mini grid installed on an island, serving around 3,783 customers, of which 80% were households (3,026). The mini grid system consisted of a 600 kWp PV system, a 385 kWh lithium-ion battery, and a 200 kVA diesel generator.

The results from an EPC eCooking pilot of 30 households in the community showed that the average electricity consumption for households with EPCs increased by 30%, per household. Modelling limited EPC penetration in the mini grid to a maximum of 200 customers due to capacity. Figure 4.15 below illustrates the modelling conducted, first for 30 EPCs and then for 200 EPCs. The diesel generator supplies the load when the battery state of charge (SoC) drops beneath 20% and there is no solar power available. It is unclear how it was determined that the mini-grid could accommodate a maximum of 200 EPCs, and how the EPC cooking load profiles were created.



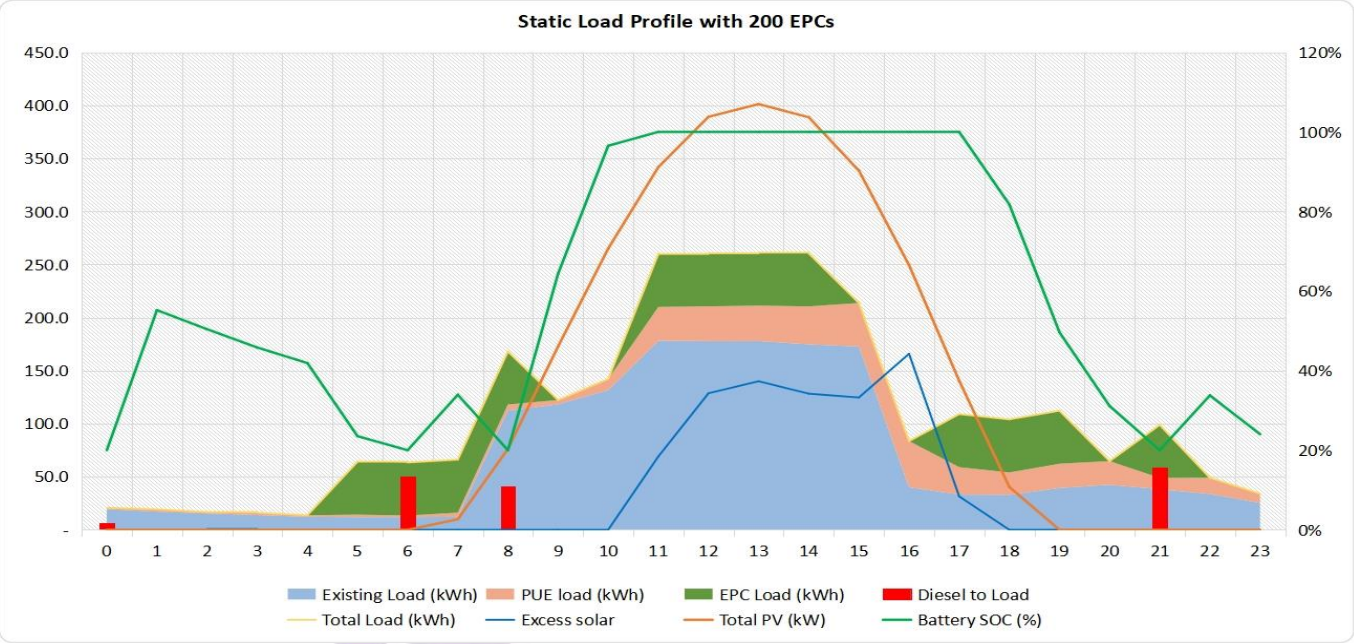


Figure 4.15: Mini-grid technical model for 30 EPCs (top) and 200 EPCs (bottom), with power flows in each scenario. Developer 5, 2023 [6].

The study reported that 200 households adopting eCooking (7% of the community) would lead to a small increase in overall electricity demand of only 2%, for which no upgrade to mini-grid infrastructure would be required.

Adding 200 EPCs to the existing load mix would increase the generator run time from 2 hours per day to approximately 3 hours per day, as shown in Figure 4.15. This would translate to approximately 30% increase in diesel fuel cost, increasing OPEX. The model was limited in that diesel generator requirements depend on the EPC load profiles, for which details on assumptions were not provided, and the resolution was only hourly, requiring averaging, and not capturing true demand peaks which would constitute short electricity usage events.

The study assessed the financial implications of adding 200 EPCs to the community mini-grid, as shown in Figure 4.16, below.

Base Case

USD "000"	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Revenue	82	219	361	429	458	488	519	549	584	619
Expenses	(219)	(265)	(244)	(240)	(240)	(243)	(246)	(249)	(253)	(256)
EBITDA	(137)	(46)	117	190	218	244	273	300	331	363

IRR=7.69%

Base Case+ E-cooking

USD "000"	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Revenue	82	220	375	446	477	508	541	573	610	647
Expenses	(219)	(267)	(262)	(257)	(258)	(260)	(263)	(266)	(269)	(273)
EBITDA	(137)	(47)	113	189	219	248	275	307	340	374

IRR=7.84%

Figure 4.16: Cashflow analyses for baseline and eCooking scenarios. Developer 5, 2023 [6].

Increased electricity sales meant that, overall, the IRR increased slightly, from 7.69% to 7.84% (an increase of 1.95%), with a payback period of two years for both baseline and eCooking scenarios. Total expenses increased by 5.7%, from USD 2,455,000 to USD 2,594,000. Details on expenses were not provided, apart from that diesel fuel costs were one constituent. The total revenue increased slightly from USD 4,308,000 to 4,479,000 across the 10 years (a 3.97% increase).

The study reported that increasing the number of EPCs beyond 200 pieces to, for example, 400 pieces would trigger a plant expansion of at least 50% for the battery bank and 16% for the solar panels. This would translate to an expansion of CAPEX of about USD 100,000. However, details on how these upgrade requirements were determined, were not provided. It was also reported that an "increase in back up will allow for up to 260 EPCs and there will be over 50% reduction in generator run hours." However, once again, battery capacity upgrade requirements were not provided.

Load management techniques would be explored to reduce diesel generator running hours, such as lower daily tariffs for cooking to move people during daytime cooking. However, surveys and experiments with load limiters showed that most people want to cook in the evening. Data collection on cooking practices was conducted twice, whilst load limits were in place, and then again once they had been disabled to enable evening eCooking. "Participants expressed concern with the load limiters", and once the limiters had been disabled, the percentage of HHs using their eCookers in the evening increased from 8% to 60%, showing that there is a desire to be able to use eCookers in the evening.

It was noted from focus group discussions that "during the fishing season, when most activities occur at night, incentivising daytime eCooking can be effective. However, outside of this period, it can be challenging". Therefore, incentives will have to be carefully designed to encourage daytime eCooking. The report did explain that: "It was assumed that at least 30% of the EPCs may be used in the evening hours beyond 6pm. This means that these EPCs will be entirely powered by the battery bank."

Additional scenarios could have been assessed, with higher penetrations of eCooking, and modelling of upgrade requirements, and their costings, to understand the economic viability of increasing electricity sales through eCooking to pay off investment in upgraded generation and storage infrastructure.

Overall, the study showed that, if staying within mini-grid load capacity limits, eCooking just increases revenue and therefore IRR, but penetration is limited to low levels.

4.2.3 Project 6

Projects should not consider very high eCooking penetrations immediately if the CAPEX required for upgrades is too high, while providing eCookers free of charge harms the financial viability of the project and may not generate ownership.

In Project 6, the scenarios integrated 105 eCookers into a community of around 124 HHs, and customers were not charged for eCookers, contributing to a high payback period, alongside assumptions of unrealistically high eCooking durations and levels of coincidence across households.

Bullet point summary:

- Solar mini-grid, 24 kW kWp PV and 28.5 kWh battery, 31 large HHs (each with around 4 families, i.e. around 124 HHs, effectively).
- Daily average redundant energy of 60 kWh, during peak solar production hours.
- First, the modelling assessed the current capacity for eCooking in the mini-grid, without upgrading the infrastructure. Then, an upscaled eCooking scenario, including mini-grid upgrades, was considered.
- Modelling using PVSyst suggested only 10 eCookers could be integrated into the mini-grid currently, although assumptions included four hours of continuous eCooking for each HH, which seems high considering that EPC cooking often takes around 40 minutes per dish or less [12], and only draws high power continuously for the preheat period of around 15 minutes, and that fuel stacking is inevitable. It is likely that many more than 10 cookers could be adopted.
- To scale up eCooking, a scenario integrating 105 eCookers into the community was assessed, with upgrading of the mini-grid power generation and storage.
- Considering only investment of the eCookers, totalling $10,340, the payback period was 4 years, with NPV $7,895 after a ten-year project period. However, this ignored the required investment in infrastructure upgrades.
- Considering the addition of a 25 kW PV generator, 20 kWh lithium-ion battery and a demand-side management solution, and the cost of the eCookers, the total investment required was $71,782. This increased the payback period to 18.4 years, with the revenue generated insufficient to counter the high CAPEX and OPEX required.
- The project could have considered refining its eCooking load profile modelling i.e. reducing the initial number of eCookers from 105, considering shorter cooking durations, short high-power periods for EPC cooking, reduced coincidence of eCooking across HHs, and fuel stacking reducing the number of eCooking dishes per meal. Customers could purchase the eCookers themselves, reducing project costs.
- The method and modelling to determine upgrade requirements was not explained.

Detailed summary:

The study focussed on a solar mini-grid, which has 24 kW solar PV capacity and 28.5 kWh battery capacity, and serves 31 large HHs (each of around 4 families, i.e. around 124 HHs, effectively).

First, the modelling assessed the current capacity for eCooking in the mini-grid, without upgrading the infrastructure. The study found that unused “redundant” solar energy was being generated, on average 60 kWh per day, mostly during peak sunshine hours from 11am - 4pm, when the battery was fully charged and the demand was low. The report explained that the during these hours “demand is usually low because customers will be in their farms/market/businesses”. Figure 4.17 provides a visual example of the mini-grid performance, in terms of power generation, nominal power, power consumption and redundant power, the latter of which is defined as the potential PV power generation that goes to waste due to low demand on the mini-grid during peak sunshine hours, when the battery is fully charged.

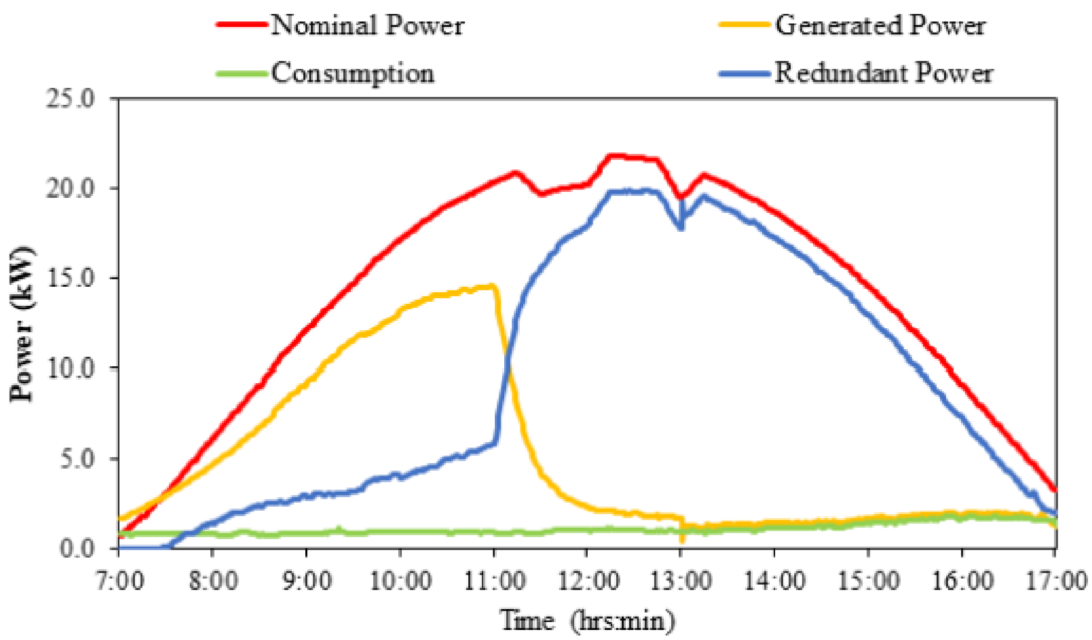


Figure 4.17: Plot of nominal power, actual generated power, consumption (demand), and redundant power. Developer 6, 2023 [7].

Analysis identified that redundant energy of over 10 kWh was being generated for each hour between 11am and 3pm for most months of the year.

Modelling using PVSyst suggested only 10 eCookers could be integrated into the mini-grid currently, although assumptions included four hours of continuous eCooking for each HH, which seems high considering that EPC cooking often takes around 40 minutes per dish or less [12], and only draws high power continuously for the preheat period of around 15 minutes, and that fuel stacking is inevitable. The model was also considering the month with the lowest redundant energy. It is likely that many more than 10 cookers could be adopted in the community. Figure 4.18 shows the PVSyst modelling setup. Notably, the model assumed every appliance was used identically across the households, failing to take diversity in practices into account.

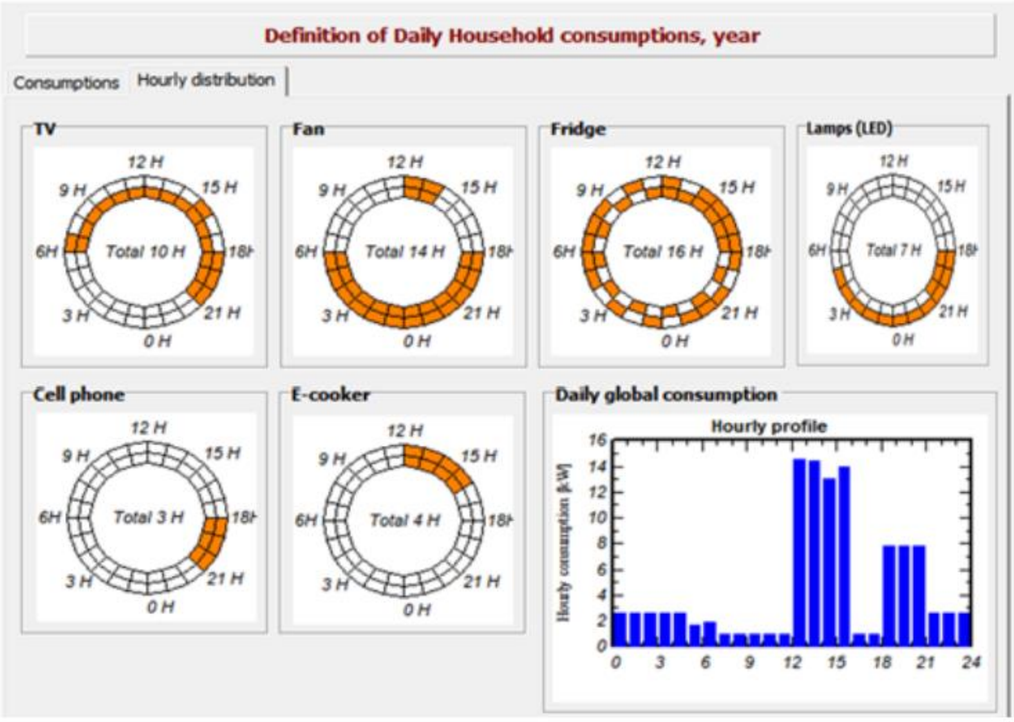


Figure 4.18: PVSyst modelling setup for including eCooking (10 eCookers). Developer 6, 2023 [7].

Figure 4.19 shows how eCooking would make use of the redundant energy depicted in Figure 4.17.

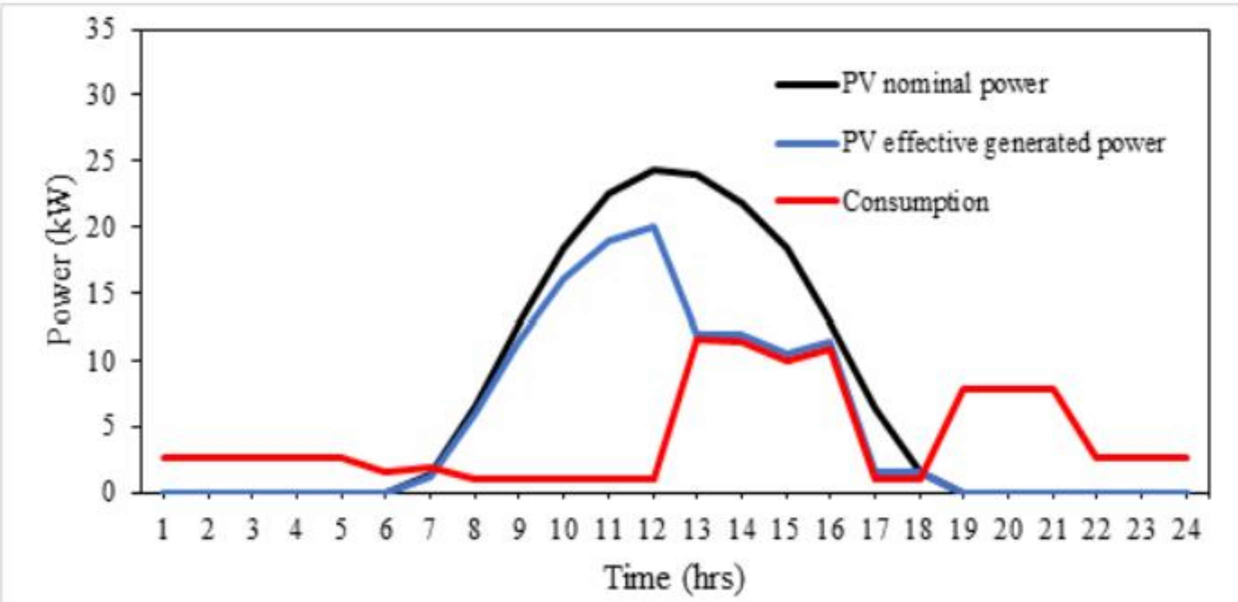


Figure 4.19: Power flows in the mini-grid with 10 eCookers adopted, showing how the load increases in the afternoon due to eCooking. Developer 6, 2023 [7].

To scale up eCooking, a scenario integrating 105 eCookers into the community was assessed, with upgrading of the mini-grid power generation and storage. The scenario included integration of 70 EPCs, each rated 1000 W, 30 locally fabricated eCookers with thermal energy storage (TES), each rated 1000 W, and 5 eCookers with TES rated at 3000 W, for small-scale commercial food vendors. The study commented: “An EPC has an advantage of relatively shorter cooking time compared to the TES cooker, of the same size. However, EPC needs electric battery storage to run in the evenings, during off-sunshine hours, whilst the TES can store heat in the daytime to cook in the night."

The study described demand-side management plans: "In the operation of the modified mini-grid, we will employ our developed model called to facilitate load." The model "integrates Advanced Metering Infrastructure (AMI) into a solar PV mini-grid system using remote sensors, metering devices, IoT and load limiters. In the special case of integrating eCooking onto the mini-grid, we would incorporate timer-switches with the eCookers. The timer-switches are programmed to operate within specific times of the day to maximise the use of the PV mini-grid energy generation. Our simulation results have shown that the best time to do cooking on a mini-grid is between the hours of 12pm and 4pm. After 4pm when the sun is setting down, the mini-grid energy generation is low, and adding large volumes of ecooking will take energy directly from the battery energy storage, which is technically and socio-economically disadvantageous."

The study in also recommended switching household lighting to low power LED bulbs in order to save energy and make use of solar power generation for high-power end uses such as eCooking.

However, the willingness of cooks to confine eCooker usage to the afternoon period was not discussed, nor were the expected levels of fuel stacking. Piloting would be required to assess the extent to which cooks are willing to use their eCookers in the afternoon only.

Regarding modelling of the 105 eCookers scenario, the report stated that the addition of a 25 kW PV generator 20 kWh lithium-ion battery would be required. However, details on the modelling that determined these upgrade requirements were not provided. Financial analysis was provided, beginning as follows:

"Scenario 1 focuses on investment solely comprising the cost of the eCookers. In Scenario 1, the initial investment for 105 eCookers is $10,340. The cooking activities involve a daily duration of 4 hours, utilising eCookers with a power rating of 0.81kW. The tariff is set at $0.048/kWh, based on the Public utilities regulatory commission tariff rate of customers of that category. Based on historical tariff data, we have assumed a yearly increment of tariff at 5%, annually. The discount rate used in the model is assumed to be 26% based bank bill rates. The analysis revealed that for scenario 1, the payback period (breakeven point) is 4 years and the NPV is $7,895 after a 10-year project period."

Therefore, the report claimed a short payback period for this scenario. However, as the scenario did not consider the costs of upgrading the PV and battery, instead including only the total cost of the eCookers in the specified CAPEX, the usefulness of this scenario is limited. Furthermore, the model specified that "the OPEX specifically includes the maintenance cost of the eCookers, which is assumed to be 10% of the revenue generated, as well as the salary of the vendor employed in the community to sell electricity credit to the customers." The rationale for setting OPEX at 10% of revenue was unclear, and the OPEX of the mini-grid infrastructure was not considered.

The analysis continued as follows: "In Scenario 2, the financial model considers investment $71,782, which includes both the expansion/modification of the mini-grid infrastructure and the cost of eCookers. OPEX including maintenance/repairs and salaries of the vendor employed to sell electricity credit is also considered."

"It is observed that the total cost of OPEX and CAPEX over the ten-year period consistently exceeds the revenue generated. Consequently, within the given timeframe of 10 years, no breakeven point is reached, indicating that cooking on mini-grids in this particular scenario is not financially profitable. Change in tariff (increment in tariff) could potentially result in positive NPV at the end of the analysis period. However, the regulatory environment does not allow private companies to develop their own tariff for decentralised solar PV mini-grid energy systems."

In this scenario, which did consider CAPEX and OPEX of the upgraded mini-grid infrastructure, the payback period increased to 18.4 years, with the revenue generated insufficient to counter the high CAPEX and OPEX required. The report therefore doubted the feasibility of adding eCooking to the mini-grid. However, there are several factors to consider:

- The eCookers were provided free of charge, with the report stating that this would be preferred by the customers. Although the preference is unsurprising, it is generally understood that customers who pay for an appliance are more likely to generate a sense of ownership for it and therefore use it and take care of it. Therefore, some of the CAPEX could have been recouped by charging customers for the eCookers, with or without subsidy.
- The number of eCookers could have been reduced, considering a lower initial eCooking penetration, to reduce upgrade requirements and therefore CAPEX. The scenarios integrated 105 eCookers into a community of around 124 HHs (31 large HHs of around 4 families each).
- eCooking modelling assumptions heavily affect outcomes and must be carefully designed, including accounting for inevitable fuel stacking. As mentioned, considering four hours of continuous coincident eCooking across every HH is unrealistic, as EPCs only draw high power for a short preheat period, cooking timings and practices vary across HHs, and fuel stacking is inevitable and would reduce total eCooking durations per day. The proposed average daily eCooking energy consumption was 3.24 kWh per HH (0.81 kW for four hours), which is much higher than that assumed by the other studies.

Therefore, the study provided an interesting insight into the difficulty of adding eCooking to an existing mini-grid at very high penetration and very high usage levels, and without recouping eCooker costs from cooks.

4.3 Connecting mini-grids to the national grid

The last category summarises Project 7, which also evaluated adding eCooking to an existing mini-grid, but included plans for connecting the mini-grid to the national grid. The micro hydropower (MHP) mini-grid system presented another difference between this study and the others.

4.3.1 Project 7

eCooking can improve load factor and revenue of struggling micro hydropower (MHP) mini-grids, and grid interconnection can enable energy sales and reduce mini-grid upgrade requirements, meeting demand during peak load periods.

In Project 7, introducing eCooking at high penetration led to an almost 50% increase in revenue. However, distribution system upgrade (transformers) costs and grid connection costs were very high, vastly outweighing increased revenue, so a high level of support was required.

- Micro hydropower mini-grid, 68 kW, 533 consumers, mostly domestic, some commercial such as mills, hotels, restaurants. The plant was struggling for financial sustainability due to low electricity consumption.
- eCooking load modelling was built on a survey finding that 377 HHs (715) were interested in adopting eCooking appliances, particularly induction cookers.

- Using historical data showing that 100% induction cooking requires 57.6 kWh per month, and assuming that households cook 50% of their dishes with electricity, modelling showed that the daily community peak load could increase up to 230 kW, depending on the level of coincidence of cooking across households.
- This peak was found to occur in the morning period, at breakfast time, aligning with peak community activity.
- Although peak loads were predicted to increase drastically due to eCooking, no mini-grid plant upgrade would be required, due to planned interconnection to the national grid, enabling import and export of electricity as required. However, five additional transformers and upgraded household wiring would be necessary, as well as system improvement to enable grid interconnection, requiring a total of USD 240,313.
    - System improvement and grid connection – USD 89,966
    - Distribution system upgrade and household wiring – USD 149,943
- The introduction of eCooking would significantly increase the demand and therefore the revenues. For example, with customers cooking 50% of their meals with electricity, the annual income increased to almost USD 11,246. This is an increase of almost 50% of the income without eCooking demand.
- Additional revenue from power export to the national grid during off-peak periods such as during the afternoon and overnight would increase the total income further, to around USD 24,557 (considering 70% grid availability), which is around 3.2 times the original revenue (without eCooking demand).
- The total costs (USD 240,313) heavily outweighed the increased revenue (USD 24,557). The study reported seeking support from Sustainable Energy Challenge Fund (SECF) and from the local government, total USD 67,474. Therefore, a high level of additional support would still be required.

Detailed summary:

The study focussed on a 68 kW MHP which supplies 533 consumers, mostly domestic, with some commercial consumers such as mills, hotels and restaurants. It was observed that though the MHP has been running for the past 9 years, the electricity was mainly being used for lighting in the evening and morning, and the remaining electricity was being wasted due to negligible electricity usage for economic activities, leading to low financial sustainability. This situation had made the community realise that action was required and productive end uses should be promoted in the community that will not only increase the profitability of the MHP but also improve the socio-economic condition of the consumers.

Load modelling

The average monthly electricity consumption per household in the community was found to be only around 7 kWh. The average peak load of each household was only 99.28 W. During the daytime period, the load was dominated by commercial loads such as mills and restaurants. The mills were not allowed to run in the morning and evening. The individual household peak demand occurred at 8pm. The measured system peak was 19.54 kW, occurring between 8pm and 9pm. The existing daily load profile was measured from the power plant and is shown in Figure 4.20. The two dips in the profiles correspond to when the generator was rested, twice per day.

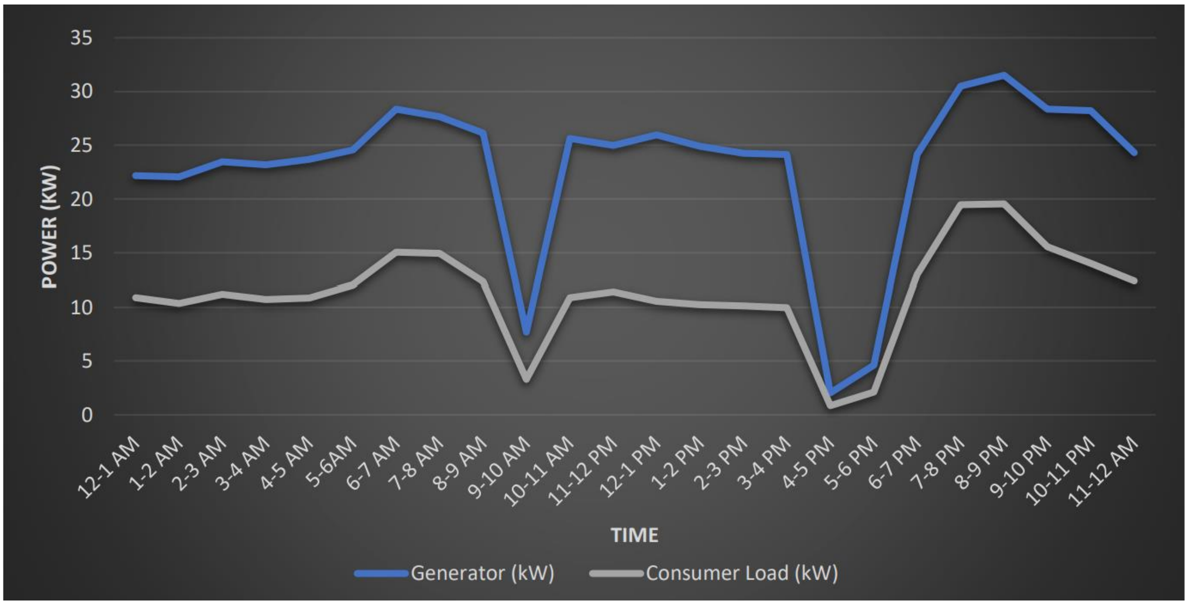


Figure 4.20: Community average generated power and load profile. Developer 7, 2023 [8].

The average monthly energy consumption of 100% electric cooking, with induction cookers, was found to be 57.6 kWh from a separate study conducted in 10 households. The baseline survey conducted in 200 HHs and 11 enterprises suggested that the morning cooking times in the community were mostly between 7am and 9am with almost 91% of households starting to cook between 7am and 8am. In the evening, however, the cooking times ranged from 5pm to 9pm. The coincidence possibility of the eCooking loads was high during the morning period of 7-8 am, suggesting that this would become the daily demand peak.

The household survey suggested that 71% of the households were interested in adopting eCooking, equating to around 377 customers. Analysis assumed the consumers would cook 50% of their meals with electricity, which would equate to a monthly eCooking energy consumption of 28.8 kWh, or 0.96 kWh per day. With 377 HHs adopting eCooking, the existing monthly average community demand would increase from 3,731 kWh to 11,950 kWh, an increase of 220%.

The study focussed on evaluating the effect of different levels of coincidence of cooking during the morning peak period, as follows:

"Considering 20-minute and 30-minute cooking time slots, the hour slot is divided into 3 slots and 2 slots respectively. Dividing the total number of consumers by the slots will give the consumers coinciding for electric cooking. The scenario 1 indicates the induction cooktop operating at 1200 W with one third of the consumers coinciding in an hour. The scenario 2 indicates the induction cooktop operating at 2000 W with one third of the consumers coinciding. The scenario 3, and 4 indicates the induction cooktop operating at 1200 W, and 2000 W with half of the consumers coinciding in an hour respectively. Finally, scenario 5 indicates the induction cooktop operating at 1200 W with all the consumers coinciding in an hour.

The additional load due to electric cooking was then added to the existing system load. The system peak demand is around 230 kW in the 7 am to 8 am slot." Figure 4.21, below, shows the modelled community-wide electricity demand profile for different levels of eCooking coincidence, assuming 377 HHs adopting eCooking and using it for 50% of their meals.

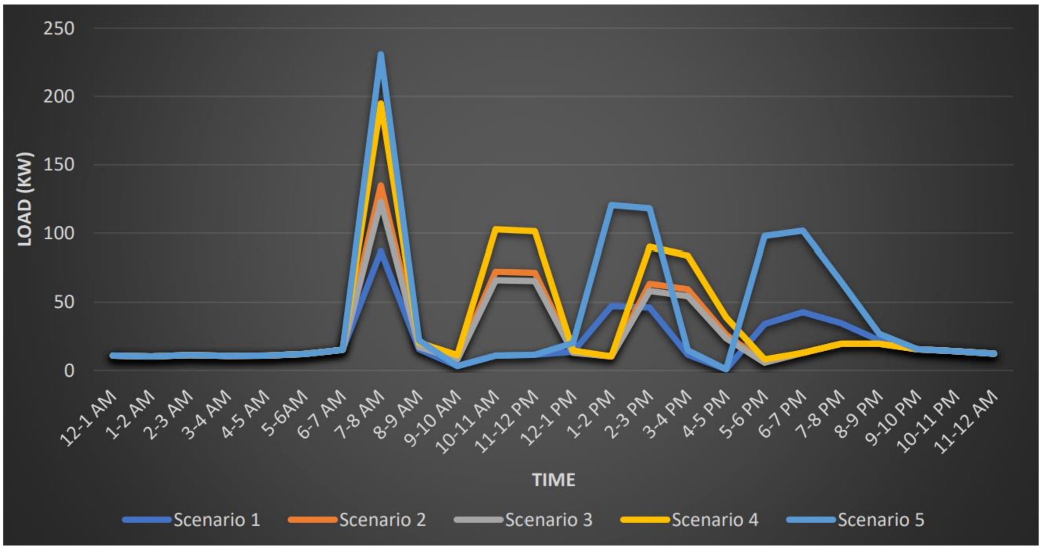


Figure 4.21: Projected daily average load profile with different eCooking coincidence level scenarios. Developer 7, 2023 [8].

The profiles show how different the peak load is for different levels of coincidence of eCooking. For example, the first scenario in which a maximum of a third of consumers are cooking simultaneously at any one time on their 1.2 kW induction cookers leads to a peak of around 80 kW, whereas, when all 377 consumers cook simultaneously in the fifth scenario, the peak reaches 230 kW. Therefore, eCooking modelling assumptions are very important for quantifying peak loads. The first scenario is likely to be more realistic than the fifth, because diversity in cooking timings and durations means coincidence levels are likely to be far lower than maximum.

The study reported that eCooking would therefore "significantly increase the system load especially during the cooking times (morning, day and evening). However, the load increment will pose no problem in load management as the MHP is being connected to the national grid in net metering mode. During cooking times, the power flows from the grid and during other times the power will flow from the MHP to grid." Selling power to the national grid when the demand is lower than generated power, and purchasing power when it is higher, is illustrated in Figure 4.22, for the fifth scenario: "In case 5, the imported electricity will be 162.95 kW, 52.64 kW, 50.135 kW, 30.115 kW, and 33.79 kW during 7-8 AM, 1-2 PM, 2-3 PM, 5-6 PM, and 6-7 PM respectively."

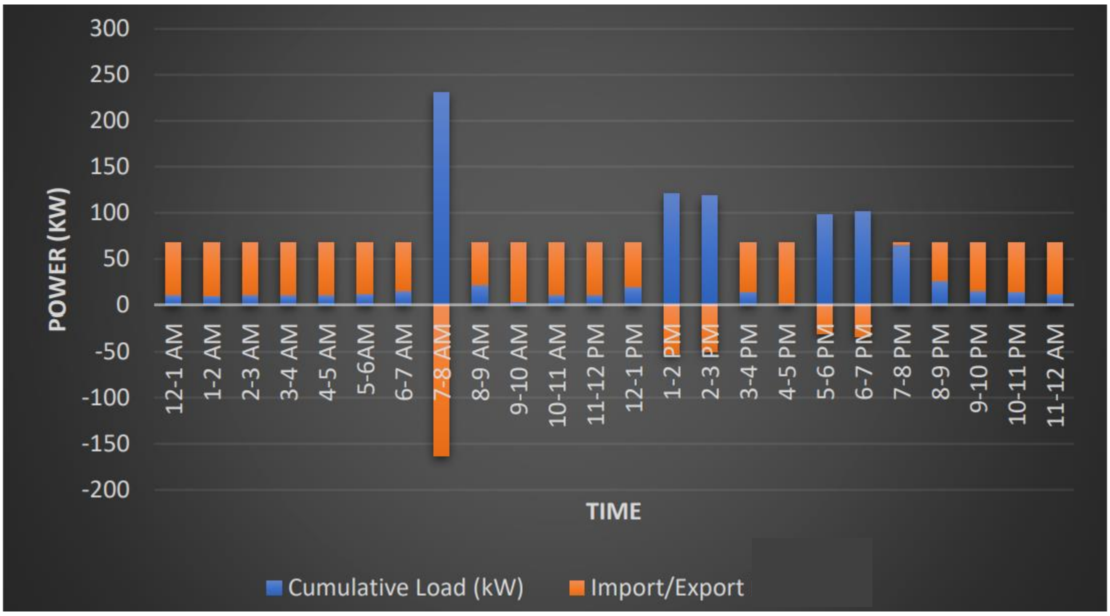


Figure 4.22: Hourly load profile for Scenario 5 depicting energy import and export to the national grid. Developer 7, 2023 [8].

Therefore, the study presented no plans to upgrade the MHP plant, instead: "The upgrade required in the model was for national grid interconnection. With this interconnection, it can be expected that power supply will be available all the time for cooking." The study reported that: "The grid connection of the MHP is already being implemented... The grid connection is targeted to be complete in January 2024."

However: "Along with the supply assurance the distribution system capacity needs to be upgraded to cater for the new demand of the consumers after eCooking uptake. The distribution system should be upgraded such that the consumers are supplied with quality electricity. Distribution transformers should be added in some load centres and upgradation of the conductors should be done to cater the electric cooking loads. The load forecast for electric cooking has suggested addition of 5 additional transformers of combined capacity 225 kVA." Details on modelling and on how these requirements were specified were not provided.

Required costs were presented: "The grid connection and the system improvement of the MHP was estimated to cost" USD 93,193, and "The cost of the retrofitting of the mini-grid or the distribution system upgradation including household wiring upgradation to support the eCooking loads is estimated to be around" USD 147,120. Therefore, total costs were USD 240,313.

Financial modelling

The report calculated how eCooking and grid interconnection would affect income from electricity sales, after first providing information on its current financial status, without eCooking. Average annual income was USD 7,575, while expenditure was USD 2,932. 76% of expenditure was for salaries, yet they were still lower than the national minimum wage. The income was insufficient to cover upcoming replacement costs of mechanical components of the MHP. Therefore, the MHP was struggling for financial viability, before the introduction of eCooking.

The study reported that the introduction of the eCooking load would significantly increase the demand and therefore revenues. For example, with all customers cooking 50% of their meals with electricity, the annual income would increase to almost USD 11,246, an improvement of almost 50%. Then, connecting the mini-grid to the national grid for power export would increase income further to a total of around USD 24,557, considering

70% grid availability, around 3.2 times the original revenue without eCooking demand. 70% MHP utilisation was deemed realistic due to the prevalence of various MHP system faults and poor national grid line reliability in mountainous regions.

Figure 4.23 shows the how income from customers and from energy exports at different levels of eCooking penetration changes. As evident, higher eCooking increases income from consumers, but reduce available power for export. Overall, the total income increases slightly with higher eCooking penetration.

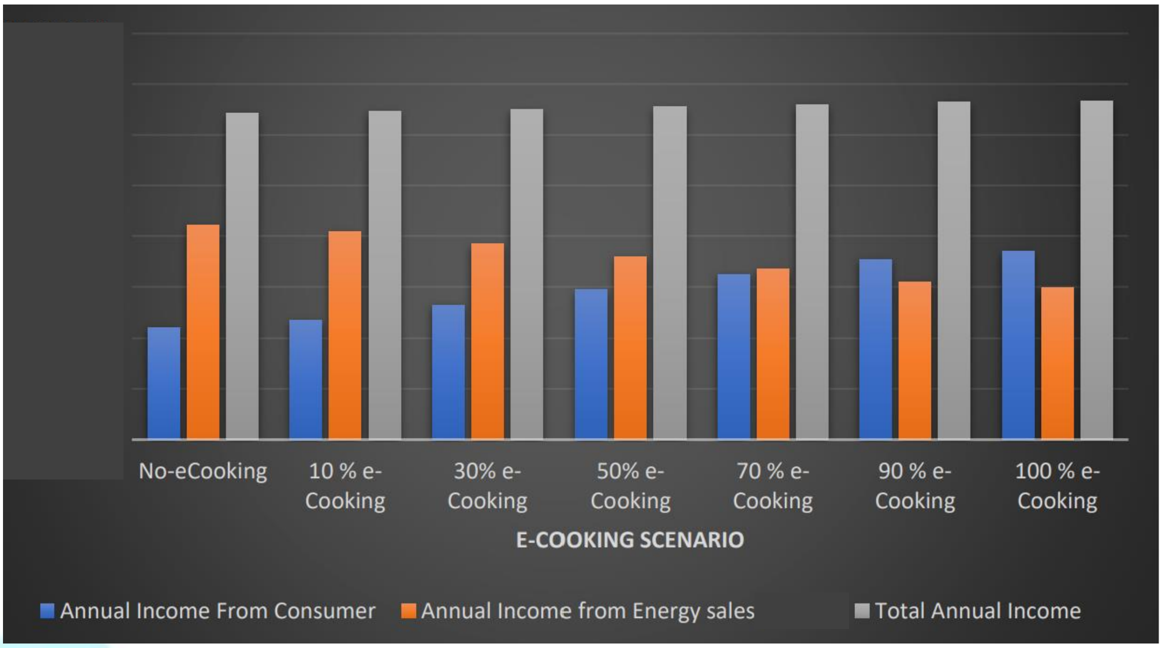


Figure 4.23: Annual income from consumers and energy sales to the national grid, at different eCooking penetrations, assuming 70% system availability. Developer 7, 2023 [8].

The study explained that: "Once the MHP gets connected to the grid, the net metering tariff rate is fixed by the regulator at USD 0.034/kWh in wet season (6 months) and USD 0.063/kWh in dry season (6 months). Otherwise, the tariff rate of the mini-grid is USD 0.75 + (0.037 * energy consumed per month)." Therefore, depending on the season, selling power to the grid could generate more revenue than selling it to MHP community consumers.

The study claimed that: "With the new income the cooperative can afford to increase the salary of the staffs, repair and maintenance works and pay the insurance premium too."

However, the projected total annual income of USD 24,557 fell far short of the total costs of system improvement, distribution system upgrades, and grid connection, of USD 240,313, totalling only 10% of the aforementioned costs. The implementers reported seeking support from Sustainable Energy Challenge Fund (SECF) and from the local government, to generate USD 37,486, and USD 29,989 respectively, leaving the remaining USD 148,282 unaccounted for. This shows that, although eCooking can improve load factor and revenue of struggling MHP mini-grids, upgrades and grid connection are very costly, so a high level of support would be required. The study did not present a detailed cashflow analysis, which would have been useful for understanding financial viability.

5 Summary of non-technical results (community context and introducing eCooking)

This section focusses on non-technical aspects of introducing eCooking to mini-grid communities, from both the cook's perspective and the mini-grid operator's perspective, summarising findings across the studies. Widespread adoption of eCooking for a significant proportion of household cooking requires an environment which supports and incentivises cooks to use their eCookers. Firstly, current cooking fuel expenditure and projected eCooking expenditure across the study contexts are compared, after which findings on mitigating eCooker upfront costs are summarised. Reported operator plans around generating awareness of eCooking benefits, sales strategies, training for cooks, after-sales services, and eWaste management are presented.

5.1 Cooking expenditure and adopting eCooking

Existing electric cooker usage in the mini-grid communities was very low or totally absent, limited to rice cookers and electric kettles only. Biomass was the most common cooking fuel for households across the different settings, with some people collecting firewood for cooking and others paying for charcoal. Collection of firewood, which took place to varying extents in Project 7, Project 3, Project 4 and Project 6, requires considerable time and effort, although those involved rarely attribute a monetary cost to it. In Project 6, the wet seasons present an extra drawback to firewood collection as the gathered wood can be sodden and difficult to burn.

Focussing on charcoal, average monthly costs ranged from $9.94 to $24.75 across four contexts in Project 1 ($9.94), Project 6 ($10.29), Project 2 ($19.07) and Project 5 ($24.75). In D5's context, where EPCs were introduced, 62% of the experimental group experienced an average cost saving of 43% with the introduction of an EPC, while 31% reported an increase in expenditure, attributed to transitioning to a higher service fee and tariff charges.

Project 7 and Project 2 projected future eCooking costs as actually increasing household cooking fuel expenditure. In D2's mini-grid portfolio eCooking was estimated to cost almost twice as much as charcoal cooking, while in Project 7, where most people collect firewood, unsurprisingly eCooking adds cost, and was predicted to approximately double or triple household electricity consumption if used for 50% and 100% of cooking respectively, from an average of USD 1.01 up to USD 2.09 and USD 3.17 respectively. However, both studies made a crude assumption of daily electricity consumption of almost 2 kWh, which is high and could be reduced if EPCs or induction cookers are used carefully. Also, for the Project 7 context, if comparing to the 36% who use LPG regularly for cooking, eCooking is almost 50% cheaper than LPG cooking (if used for all cooking).

An interesting point was made on how eCooking can enable saving to pay back upfront costs in Project 7: "The initial investment required for uptake of induction stove is around USD 74.97 per household which includes cost of electric cooktop and compatible set of utensils (pressure cooker, sauce pan, frying pan). The average monthly cost of LPG gas for household is USD 3.89, and while average monthly cost of e-cooking is about USD 0.86. The payback period analysis suggests the investment cost of consumers will be recovered in 25 months."

Project 2 reported the following, paraphrased: "under current proposed average tariffs, $0.56 / kWh, 1.94 kWh/day of eCooking electricity consumption amounts to USD 1.13/day. This value is considerably higher than charcoal costs of USD 0.60/day (self-reported) and USD 0.76/day (based on purchasing patterns) from the survey results."

Time-of-use tariffs and carbon financing were put forward to decrease eCooking running costs: “If for example cooking is done on an average daytime rate ~$0.45/kWh, the cost of electric cooking becomes USD 0.90/day.”; “Carbon finance could also be an elegant way to increase revenues while keeping costs low for customers and keeping the weighted average tariff charged to the end-customers below the regulated limit. Carbon financing might be able to deliver upwards of $0.1/kWh.”

In the mini-grid community in Project 4, 29 respondents were asked what it would take for them to want to switch to eCooking in terms of cooking fuel costs. As Figure 5.1 shows, the majority (60%) expressed their interest only if it is cheaper compared to their current cooking spending and delivers other benefits such as health and convenience. However, 31% of the respondents were willing to switch to eCooking even if it costs the same as their current cooking fuel cost, as long as there were additional benefits.

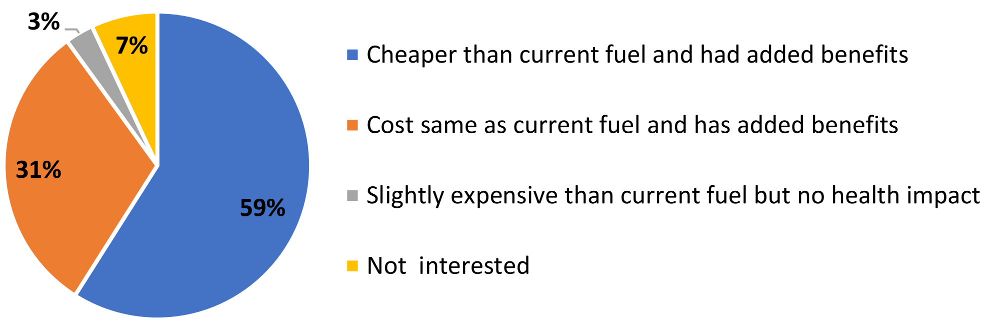


Figure 5.1: Willingness of mini-grid customers to switch to eCooking in Project 4. Developer 4, 2023 [4].

In D3’s mini-grid, a survey of 3,000 households found that people would be willing to pay up to $20.74 for their electricity per month, reducing to $15.56 in more challenging, mountainous regions. In Project 7, 55% were willing to pay the increased electricity cost for eCooking, while 38% were unsure. In Project 1, D1 found that customers would prefer small payments often, finding these more manageable than less frequent, larger payments.

A key finding across the studies was that geographic isolation and transportation costs can make traditional fuels expensive in certain areas, such as island communities. This presents an opportunity for eCooking in certain mini-grid communities. However, there are challenges to eCooking adoption which need to be addressed first, including awareness levels and financing options.

Overall, in three of the seven study contexts, most households were paying for charcoal, while in the D6’s context there was a mixture of purchased charcoal usage and collected firewood usage. Therefore, many people in mini-grids could transfer their charcoal expenditure to pay for electric cooking and, even when firewood is collected for free, reduced drudgery could free up time for income generation, increasing the feasibility of switching to eCooking.

There is a wide variety of expenditures on cooking fuel by businesses in mini-grid communities. As in domestic settings, biomass was the most common cooking fuel in businesses, although gas usage was more common than in households, especially in Project 7 and Project 3. Interviewed respondents in multiple studies indicated that their cooking fuel expenditure was high, reaching 40% of business income in Project 1. In Project 3, respondents said that the number of restaurants and street vendors could increase if the cost of cooking fuel decreased. This suggests a latent demand for more affordable energy solutions for cooking, which eCooking appliances could meet.

Others reported that business cooking takes a long time, especially when using charcoal or firewood. A transition to eCooking could drastically improve the experiences of businesses in mini-grid contexts, because the large amount of food cooked each day means that cost and time savings would be very high, higher than savings made when cooking two or three meals in households.

5.2 Mitigating upfront costs of eCooking appliances

A number of mechanisms for reducing the upfront costs of eCooking appliances were proposed. Asset financing was put forward by multiple studies and could be enabled through partnerships with SACCOs, co-operatives or companies. Subsidies could also be introduced to reduce upfront costs. Some studies proposed that grant funding would be highly effective, including results-based financing, detailing some of the available grant schemes. Several organisations described an intention to explore carbon financing opportunities but asked for technical support to understand and negotiate the process. One study proposed monetising the gender co-benefits of eCooking to enable further financing.

The mini-grid operator in Project 3 described a system whereby customers are provided appliances on credit according to their credit rating, with the amount of credit and specific terms tailored based on their historical consumption data. The system includes the potential for on-bill financing, described in this case as an option in the event of late repayment, through applying a surcharge to a customer's tariff.

5.3 Sales and awareness campaigns

To promote eCooking in their communities, all organisations reported that cooking demonstrations were very important and either conducted them or outlined plans to do so. Demonstrations allow customers to see and directly experience new technologies, providing opportunities to ask questions. The idea of allowing customers to try using the appliances was also put forward. Further measures and ideas for raising awareness included: radio and TV advertising, flyers and leaflets, billboards, public address systems, social media, eCooking videos, prize giveaways, leveraging community meetings, and training sales agents. Recipes could be provided through several of the aforementioned media.

Clear messaging on how the use of eCooking saves cooks money and, with Time of Use (ToU) tariffs, providing even bigger cost savings during the day, was proposed. One study asserted that distribution should be timed towards the end of the month so that more people could afford the eCookers. The studies also found that eCooking reduces cooking time and that participants responded well to this information. In Project 4, one participant said: "When you started cooking and told us that beans could be ready in 45 minutes, I did not believe it, but after the demonstration, I have believed that e-cooking is faster." Time-saving is another key benefit which should be communicated to cooks.

5.4 Sustainability and after-sales services

To ensure high customer satisfaction, and continued and sustainable usage of eCooking appliances, all studies described plans to provide detailed training to participants, resources to improve their cooking experience, and after sales services to combat any issues with the devices. The organisations emphasised that all eCooking appliances would have warranties which would be a key factor in sustainability and also described how repair and maintenance services could be provided. However, they also explained that the remote locations of many mini-grid communities combined with the lack of in-country manufacture and assembly of eCookers means that it is difficult to provide comprehensive after sales services such as repair capability and eCooking support and training.

For example, the eCooking market in Project 3's context is dominated by appliances imported from China, as is the case in many countries. Therefore, without local manufacturing plants with spare parts for repair of eCookers, and with many communities located in rural areas, the organisations explained that the initial focus should be on ensuring the quality and performance of the appliances and providing comprehensive initial training and support to customers. The introduction of eCooking appliance standards and testing protocols which ensure appliances are safe, easy to use, and cook local dishes effectively, is critical for ensuring quality, while local manufacture and assembly should also be pursued when feasible.

To reduce the need for repair, organisations proposed measures which overlap with the aforementioned awareness raising tactics, such as: demonstration events and in-person trainings, guidance documents including eCooking recipes, and cooking tutorial videos. Training should demonstrate proper usage techniques, cooking methods, and tips for optimising energy efficiency, while also focussing on troubleshooting of common issues, and safety features. Project 2 recommended group training sessions on safe and effective use of the appliances and in-situ safety and usage training when they are installed in the households or businesses, to ensure customers are comfortable cooking common dishes in a safe manner. Project 6 recommended diagrammatic illustrations in user manuals for residents without high levels of education.

Regarding after sales services, the importance of training local technicians and electricians to provide eCooking appliance repair services was emphasised by several studies, because warranties might require customers to take their eCookers to faraway locations for fixing which is often unfeasible. Local repair centres could be established and stocked with an inventory of spare parts, such as sealing rings and pressure valves for EPCs. In Project 7, initial discussions with the eCooking appliance supplier suggested that the supplier would provide repair and maintenance training to one person from the community. In Project 3, the idea of local appliance shops was put forward, from which appliances could be sold, training could be provided at the point of acquisition, and repair services offered. In Project 1 and Project 3 there were plans to provide customers with helplines and email support as well as routine visits from operator technicians to troubleshoot issues.

The studies also touched briefly on household wiring, emphasising the importance of having electricians assess wiring according to standards and implement upgrades where necessary based on load assessments. Local technicians and electricians could be trained as part of community capacity building to carry out household wiring assessments.

5.5 eWaste management

eWaste management is a crucial aspect of scaling eCooking. The studies acknowledged that further work is required around eWaste management and that recycling capability is currently limited. Project 4 explained that, as the eCooking supply chain within the country is still nascent, devices are usually replaced rather than mended, leading to a proliferation of eWaste. However, all studies emphasised the need to repair and reuse eCooking appliances as much as possible. Beyond that, the organisations planned to partner with recycling companies, set up collection points in the communities, raise awareness of eWaste so that cooks do not dispose of broken appliances, and partner with local electrical goods shops which could store spares from defunct appliances. Regarding partnerships, eWaste could be stored at agreed collection points in communities and, once a certain volume has been gathered, recycling companies could collect the appliances as part of an agreed partnership, or mini-grid operators could deliver to them. Creative arrangements around eWaste management are required alongside accelerated development of repair and recycling facilities at local and national levels.

6 Discussion

This section collates key technical findings across the study and discusses crucial aspects of integrating eCooking into mini-grid communities, such as daytime eCooking, DSM and ToU tariffs, fuel stacking, modelling tools and assumptions, diesel generators, and capacity shortage.

6.1 Overview of technical and financial results

Error! Reference source not found. Table 6.1, below, presents the key technical modelling findings across the studies, focussing on eCooking penetration and demand, community demand, and resulting upgrade requirements.

Table 6.1: Key technical modelling findings across the studies.

	Study	Customers	eCooking %	Daily average eCooking demand (kWh/HH/day)	% increase total demand	PV capacity % increase	Battery capacity % increase
New Build	Project 1 Portfolio	2,605	50	0.73	157	33	23
	Project 2 Portfolio (case study)	28 mini-grids (2,000)	10	1.94	34	47	0
	Project 3 Portfolio (case study)	30,000 (150)	50	0.36	45	N/A Assumed 0	N/A Assumed 0
Existing	Project 4	84	26	0.65	34	50	21
	Project 5	3,783	7	30% increase	2	0	0
	Project 6	124	85	3.24	N/A	104	70
Hydro	Project 7	533	71	0.96	220	N/A	N/A

Reading the table – a high percentage of ecooking is considered good, in column 4, as is increased total demand in column 6. Since batteries are often a significant expense, the need to not increase battery size is considered good in column 8.

In Project 1, the increase in total electricity demand across the portfolio when including eCooking was very high (157%). The required upgrade to total battery capacity was relatively low at 23%, with only two of the 12 mini-grids requiring battery upgrades, although upgrade modelling details were not provided. DSM measures of ToU tariffs and planned smart scheduling were assumed to enable mostly daytime cooking.

In Project 2, similarly, no battery upgrade was required for the case study, although some sites in the portfolio were reported to require battery capacity upgrades (details not provided). Therefore, once again, DSM was assumed to confine eCooking mostly to daytime, although evening fuel stacking was expected. In this study, DSM measures included ToU tariffs and power limits, as well as community engagement initiatives.

Project 3 presented reasonable assumptions. The developer naturally oversizes their grid design for future growth and so assumed eCooking can be added without extra CAPEX on the solar PV and battery storage installed capacities.

In Project 4, substantial upgrades were required to the existing mini-grid infrastructure, though again the battery upgrade requirement was lower than that of the solar PV capacity. DSM measures including ToU tariffs and plans for smart scheduling were specified.

In Project 5, no upgrades were required due to low eCooking penetration of 200 HHs with EPCs (7%). However, for 400 EPCs, the battery capacity upgrade specified was high at 50%, the only study to specify a higher battery upgrade than PV upgrade, although the modelling behind this was not explained.

In Project 6, high eCooking penetration, and very high modelled eCooking energy consumption, led to very high mini-grid upgrade requirements, necessitating unfeasibly high CAPEX.

In Project 7, high eCooking penetration was modelled, leading to a huge increase in demand, and hence very high CAPEX of system improvements (transformers) and grid connection.

Overall, most studies specified necessary upgrades to solar PV and battery storage installed capacities to accommodate increased eCooking. However, generally PV capacity upgrades were higher than battery upgrades, due to assumptions that DSM measures, particularly ToU tariffs, will encourage daytime eCooking rather than evening eCooking. Section 6.2 analyses DSM and ToU tariff proposals further.

Generally, it was found that introducing eCooking increased household electricity demand, and in turn, community-wide demand (both considered a good thing by developers), as well as increasing peak community demand (which was not always considered helpful). For most studies, upgrades to mini-grid infrastructure (solar PV capacity, battery storage capacity) were required to accommodate the increased peak demand. The outcomes are context specific, and it is clear even from Table 6.1, that for instance, for Project 6 to upgrade a small grid to accommodate eCooking for about two thirds of its consumers, it would have to double the PV panels, and increase the battery size by about two thirds. The introduction of eCooking in this context would significantly increase the CAPEX. However, in contrast a large network of grids in Project 1 reaching almost 25 times the households of Project 6, would require only a one third increase in PV Panels and 20% increase in batteries. The resulting impact on the mini-grids would be a very significant 150% increase in demand.

However, does this increase in demand translate into increased revenues and overall financial security?Table 1.2 Table 6.2 presents key aspects of the financial modelling conducted by the developers, providing percentage increases in key indicators where possible, and monetary figures where no baseline scenario was presented.

Table 6.2: Key financial modelling results across the studies.

	Study	Project period (years)	CAPEX % or USD$ increase	OPEX % or USD$ increase	Revenue % or USD$ increase	NPV % or USD$ increase	Payback period
New Build	Project 1 Portfolio	15	6.7	71	157	485	-56% (9 years to 4)
	Project 2 Portfolio	24	9	14	25	20	+18% (11 years to 13)
	Project 3 Portfolio	22	0	0	45	IRR +3%	-33% (9 years to 6)
Existing	Project 4	10	USD 31,250	-34	182	213	+125% (4 years to 9)
	Project 5	10	0	5.7	4	IRR +1.95%	2 years (no change)
		10	USD 71,782	USD 15,704	USD 79,917	USD -53,563	18.4 years

	Project 6						
Hydro	Project 7	N/A	USD 240,313*	USD 2,932	224%* (up to USD 24,557)	reduces	increases by 10 years or more

*while revenue greatly increases, the extra CAPEX (on transformers and wiring, not generation) is disproportionately high and greatly reduces its attractiveness.

In Project 1, high eCooking penetration led to a very positive financial evaluation of integrating eCooking into mini-grid planning, with huge increases in revenue and NPV and a 5-year reduction in payback period. As mentioned, this modelling could represent 100% eCooking penetration at 1-2 EPC dishes per day, or 50% at 2-4 dishes, or even 33% at 3-6 dishes, providing interesting insight into the effects of eCooking penetration and usage levels.

In Project 2, integrating eCooking into planning also led to increases in revenue and NPV, and the operator was able to reduce the tariff by 10%. The payback period increased slightly due to reduced tariff, increased equity payments and increased costs. eCooking penetration was lower than in Project 1, but with high assumed usage at 1.94 kWh per HH per day. As mentioned, an equivalent would be 20% penetration at 0.96 kWh/day.

Project 3 examined a large portfolio, and presented the entire investment plan. Inserting a 45% increase in revenue increases the IRR by 3%, however the developers concluded that "*with the inclusion of ecooking, we anticipate the ability to access capital on more commercial terms for future growth and replication of the mini-grid business case. This is a key outcome we aim to demonstrate through the second phase of the MECS COSMO program*."

In Project 4, introducing eCooking to the existing mini-grid also led to huge increases in revenue and NPV. As in Project 2, the daytime tariff was reduced by 25%, incentivising eCooking. The payback period increased due to high CAPEX of upgrade requirements for integrating eCooking as opposed to zero for the existing baseline scenario.

In Project 5, there were small increases in revenue and IRR (representative of NPV) due to low eCooking penetration and there being no upgrade requirements. The study also proposed doubling the number of EPCs, which would require USD 10,000 for mini-grid upgrade requirements. The generated revenue should be able to cover the CAPEX of upgrades, as the total revenue from 200 EPCs across the 10 years was USD 4,479,000, and would increase further with 400 EPCs. However, details on expenses were not provided, and further modelling would be required to assess higher eCooking penetration scenarios.

In Project 6, no baseline scenario was provided so the figures in Table 6.2 are actual costs and revenue in USD. CAPEX and OPEX were too high to be recovered by the generated revenue from eCooking, leading to a highly negative NPV after 10 years.

Project 7 did not provide a cashflow analysis, so figures are again provided in USD. There was a 48.5% revenue increase from eCooking, and 224% overall revenue increase including energy sales to the grid. However, the CAPEX of improving the mini-grid and connecting to the national grid vastly outweighed revenue, requiring a very high level of support.

While increases in demand translated into increased revenue, some of the key financial metrics were also very context specific. Project 1, cited above as increasing its demand by 157%, does indeed project a corresponding increase in the revenue (of 157%). A relatively small increase in CAPEX (6.7%) albeit with a relatively high increase in OPEX (71%) means the extra revenue makes the whole mini-grid portfolio much more viable than without eCooking. The payback period reduces from 9 years to 4 and there is a very substantial increase (nearly 500%) in the Net Present Value (NPV) of the development. For Project 3 there is a very detailed investment model, and while increased revenue could reduce the payback period (with existing investment offers), the developer felt that the relatively modest inclusion of eCooking would ensure more favourable investment terms.

However, that good news example potentially masks complexity. Other systems such as Project 2, found that introducing a more modest penetration of eCooking (10%), would require similar upgrades on the CAPEX (9%) (although a modest increase in OPEX (14%)) but would generate much less extra revenue than in Project 1. This output of the financial modelling is confounded by a planned reduction in tariff. Overall, the NPV only increased by 20% and the payback period actually extended by 2 years. Project 4, with its small existing grid, 26% eCooking penetration and low value CAPEX upgrade, reduces its OPEX, has greater revenues (182%) but increases its payback from 4 years to 9 years.

The studies range from 7% to 81% penetration of eCooking and there is no direct correlation between that penetration and financial viability. Increases in CAPEX and OPEX vary across all the studies and again there is no simple relationship between such upgrades and financial stability. As expected, each mini-grid analysis was context specific. What we can see is that in all cases the introduction of eCooking increases revenue. Such an increase in revenue varies from modest to significant and does not always result in a lower period of time to reach payback. It does however generally enable increased NPV and/or Internal Rate of Return (IRR).

6.2 Demand-side management and variable tariffs

Surveys from different mini-grids' consumers suggested that cooking practices of households are mostly similar, with the majority cooking breakfast in the morning, lunch during daytime, and dinner in the evening hours. As the latter adds to what is usually the peak demand in a non-electric cooking load scenario, i.e. the evening demand, most models assumed the adoption of Demand Side Management approaches that minimise the evening demand by either shifting some of the demand to daytime hours, to reduce the requirement of a large battery storage system, or to simply only allow cooking during daytime hours. While not ideal, such restrictions on evening cooking can be accommodated by the pragmatic acknowledgment of fuel stacking.

Encouraging change in electricity usage in households takes many forms. Some of the main approaches considered across the models were:

- Community engagement initiatives (e.g., energy literacy, energy efficiency training)
- Energy efficient appliances (EPCs)
- Tariff rate structuring (e.g., time of use pricing, lower tariff)
- The use of technology (smart meters, smart plugs, load limiters, etc.)

Several studies described using time-of-use (ToU) tariffs to encourage customers to schedule their electrical appliance usage, including electric cooking activities, during daylight hours when solar radiation is abundant, reducing reliance of stored battery power, and saving customers money. In Project 5, lower tariffs were planned to be offered during high solar radiation times, typically during the day. In Project 2, daytime tariffs were 80% of the base tariff (7 AM to 5 PM), while nighttime tariffs were higher at 120% of the base tariff. Project 2 described the possibility of introducing special eCooking tariffs to incentivise usage and uptake of EPCs.

Some of the studies presented evidence that daytime eCooking could be incentivised, such as the following:

- In Project 1, surveys were conducted (of 200 participants across different communities) to understand cooking behaviours, finding that cooking in rural areas mostly occurs: (i) 8-10 am, breakfast, (ii) 12-2 pm, lunch, and (iii) 4-5 pm, dinner preparations, suggesting that a high proportion of eCooking could be confined to late morning and afternoon hours.
- Project 2 reported on a previous study finding that 61% of electric cooking load occurring between 9 AM and 4 PM (this was the natural consumption pattern without any additional price signals or customer training to influence shifting/alignment).
- In Project 4, 48% of 29 respondents who cook in the morning said they would be able to move cooking to after 9am, and 55% said they would be able to move from evening cooking to afternoon.

However, there were also negative opinions in Project 4 on shifting cooking times, as presented in Section 4.2.1. Furthermore, in Project 5 surveys and experiments with load limiters showed that most people want to cook in the evening. Project 6 did not report any assessment of willingness to shift cooking times. Finally, Project 7 did not try to shift any cooking to daytime, as MHP plants generate roughly continuous power 24/7. In MHP mini-grids, it may be important to shift eCooking times away from community peak demand, depending on capacity constraints.

Encouraging daytime eCooking means that higher levels of fuel stacking are likely, and even expected, both in the evenings and in the daytime (when solar insolation is insufficient to meet daytime eCooking demand). This was acknowledged by Project 2, which discussed "setting the expectation with customers that they should maintain backup supplies for their cooking needs can be readily managed. This allows for only meeting mid-day cooking needs on days that align with excess solar and [for eCooking to] be the first load to curtail when the system requires." However, generally the studies suggested that DSM measures would be sufficient to encourage shifting of cooking from morning and evening to daytime periods of high solar insolation. Further evidence through piloting and surveys is required to assess this assumption.

Project 2 presented useful guidance on demand management, including on strategic placement of eCooking customers throughout the distribution network. This involves allocating a specific number of eCooking customers per subnetwork, according to infrastructure capacities. The study also suggested that eCooking rollout could take place in a phased approach, where standard customers could use their service for a period, for example, 2-6 months before further eCooking introduction.

6.3 Modelling and assumptions

The models generally estimated electricity demand on an hourly resolution, compatible with energy system software packages such as HOMER. Due to variability in user behaviours and the short periods of rated power consumption which characterise energy efficient eCooking, finer resolution modelling such as per minute would lead to more accurate representations of multiple customers cooking with electricity. However, this requires more complex, stochastic modelling, to approximate diversity across users, which in turn requires further assumptions, and therefore a detailed understanding of the electricity demand in the community and of eCooking. Five-minute resolution load modelling would also improve accuracy, as presented in [13].

Six models used hourly resolution, three of which used HOMER, and one of which used PVSyst. Some of the models assumed high levels of cooking coincidence across users. Therefore, their modelling may have overestimated total electricity demand and peak demand, leading to oversizing of solar and battery storage capacities by HOMER and PVSyst. If hourly resolution modelling is used, it is important the specified load profiles aggregate higher resolution usage, generating average eCooking load levels each hour which represent diversity in cooking timings across different users.

Project 7 did break down each mealtime hour and consider different levels of coincidence of cooking within each hour, leading to vastly different peak demand results depending on coincidence level. This illustrates the importance of eCooking modelling assumptions and coincidence levels, which are easier to model with higher resolution load profile modelling. Peak demand is crucial in dictating mini-grid infrastructure capacity requirements. Only Project 2 and Project 7 assessed community peak demand and, as mentioned, Project 7 was unable to assert the most likely peak demand, instead presenting a sensitivity analysis of different coincidence levels. The other studies did not fully specify load profiles, nor did they report exactly how eCooking contributes to community demand and peak demand. Sophisticated, high resolution, stochastic modelling is required to accurately represent household eCooking profiles and aggregated profiles. Similar sophistication is required to estimate representative community-wide profiles, to understand how much eCooking adds to the community load profile, and how this varies across days.

6.4 Diesel generators and capacity shortage

Mostly, diesel generators were not included in the models. Only Project 2 and Project 5 discussed diesel generators. In Project 5, a diesel generator was included in modelling and its required runtime increased after the introduction of eCooking, but details on assumptions and load profiles were not presented, and the model was limited to hourly resolution.

Project 2 described how historically a reliable electricity service was provided through a combination of high solar PV penetration (90-95% of total energy demand) and backup diesel generators (5-10% of total energy demand). The case for 100% renewable mini-grids was then presented, as follows: “Diesel is expensive, supply chains are vulnerable, maintenance requirements are high, and the transport of diesel fuel requires significant logistics support, especially in rural communities with poor infrastructure.” The study recommended the following resilience measures for transitioning to 100% renewables:

- “Implementing load management practices (e.g., time of use pricing, education and outreach, etc.) to shift 50% of expected nighttime load to daytime and mitigate potential downtime from edge-case peak-loading conditions.
- Oversizing solar PV on AC-coupled system configurations to better allow solar PV to solely meet the daytime energy demand.
- Oversizing battery inverters to better optimise battery charging.
- Switching to lithium-ion battery technology for more optimised battery capacity use.
- Sizing systems to allow for a 5% capacity shortage across a given year.
- Maintaining a larger list of essential spare parts on site, in case of need of equipment troubleshooting and replacement.
- Deploying additional distributed renewable energy assets interconnected with the microgrids to help island critical services (e.g., healthcare, telecommunications).”

Therefore, Project 2 presented useful guidance on transitioning away from diesel generator usage. It continued: “To eliminate the cost and headaches of diesel, grid developers generally must choose between massively oversizing solar and battery systems and ‘spilling sunshine’ (over producing) during much of the grid’s working hours, or sacrificing reliability during the hours when the generation system is depleted. The former raises capital costs and severely limits financial viability while the latter diminishes quality of service for customers." The concept of capacity shortage is important here, and was discussed by multiple studies.

In Project 2, generally upgrading the PV capacity for increased eCooking satisfied need, with battery storage upgrades deemed unnecessary. Capacity shortage was a key factor, enabling PV and battery storage to be sized to meet most of the demand across the year, without oversizing to meet 100% of demand, which would require large systems at very high costs. A capacity shortage of 5% was permitted as follows: "This shortage in energy demand met across the systems was determined as sufficient for sizing generation systems large enough to supply energy needs but not too large so that the expected revenue cannot adequately meet project economic viability." Project 4 sized the mini-grid according to the "maximum allowable 4% (precisely 3.8%) capacity shortage. Capacity shortage beyond this limit will not be acceptable for Tier 4 and 5 electricity access according to the 'Multi-tier Matrix for Measuring Access to Household Electricity Supply' [11].

6.5 Carbon finance

Although the terms of reference for Phase 1 of COSMO invited observations and impact analysis of Carbon finance none of the developers laid out the financial effects. Carbon finance has had a turbulent 12 months, with analysis by Berkely University stating that most recent carbon financed cookstove projects were overclaiming by up to a factor of ten [14]. This has prompted many carbon buyers to reduce their offering (both quantity of purchases and price). In contrast the Berkeley paper stated that digital metered monitoring methods did not overclaim when applied to eCooking (marginally when applied to briquettes), and the new methods give accurate and verified carbon finance. Users of the new metered methods are currently able to acquire premium carbon prices [15].

At the same time while the above references the voluntary carbon market, Article 6 of the UNFCCC processes is making its way through to law in a number of countries [16]. 'Official' or formal carbon finance is set to grow.

How does this apply to mini-grids? With smart meters it is possible to know the actual electricity consumption of each household. With appliance specific monitoring or smart software looking at the load profile of the consumption, it would be possible to monitor appliance use and apply for carbon finance through the metered methods. This could be very important in the near future.

Registering for a carbon project is at the moment quite costly, of the order of $120,000. Including carbon finance at the planning stage, investments could include that registration fee and the verification through metering, and that could add another income and revenue stream to the mini-grid. This was not explored in the Phase 1 projects.

7 Conclusions

eCooking does increase household electricity demand, and in turn, community-wide demand, as well as increasing peak community demand. The impact of such demand increase depends on the mini-grid design and that in turn depends on the context. The studies showed that the impact of eCooking on a mini grid is very context specific. In Project 3 for instance the developer naturally oversizes their grid design for future growth and so eCooking can be added without extra CAPEX on the solar PV and battery storage installed capacities. On the other hand, planning for eCooking during the design phase for Project 1, meant that a modest 7% increase in CAPEX enabled a 150% increase in revenue with eCooking. While this picture is very positive, it stands in contrast to the very small grid of Project 6, that basically has to double the size of its existing grid (and its CAPEX) to accommodate an eCooking uptake, and with the interesting contrast of Project 7 (micro hydropower) which can increase revenue by eCooking, but would need to upgrade the transformers and wiring to accommodate significant adoption of eCooking in mini-grid communities because it was not planned from the start.

There is some evidence that some people are willing to shift cooking times to peak solar insolation hours (late morning and afternoon) with incentives, but willingness to do this will vary between contexts and consumers. Generally, PV capacity upgrades were higher than battery upgrades, due to assumptions that Demand Side Management measures, particularly ToU tariffs, could encourage daytime eCooking rather than evening eCooking. ToU tariffs require piloting to test their efficacy. It can be expected that, if solar mini-grids are not sized to accommodate evening eCooking loads, it is likely there will be high levels of fuel stacking for evening cooking. While this reduces eCooking usage levels within households it still improves the users' choice of cooking fuel and more often than not increases mini-grid financial sustainability through increased afternoon electricity sales.

Load modelling should be specified at high resolution (higher than hourly where possible) to capture realistic eCooking (and other appliances) coincidence levels across users. This will enable developers to determine realistic community electricity demand peaks and total electrical energy consumption, which the mini-grid must be able to deliver. Modelling assumptions to construct eCooking load profiles and community load profiles heavily affect outcomes and resulting capacity requirements. Furthermore, realistic eCooking usage levels should be specified which take fuel stacking into account, and different eCooking penetration levels in the community population should be evaluated to understand resulting upgrade requirements and financial feasibility, as opposed to say only considering one scenario, e.g. 80% eCooking uptake.

Regarding financial sustainability, the studies showed that introducing eCooking enables increased revenue generation from increased electricity demand. Although costs of mini-grid upgrades are sometimes high, increased revenues often enable increased NPV across project periods, even with reduced tariffs, and can reduce the payback period. The benefits are particularly clear for integrating eCooking into mini-grid planning, where much of the system CAPEX is required with or without eCooking. In these cases eCooking represents a relatively energy intensive and reliable load which is likely to generate significant mini-grid income on a daily basis, and which the mini-grid infrastructure can be designed around, improving the mini-grid business case. Integrating eCooking from the beginning has further benefits such as enabling a reduced average tariff due to increased demand, increasing low-interest debt accessible by raising CAPEX and "ticket size" for large institutional investors, and enabling better equity payments for investors.

The studies range from 7% to 81% penetration of eCooking and there is no direct correlation between that penetration and financial viability. Increases in CAPEX and OPEX vary across all the studies and again there is no simple relationship between such upgrades and financial stability. As expected, each mini-grid analysis was context specific.

Overall, integrating eCooking into mini-grid planning confirms its potential benefits immediately by financial modelling. Introducing eCooking to communities with existing mini-grid systems at significant penetration is more variable and tends to require capacity upgrades. It can improve financial sustainability over a sustained period by increasing community electricity demand, but not always. It can be seen as a reliable and significant load addition which can increase revenue, enabling increased profits once upgrades are paid off. It is worth keeping in mind that mini-grids already in operation will, with or without eCooking, require infrastructure upgrades or component replacements due to load growth or exhausted lifespans, at which point integrating eCooking becomes similar to integrating it into initial planning.

Beyond technical and financial modelling, the studies showed that the nature of mini-grid communities creates both opportunities and barriers for eCooking. In some contexts, consumers pay inflated prices for charcoal and firewood due to geographical isolation and transport costs, creating transferrable expenditure. Electric cooking could save both money and time for people in such communities. Even when firewood is collected for free, reduced drudgery could free up time for income generation, increasing the feasibility of switching to eCooking. The corollary of this is that mini-grids tend to have a relatively high tariff per kWh. While eCooking can be affordable and save households money when utilising a grid, the use of it on mini-grids does not always save households expenditure on alternative fuels. Realistic expectations on eCooking penetration and uptake are required when planning, and balanced with an understanding of fuel stacking behaviours among the community. Fuel stacking can often be helpful in that it mitigates the evening use of eCooking, although fuel stacking with polluting fuels still carries health and environmental damage risks.

To mitigate the upfront costs of eCookers, asset financing, subsidies, grant funding, and carbon financing should be explored. The mini-grid developer is in a good position to offer its users mechanisms for mitigating upfront and ongoing costs. The appliance financing required even for significant penetration of eCooking is small compared to the overall CAPEX of the mini-grid. Developers can carry the credit risk because a) they have a clear and constrained cadre of clients, b) they have mechanisms for taking payment from their clients which can be leveraged to include repayments for appliances, and c) it is in their own interests to stimulate increased demand and revenue on their mini-grid. Whether a subsidy is required for the appliance can be built into the overall financial model – selling or providing eCooking appliances at less than commercial price could still be an overall win for the mini-grid as they get a return based on 10 to 20 years of increased revenue.

None of the submissions explored accessing and including carbon finance in their models. Accessing international carbon finance requires registration fees that are often too high for very small projects (currently of the order of $120,000). While there are moves to reduce this entry cost, the mini-grid developer who may be raising $2m or more for their grid, may be able to include carbon registration fees in their financial model, and the carbon revenue could significantly improve the financial dynamics of the grid.

Although eCooking could provide cost savings in many contexts, provision of after sales services is inherently more difficult in remote communities, especially with eCooking supply chains mostly still nascent. The mini-grid operators highlighted this difficulty and planned local capacity building to reduce it, including training of local technicians and electricians to provide eCooking appliance repair services and establishment of local repair centres or appliance shops. Such measures will be essential for eCooking to scale in mini-grid communities. Appliance standards and testing protocols must also be introduced, which ensure appliances are safe, easy to use, and cook local dishes effectively, to reduce the need for repairs by increasing product quality.

Another crucial aspect of introducing eCooking was awareness raising and consumer training, with the importance of cooking demonstrations and safety training highlighted, and plans for advertising and provision of recipe books and other resources outlined.

As eCooking is adopted the importance of eWaste management will increase, and must be highlighted now, as recycling capability is currently limited, and remoteness of mini-grid communities requires creative solutions. The organisations planned to partner with recycling companies, set up collection points in the communities, raise awareness of eWaste so that cooks do not dispose of broken appliances, and partner with local electrical goods shops which could store spares from defunct appliances.

Overall, the Phase 1 studies give a deep and useful insight into the possibilities of mini-grids. While it can be frustrating to say that the technical, financial and even social dynamics are context specific, there are general lessons to be learned from the seven studies. It is clear that under certain conditions, mini-grids with eCooking could have a higher demand than without, and therefore have a higher revenue with a better investment return. However, there are also situations where adding eCooking increases the peak loads and energy requirements beyond the original design parameters, requiring an upgrade of the system which increases the CAPEX and where improved investment returns are not clear cut.

Some of the impact of improved revenue and improved returns is sometimes not obvious in the financial modelling. For instance, the end result of a better financial model could be better terms on the borrowing for the initial investment, or increased flexibility in setting the tariff rates.

Focusing on midday peak of power generation in a Solar PV mini-grid may require behaviour change of the consumer, but barely explored options of time of use tariffs seem feasible, and a pragmatic and realistic approach to fuel stacking are possibilities. eCooking does not have to be the primary cooking fuel to improve the quality of life of women and children in the community. Partial use would still release time, and while ongoing use of polluting fuels is not ideal and may continue to impinge on the health of the cook, even partial use can save climate emissions. Crucially, partial use would still lead to increased demand and revenue for the mini-grid.

Of the projects described above, four have been taken on to Phase 2 where MECS will contribute finance to the building or upgrading of the mini-grid based on Phase 1. If these projects succeed in including eCooking, they will help 28,000 people to access renewable energy and include Tier 5 stoves as part of their daily experience. Assuming only one meal a day is cooked with the mini-grid, then 2,300 tonnes of wood per year would be saved, over 10,000 tonnes of CO2 equivalent emissions and approximately 70,000 hours of women time saved per year and released for other activities (Based on the BARHAP model). The BARHAP model does include fuel stacking, but it was not possible to say how many Disability-Adjusted Life Years (DALYs) would be saved per year, by that partial use of eCooking. Nevertheless, the net social benefit could be monetised at $26,000 per year – and that is an externalised benefit that none of the financial modelling above took into account!

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